An Exploratory Study of Emotional Responses to Vibro-Tactile Music

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vibrotactile
/ˌvʌɪbrə(ʊ)ˈtakθʌɪl/
adjective
adjective: **vibro-tactile**

relating to the perception of vibration through touch.

Abstract

The sense of touch in humans is an important component of the way we perceive the world around us. In recent literature, studies focused on the sense of touch from a musical perspective and the possibility to use tactile illusions to convey meaningful musical aspects. The present study explored the emotional response to vibro-tactile music, with potential for enhancing the musical experiences of people suffering from hearing loss. Categorical and continuous models were used to measure emotional response. Several differences were noted between ratings of felt/recognized emotions, hearing and non-hearing participants, musicians and non-musicians. Musical and imaginative associations were also experienced by the participants in most cases. Overall, irrelevant of the intended emotion, nearly all excerpts were considered happy, and a few peaceful, suggesting a bias towards rating vibro-tactile as pleasant, which is consistent with participants' opinions. This suggests that vibro-tactile music is successful in conveying emotions and should be explored further.

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1. Introduction

1.1 Motivation

As humans, we perceive the world around us through our senses. Arguably, the visual and auditive sense have the higher perception impact – when we're faced with a new situation the visual and auditory sensory information are the first to reach us. Similarly, we are basing a lot of the judgements about the world surrounding us on sensory information, as well as our likes and dislikes – think about your favourite plushie as a kid… why was it so? Its texture, colour, softness, smell perhaps? Probably all the above, combined with a sense of familiarity and comfort associated with it. This brings us to the sense of touch. I like to imagine that, if senses would be a group of friends, the visual and auditive senses would be the extroverts who are always in the middle of the action and who need constant (new) stimulation, while the sense of touch would be the quiet introvert who notices everything and who is the glue that holds the group together - just because it is not always central it does not mean it is any less important. If you make an effort, you will realise that you associate certain actions, people, objects with how they feel – if I ask you to imagine that you are in a truck speeding on the highway, the first thing to come to mind might be the roaring noise and the passing of fields on the window, but close behind will be the feeling of being jilted from one side to the other or up and down (awful suspensions!), perhaps the constant vibration of movement and the heat of the cab (no air conditioning, of course). For each person, the sensory focus is different. For people who suffer from any sort of hearing loss, touch becomes an even more important sense that helps them navigate the world around them. It substantially shapes their perception of music, compared to people with normal hearing who are used to associating music with sound first.

Many studies have used tactile feedback in combination with the auditive to enhance their musical experiences. It is still unclear whether it is a viable solution. Firstly, to hear anything, most deaf or hard of hearing individuals wear hearing aids or cochlear implants to amplify the volume of the auditive stimuli reaching their ears. These distort the sounds to some extent, by cutting low and high frequencies. They also do not help with sound localization, so using them in an installation together with vibro-tactile stimuli might not be a very pleasurable experience for people wearing them. Secondly, an important consideration is whether it is fair to even ask them to wear aids in the first place, to fit into our idea of society – where the lack of auditive feedback can be a major drawback. It might be egotistical to deny them the pleasure of experiencing music, or to expect them to find ways around sound in order to perceive it.

That is why the idea of music designed only for the sense of touch holds a lot of appeal. In order for it to be comparable with music meant for ears in terms of complexity and capabilities to evoke or convey emotions, it would need to use more than just the vibrational feedback that accompanies sounds anyways (since all sound is after all vibration). A distinction is made here between the emotions recognized in a musical piece and those emotions evoked in the listener. Using tactile illusions – i.e., a surprising illusory sensation resulting from the mismatch between actual stimulation and what is perceived – to enhance the vibro-tactile feedback based on an audio signal is a novel approach with a lot of potential. By having more than one stimulation point (which is required for an illusion to work), dimensionality is added to the perception of the vibration. Dynamics that are often used in music (tempo, rhythm, melody) can be preserved through a sensation close to panning – when wearing headphones, a stereo signal uses panning to give someone the feeling of the sound travelling from one side to the other; similarly, with two points of tactile stimulation, vibro-tactile feedback can evoke a similar sensation.

Although it is somewhat intuitive in which ways tactile illusions can enhance dynamicity, it is still unclear how they influence the perception of emotions, or even if they can carry emotional information at all. Thus, this project is based on exploring vibro-tactile music in form of tactile illusions and how individuals respond to it from an emotional point of view.

Ultimately, this type of music is intended for people suffering from hearing loss, but it is not an exclusive experience reserved to individuals suffering from hearing loss. If their auditory is muffled, to concentrate on the sense of touch, it was considered that they would respond in a fairly similar manner to non-hearing individuals. Although considered sufficient for this novel exploratory thesis, later studies should focus on learning more about the emotional responses of people suffering from hearing loss in particular.

1.2 Main goal

The main goal of this study is to explore the emotional content conveyed by vibro-tactile music rendered from musical excerpts used in previous research (Vieillard et al., 2008) to tactile illusions. Empathy, musicianship level and hearing loss level were considered as individual characteristics which might have an influence on the perception of vibro-tactile (musical) emotions.

Moreover, the best apparatus for relaying clear tactile illusions was tested from a choice of three pairs of actuators (two commercially available and one purpose-built based on literature indications).

1.3 Research Questions

The main research question related to whether vibro-tactile music can carry any emotional information. Considering the goal of the study, several more specific questions were formulated:

RQ 1. Are voice-coil actuators purpose-built based on literature indications effective in transmitting accurate tactile illusions?

RQ 2. Do ratings of felt and recognized emotion differ in vibro-tactile music?

RQ 3. Are tactile illusions a meaningful and consistent way to transmit emotional information present in musical stimuli?

RQ 4. Are individual differences such as empathy, hearing loss level, and musicianship level influencing emotional ratings?

RQ 5. Are valence and arousal scores consistent with the ratings of their discrete counterparts?

RQ 6. Does vibro-tactile music evoke associations, and if so what kind?

1.4 Scope and limitations

This thesis was written in the context of a Master's degree in Music, Communication and Technology. It is focused on the music cognition perspective of musical emotions, with a music technology twist – instead of exploring the response to "traditional" music for ears, it is an exploration of the emotional response to vibro-tactile music (i.e., music for touch) expressed through a pair of actuators and with the help of three tactile illusions (phantom motion, cutaneous rabbit, funneling).

This decision was supported by my background in Cognitive Science and Music Psychology. Moreover, working as a research assistant at the RITMO Centre for Interdisciplinary research in Rhythm, Time and Motion I learned a lot about how technology can be used in the most creative ways, in almost any topic. After the idea of researching haptics (i.e., referring to the sense of touch) was planted, in was a great environment to find a more specific project/topic to consider.

This is not a cross-cultural study despite the collection of data from two countries, with many other international participants included as well. The sociological impact of vibro-tactile music for non-hearing individuals is only briefly mentioned as a motivation for the study and was not considered further. Due to my music cognition interests I chose to focus on how technology can be used to express emotions in music, rather than focusing on the technical aspects of the apparatus used, or the translation process from audio to tactile music.

1.5 Content overview

In section 2, a comprehensive theoretical background is presented, divided into two main sections: music and emotions, and musical haptics. The bulk of this thesis is structured around the design and results of the two experiments ran as part of this project. In section 3, the methods, results, and discussion of the pilot study are presented – which was design to test three pairs of actuators and decide on the one conveying the clearest illusions. In section 4, the methods, results and discussion of the main study can be seen – where the emotional response to vibro-tactile music was explored. Finally, in section 5, a general discussion of the results in the light of literature is presented, as well as suggestions for future work and conclusions.

2. Theoretical background

2.1 Music and emotions

In this section, music is considered from the point of view of its emotional effects. First, a discussion of music-evoked emotions and ways to measure them is offered, followed by a presentation of relations between certain aspects of music and their emotional correlates, and a discussion of the distinction between the felt and recognized emotions in the context of music. Lastly, empathy is introduced as potentially explaining certain individual differences regarding musical affectivity.

2.1.1 Affective responses to music

Music can be seen as braided through with emotions, and there are several approaches used to explain human affective responses to music. On one hand, a general agreement in the literature is seen regarding the ability to recognize emotions in music (the way a piece *sounds*). On the other hand, the idea that music also elicits ‘true’ emotions in the listener is still debated (Konečni, 2008). Researchers (e.g., Juslin & Västfjäll, 2008) have suggested multiple different psychological mechanisms that could account for the emotions induced by music.

It was initially postulated that rather than ‘true’ emotions, music elicits experiences of tension and relaxation in listeners, based on whether their musical expectation are violated or met, respectively (Meyer, 1956). More recent studies using behavioral, physiological and neurological techniques to measure the emotional responses to music found that people, in fact, respond to music in an affective way (e.g., Gagnon and Perez, 2003; Witvliet & Vrana, 2007). Moreover, even assuming that music affects us, there is no consensus regarding the nature of the response; nothing on this topic is yet a settled matter (e.g., Konečni, 2008).

Emotional responses to music can be categorized in a discrete or dimensional manner. The former approach is reminiscent of the basic emotions paradigm (Ekman, 1984), where emotions are measured using categorical scales (e.g., one rating scale each for individual emotions such as happiness or sadness). The latter approach is based on dimensional models of emotion. One such example is the *circumplex model* (Russell, 1980); it suggests two dimensions on which affective experiences can be evaluated – arousal (high to low) and valence (positive to negative). Although most emotions can be accurately described using these variables (e.g., happiness would have positive valence and high arousal, as it is considered a positive emotion with a high level of stimulation, and scariness would have negative valence and high arousal, as it is a negative emotion with high stimulation), the two dimensions are still insufficient for finer distinctions between emotions that would fall under the same quadrant (e.g., fear and anger; Hunter & Schellenberg, 2010). Nevertheless, this model has been used extensively to explore the affective response to music-induced emotions (e.g., Eerola & Vuoskoski, 2011; Vieillard et al., 2008), and seems to be most effective so far (see the systematic comparison by Vuoskoski & Eerola, 2010).

2.1.2 Musical characteristics and their related emotional connotations

Music can be characterized through several aspects – tempo, mode, loudness, pitch, timbre, melody – which presumably influence the affective responses people have. Many studies in the literature have attempted to find consistent relationships between these musical dimensions and specific emotions. A few general findings are presented below.

Tempo & Mode.

From early on it was found that tempo and mode were important factors in deciding the emotion of a musical piece (Hevner, 1935) – with the mention that it was not made clear whether the participants evaluated their felt emotions evoked by the music or the emotions recognized in the music. More specifically, happiness – fast tempo, major mode, and sadness – slow tempo, minor mode, were most consistently associated thorough literature (for a review see Juslin & Laukka, 2004).

Loudness.

Louder musical pieces were found to be more arousing, without a clear distinction of their pleasantness (e.g., they were found as both triumphant or uneasy; Gundlach, 1935). Balkwill et al. (2004) found anger to be perceived as related to loudness across music styles, which indicates that loudness could be a universal cue to anger (Hunter & Schellenberg, 2010). More recently, changes in loudness were found to correlate positively with arousal (e.g., crescendos increase the arousal level; Schubert, 2004).

Timbre.

As a musical characteristic, timbre has been studied less with regard to its emotional transmission capabilities. Early findings suggest that soft and sharp timbres are associated with tenderness/sadness, and anger, respectively (Juslin, 1997).

Overall, musical dimensions are hard to associate consistently with emotional responses, with a few exceptions. However, there seems to be a trend towards successfully expressing and decoding emotions (mostly happiness and sadness) in short melodies where only one emotion is tackled at a time (Juslin & Laukka, 2003).

2.1.3 Felt versus recognized musical emotions

Assuming that emotions can be recognized in music, as well as evoked by it, a logical consideration arises – how do the two types of emotional responses differ, if they do. This is a complex problem without a general conclusion, as often studies differ in their methodologies (the questions deemed appropriate are not consistent, and sometimes there is no apparent distinction or specification of which type of emotional response was desired from the participants). There are several discrepancies which can be observed in literature.

In the study by Juslin and Laukka (2004), 70% of the participants reported that the recognized musical emotion often evokes a similar one. Vieillard et al. (2008) found that felt emotions were rated higher than recognized ones. This is disputable, considering that the musical stimuli were short and created electronically, and one would expect the unfamiliar and relatively unexpressive pieces to evoke less feelings – a potential explanation is the different populations which rated each type of response, when a better approach would be to explore how the ratings interconnect within participants (Hunter & Schellenberg, 2010). Nevertheless, most studies are ambiguous in specifying and distinguishing which type of emotional response they desire; even when they do, the methods and questions used for differentiating between felt and recognized emotions are not consistently used (Kallinen & Ravaja, 2006). All this results in an amalgamation of findings which might convince any new researcher that treating the affective response to music as a whole is the better approach.

2.1.4 Musical emotions and empathy

Empathy refers to one's ability to understand and experience what someone else is experiencing. Davis (1983) developed a scale (the Interpersonal Reactivity Index; IRI) to measure the general disposition to experience empathy, which differentiated between its cognitive and affective components. Cognitive empathy is an intellectual state during which one constructs an internal model of other's emotions and uses it to understand their perspective. Affective empathy is a quick, instinctive emotional reaction to other's feelings. While the first requires higher processing mostly in the prefrontal brain regions, the latter is considered an involuntary, automatic response mechanism (Wöllner, 2012).

Music can be considered a social interaction between composers, performers and listeners (North & Hargreaves, 2008), which is highly relevant to the important role empathy has in interpersonal communication. Seeing gestural movements made by musicians during performances is believed to enhance listeners' emotional responses (Scherer & Zentner, 2001). Consequently, as empathy is at least to some extent dependent on another's actions, it is argued that it influences the interpretation of emotional expression in music. Indeed, the affective and overall empathy levels of participants were positively correlated with the appreciation of music (when it is correlated with visual information as well) in a more recent study (Wöllner, 2012). Some findings suggest that musicians have higher empathy (Cho, 2021).

Emotional contagion could be considered an important mechanism underlying the emotional effects of music. It refers to the capability of internally mimicking the expressed musical emotions (Juslin & Vastfjall, 2008). This underlying mechanism may interact with certain individual differences, such as empathy, which may be the reason why some people are more susceptible to music-induced emotions than others. In line with this suggestion, Vuoskoski and Eerola (2012) found that individuals with higher empathy felt more sadness in the presence of unfamiliar (sad) music.

The Interpersonal Reactivity Index has four subscales, two of which are used in the present thesis: *empathic concern* – tapping into feelings of warmth, compassion and concern for others undergoing negative experiences; and *fantasy* – measuring the tendency to transfer oneself through imagination into the shoes of fictional characters (Davis, 1983). These two subscales, representing both affective and cognitive components of empathy, were considered the most appropriate for a musical response (especially for music without lyrics or accompanying video; see e.g., Vuoskoski et al., 2011).

2. 2 Musical Haptics

In this section, the sense of touch in humans is first introduced, then force feedback in the context of haptic technology, followed by a presentation and classification of haptic music players, audio-tactile rendering methods, vibro-tactile music, and lastly, tactile illusions in this context.

2.2.1 The sense of touch in humans (hands)

We identify the temperature and roughness of surfaces through touch. More specifically, through complex brain mechanisms part of the somatosensory system which are taking their information from mechanoreceptors inhabiting our skin (Birnbaum & Wanderley, 2007). Proprioceptors, found in our joints, muscles and ligaments allow us to feel the weight, positioning and location of our limbs and are an important part of our effective functioning in the world. Perception of vibro-tactile stimuli is done through the skin, by mechanoreceptors (Birnbaum & Wanderley, 2007). Intuitively, depending on the intensity of the stimuli and the body part that it is in contact with, the limits of vibro-tactile perception differ. Several studies (Chafe, 1993; Verrillo, 1992; Young, Murphy & Weeter, 2015) have investigated the frequency range of vibro-tactile perception, establishing 0.3 Hz and 1000 Hz as the lower and upper limits, respectively.

Of the fingertip, forearm and abdomen, the fingertips were found to be more sensitive (Jones & Sarter, 2018) – requiring less energy (lower intensity) for perceiving vibro-tactile stimuli at the same frequency. Together with the lips, the hand is also at the higher level of spatial resolution (how well stimuli presented in different body locations are recognised, see the sensory homunculus) with 10 mm, compared to over 40 mm in the calf or back (Goldstein, 2010).

These findings about the high sensitivity of fingertips found in haptic research are not surprising considering the distribution of mechanoreceptors in the hand. There are four main types of mechanoreceptors specialized in absorbing information about touch, pressure, vibration and cutaneous tension and sending it to the central nervous system for complex processing: Meissner's corpuscles, Pacinian corpuscles, Merkel's disks and Ruffini's corpuscles (Purves et al., 2001), which can be seen in Figure 2.2.1.1 below. These are known as the high-sensitivity (meaning they have a low threshold) mechanoreceptors because they are induced to produce action potentials even from weak stimulation of the skin – they transmit tactile information rapidly to the nervous system by being innervated with largely myelinated axons (for more details on the major somatic sensory receptors see Table 9.1 in Purves et al., 2001). In short:

- Meissner's corpuscles are the most common in smooth, hairless skin (such as the fingertips) and are particularly sensitive to low-frequency vibrations (30-50 Hz), accounting for 40% of the sensory innervation of the human hand.
- Pacinian corpuscles act as a filter which only allows high frequencies (250-350 Hz) to activate the nerve endings, have a lower response threshold and a faster adaptability than Meissner's corpuscles, accounting for 10-15% of the receptors in the hand.
- Merkel's disks are particularly dense in the fingertips (and lips), are sensitive to light pressures, and have slower adaptability, accounting for 25% of the cutaneous receptors in the hand.
- Ruffini's corpuscles account for 20% of the receptors of the hand; however, they are not sensitive to any particular tactile sensation, but to the cutaneous stretching resulting from digit or limb movements (these are thought to be more similar to proprioceptors that also answer to internally generated stimuli).

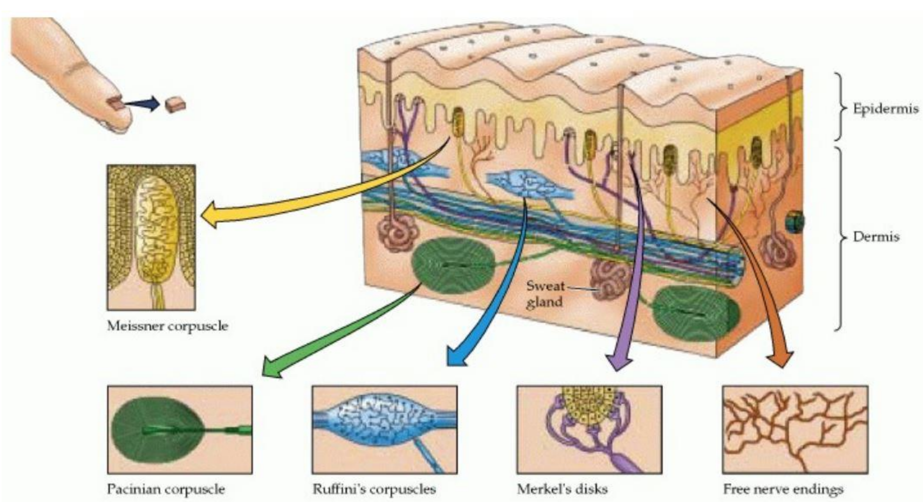


Figure 2.2.1 The major types of mechanoreceptors found in the smooth, hairless skin of the fingertips. *Retrieved from Purves et al. (2001) where it can be found as Figure 9.3.*

Based on this sensory knowledge, as well as the previous studies which have found the fingertips to be highly sensitive to vibro-tactile stimuli (Chafe, 1993; Verrillo, 1992; Young, Murphy & Weeter, 2015), actuators were placed between fingertips in the main experiment of this study. In the pilot study, placement on wrists was also tested, with inferior results.

2.2.2 Haptic technology – Force feedback

To enhance the interaction between humans and technology, the sense of touch has been employed through human-computer haptic interfaces – vibrating actuators which generate force feedback at the contact with users' skin to facilitate interaction (Hayes, 2011). Vibratory stimuli incorporated in mobile phones to alert users of incoming notifications, or the haptic feedback present when using a touch screen keyboard are widely used applications. Additionally, human-computer haptic interfaces can be used in designs of sensory substitution systems aimed at facilitating information transfer to people suffering from hearing loss or blindness (Giordano & Wanderley, 2013).

Besides its extensive use in enhancing human-computer interfaces, this type of haptic technology is also used to enhance the music listening experience, live or recorded, (Turchet, West & Wanderley, 2020) and the playing of digital musical instruments. These applications are known as *musical haptics* (Papetti & Saitis, 2018). Moreover, vibro-tactile feedback can be used to convey musical information through the skin, although there are limitations regarding how many musical features can be mapped to vibrations (Chafe, 1993). Strategies for rendering musical features to vibratory stimuli exist and are under continuous development (Birnbaum & Wanderley, 2007; Eitan & Rothschild, 2011; Romagnoli, Fontana & Sarkar, 2011). Details about audio-tactile rendering are presented in section 2.2.5.

2.2.3 Haptic music players (HMP)

In the field of music, haptic technology can be divided into displays used when playing digital music instruments, and displays used for *playing* haptic music (based on the categorisation made in Remache-Vinueza et al., 2021). This study focuses on the latter, also known as haptic music players (HMP), more specifically on the wearable types, as described in section 2.2.4.

The architecture of a HMP consists of audio signal processing software (for the extraction of musical information from an audio signal and its subsequent translation to vibratory signals), digital to analog converter, amplifier (to control the intensity) and actuators (which have contact to the skin; Remache-Vinueza et al., 2021). From the existent sensory modality variations in literature (e.g., Boer, Cahill & Vallgårda, 2017; Florian et al., 2017; Mazzoni & Bryan-Kinns, 2016; Sharp, Bacon & Champoux, 2020), the present study focuses on haptic stimulation (with the absence of auditory or visual feedback).

The vibrating device that transmits the vibro-tactile stimuli to the skin of the user through direct contact is called an actuator. Depending on the purpose and design of research, studies can use from one to several actuators. There are several types of actuators that are used in vibro-tactile musical displays (for a comprehensive overview see section 3.2 in Remache-Vinueza et al., 2021).

For each desired application of haptic technology there are certain criteria that should be considered when choosing a type of actuator. In musical applications, vibro-tactile stimulation of the skin is employed to enhance the experience of listening to music, to convey musical compositions to people with hearing loss, or to render vibro-tactile music compositions (Giordano & Wanderley, 2013).

As suggested in Remache-Vinueza et al. (2021), the step of selecting the proper actuators was extended into a comparison between two types of actuators; their capabilities and limitations regarding the desired application of transmitting vibro-tactile music and accuracy for transmitting vibro-tactile music made of tactile illusions. More specifically, voice coil and piezoelectric actuators were explored (see section 3.1 where the pilot study apparatus is detailed). The former is a popular choice due to the little signal processing required from audio to vibrations (pitch is mapped to frequency and loudness to intensity of vibrations; Petry, Huber & Nanayakkara, 2018) as well as their low-cost efficiency (Birnbaum & Wanderley, 2007). The latter, also known as piezo-buzzers, use changes in an electric field to generate vibrations and require specific electronics (Papetti & Saitis, 2018); even so, they remain a flexible, low-cost and energy-efficient choice. The differences between the two types of actuators reported by participants in the pilot study are discussed in section 3.3, including feedback from experts in the fields of music technology and music cognition.

2.2.4 Categorising haptic music players (HMP).

Depending on the way they are attached to the body of the user and where, three main categories can be distinguished: haptic installations, haptic wearables, and hybrid.

Haptic installations.

As the name suggests, these are arrangements of fixed haptic devices. HMP-installations are mainly used in research to explore how people with hearing loss respond to vibro-tactile musical stimuli. Ever since Komatzu (2002) introduced the idea of using a chair as a HMP, haptic chairs have been widely used in research (e.g., Fontana et al., 2016; Karam et al., 2010; Yamazaki, Mitake & Hasegawa, 2016). Even before, between 1970 and late 1980s, the Norwegian educator and therapist Olav Skille developed the first VibroAcoustic Chair to use in music therapy (as referenced in Skille & Wigram, 1995). While limited from a portability and customisability perspective, the chair has a bigger spatialisation area available as a resource to augment the perception of vibro-tactile music stimuli (Gunther & O'Modhrain, 2003).

Haptic wearables.

The idea of wearable HMPs dates back to the concept of a vibro-tactile compositional tool "Skinscape" (Gunther, 2001) which was later implemented in a whole-body wearable haptic interface (Gunther & O'Modhrain, 2003). For almost two decades, the idea of wearable HMPs evolved. The developed designs of prototypes start from covering small portions of skin to whole-body wearable haptic garments – bracelets (Turchet, West, Wanderley, 2020), gloves (Sharp, Bacon & Champoux, 2020), mobile device mockups (Yoo, Hwang & Choi, 2014), belts (references Branje et al., 2010, Vallgårda, Boer & Cahill, 2017; Yamazaki et al., 2018), jackets (Boer, Cahill & Vallgårda, 2017; Hattwick et al., 2015; Turchet, West, Wanderley, 2020), body-suits (Gunther & O'Modhrain, 2003; West et al., 2019). Depending on the body part they are intended to be attached to, the design of wearable HMPs considers the correlated perception thresholds (Remache-Vinueza et al., 2021) as well as its intended usage – as vibro-tactile feedback only, or in combination with auditory and visual feedback (e.g., Boer, Cahill & Vallgårda, 2017; Florian et al., 2017; Mazzoni & Bryan-Kinns, 2016; Sharp, Bacon & Champoux, 2020; Yamazaki et al., 2018).

Haptic hybrid installations.

These setups combine fixed and portable elements from the previous two categories: e.g., using vibrating objects, haptic jackets and platforms in a concert setting meant for deaf people (Garrix, 2016). Vibro-tactile music input devices allow for composing and performing vibro-tactile music that the audience can perceive in real-time – e.g., the Vibrochord (Branje, 2014; Branje & Fels, 2014; Jiam & Limb, 2019) – and are distinguished from haptic-enhanced digital musical instruments by their lack of sound generation as well as by their intent towards vibro-tactile music composition and/or execution.

Figure 2.2.4 The final version of the Vibrochord. *Retrieved from Branje, 2014.*

Overall, the literature fluctuates towards designing new and improving existing wearable HMPs – in the review by Remache-Vinueza et al. (2021), 50% of the included publications explore wearable haptic music players, with more than half of these published very recently (6 years). Of these, various focused on pairing the vibro-tactile feedback with visual and/or auditory feedback, while the designs were all over the range mentioned above. It is then a state-of-the-art topic to explore HMPs in the context of vibro-tactile music considering individuals with hearing loss. The present study focused on literature that used only vibro-tactile feedback in their design; however, many relevant studies that used audio and/or visual feedback are included.

2.2.5 Audio-tactile rendering

Ideally, rendered audio to vibro-tactile stimuli should be able to convey all musical features – such as rhythm, pitch, melody, timbre, loudness – as richly in the vibratory music. However, this is not the case, however, even with currently proposed audio-tactile mapping algorithms. In this section relevant information about translation techniques is presented for each musical feature mentioned above.

Rhythm.

Rhythm seen as a pattern repeating over time (Jiam & Limb, 2019) can be easily perceived through vision, audition, and touch (Giordano & Wanderley, 2013; Mazzoni & Bryan-Kinns, 2016). Furthermore, in vibro-tactile music rhythm appears to account for a greater part of the experience than the other elements (Baijal et al., 2012; Jack, Mcpherson & Stockman, 2015). Depending on the frequency band of the original auditory stimulus, filters can be used to enhance the vibro-tactile rhythm (Jack, Mcpherson & Stockman, 2015) – e.g., a low-pass filter to enhance the bass in a jazz piece. On the other hand, vibro-tactile rhythm can be created from scratch (Vallgårda, Boer & Cahill, 2017) by synthesizing signals into patterns of high intensity pulses; however, without great control over the signal received by the actuators. Both techniques have their limitations, and it has to be considered that the type and size of the actuators used, as well as their positioning can widely affect the perception of rhythm. When designing HMPs for people with hearing loss, who appear to proficiently identify rhythms (Alves Araujo et al., 2017), a clearer understanding of how they perceive rhythmic patterns (compared to hearing individuals) has to first be established.

Pitch.

Considering the limited skin perception of frequencies (between 0.3 Hz to 1000 Hz; Chafe, 1993; Verrillo, 1992; Young, Murphy & Weeter, 2015), translating pitch to vibratory stimuli is a complex and challenging task. A common method is to use voice coil actuators that simply convert the pitch and loudness of the auditory stimuli to frequency and intensity in the vibrations (Petry, Huber & Nanayakkara, 2018). However, in this case information from high frequencies (above 1000 Hz) could be lost, even when transposed in lower register. Remache-Vinueza et al. (2021) has done a more comprehensible analysis of the different translation methods (see section 4.2). Another interesting finding is the association between tactile metaphors and musical aspects (Eitan & Rothschild, 2011) – e.g., using sharpness, softness and/or heat to describe different pitches. This concept is especially relevant for people with congenital or early-detected hearing loss, who have little to no experience of (auditory) music, and for whom associations with textures, heat, and pressure may be more intuitive and may help to understand existing music – or experience directly synthesized vibratory music that uses tactile metaphors (Chang & Sullivan, 2008).

Melody.

Seen as (patterns of) pitch changes over time, melody has similar tonal-translation limitations as described above. Some solutions have been explored in the literature (see section 4.3 in Remache-Vinueza et al., 2021). West et al. (2019) represented vibro-tactile melody with a distribution of frequencies across the body varying over time, and spatio-temporal tactile illusions (which are detailed in section 2.2.7). Melody is characterized by intervals – depending on the placement of the actuator(s), a difference of around 8 Hz between the vibro-tactile stimuli was found to be noticeable (Egloff, Wanderley & Frissen, 2018), with larger intervals being identified easier. This suggests that compared to the auditory sense, touch has a lower resolution for pitch discrimination. For individuals suffering from hearing loss, it is even more challenging to grasp, since their conception of music and tonality may differ wildly than that of hearing individuals (Petry, Huber & Nanayakkara, 2018).

Timbre.

Understood as the texture of sound, timbre is based on its frequency content, which can be reliably transmitted through vibro-tactile devices. A previous study (Russo, Ammirante & Fels, 2012) showed that the reducing of the frequency range for tactile perception from auditory signals limited the capability to recognise small spectral variations of timbre; nonetheless, the timbre of the different musical instruments was identified reliably in vibro-tactile stimuli. Mechanoreceptors found in skin enhance our capability to differentiate between waveform signals through touch (Gunther & O'Modhrain, 2003) by acting as tactile filters (Young, Murphy & Weeter, 2015)), aptitude which may be considered when rendering sound texture to vibro-tactile texture. Another possible tool for rendering timbre that could be explored in future studies are tactile metaphors (Remache-Vinueza et al., 2021).

Loudness.

Vibro-tactile loudness can be said to correlate with the amount of displacement of skin by the actuators (Birnbaum & Wanderley, 2007). For vibro-tactile musical stimuli, loudness of the original audio signal can be translated directly onto the intensity of the vibrations (Petry, Huber & Nanayakkara, 2018). Regardless, rendering audio loudness onto vibration still has challenges, such as psychophysical effects present when more than one actuator is used (e.g., summation or suppression, i.e., the perceptual increase or decrease of loudness; Verrillo, 1992) – which has significant implications for HMPs which employ several actuators.

2.2.6 Vibro-tactile music compositions (VMCs)

Vibro-tactile music compositions (VMCs) as a way of composing for the sense of touch is very new compared to the already established "music for the ears" and is still being explored, with new methodologies developing as we speak. This type of music is primarily intended for individuals with hearing loss, while allowing for the enjoyment of hearing individuals too. VMCs are meant to be transmitted through HMPs and can be rendered from audio or composed from scratch (Boer, Cahill & Vallgårda, 2017; Hattwick et al., 2015; Vallgårda, Boer & Cahill, 2017), to be played and enjoyed in live (Branje, 2014; Branje & Fels, 2014) or other circumstances. Apart from using the musical features detailed above, VMCs have another characteristic to consider – space (Gunther & O'Modhrain, 2003) – which can be expressed through spatio-temporal tactile illusions. Without having a precise correlation with an element of auditive music, the apparent sensations resulted from vibro-tactile illusions have the potential to carry and transmit meaningful musical information – e.g., the illusion of a phantom motion could be associated with dynamics present in the music or musician, or emotions (Gunther & O'Modhrain, 2003). The potential of vibro-tactile illusions has been considered for VMCs (check Giordano & Wanderley, 2013; Gunther, 2001; Gunther & O'Modhrain, 2003; Hatwick et al., 2015; Hayes, 2015; Turchet, West & Wanderley, 2020; West et al., 2019) and found to be ample enough to warrant continuous exploration in future studies. In the next section, the three major tactile illusions (also utilized in this thesis) are described. VMCs have great potential for people with hearing loss¸ and could be investigated as only vibro-tactile stimulation (without pairing with audio and/or visual feedback) in similar ways to already existing studies (Hattwick et al, 2015; Vallgårda, Boer & Cahill, 2017), to find meaningful ways for deaf or hard of hearing individuals to enjoy music.

2.2.7 Tactile illusions

An illusion is commonly understood as occurring when one's perception is not matched by the physical stimulation. Tactile illusions refer to tactile stimulation that induces an illusory sensation which could be surprising and/or perplexing (Hayward, 2015).

Based on the classification by Lederman and Jones (2011), tactile illusions are active or passive – in a similar way to how touch is active (movement of the skin over a surface) or passive (movement of something over the skin). Likewise, tactile illusions can be classified as related to the perceived propertied of physical objects (e.g., tactile diplopia), or regarding the *haptic space* – of this category, most common are the phantom motion (Alles, 1970; Kirman, 1974), cutaneous rabbit (Geldard & Sherrick, 1972) and funneling (Békésy, 1958), which are also used in this thesis.

Due to the existence of two stimulation points (a pair of actuators), tactile illusions can convey direction (Luces, Okabe, Murao & Hirata, 2018). The perceived illusion can be discrete (such as the cutaneous rabbit; Geldard & Sherrick, 1972) or continuous (such as the phantom motion; Alles, 1970).

Spatial haptic illusions make use of the space available on the skin of a person and could express movement through their temporal and spatial properties – i.e., change in direction, localization and tempo, when an event is influenced by the presence of another within certain temporal and spatial bounds (Patel, Ray & Manivannan, 2019). It was initially thought that such illusions can only be felt "on the body", but recent studies have shown that "out of body" perception is also possible (e.g., between right and left forearms; Eimer, Forster & Vibell, 2005; Lee, Lee & Kim, 2013; Miyazaki, Hirashima & Nozaki, 2010; Patel, Ray & Manivannan, 2019).

From a neurological perspective, the findings are inconclusive regarding which brain areas are activated when processing tactile illusions. Initially, it was believed that these phenomena trigger the somatosensory cortex, activating the somatotopic location equivalent to the location of the illusory sensation (Blankenburg et al., 2006; Gedard, 1985; Gross, 2006). They also found activation in higher order brain areas such as the secondary somatosensory cortex. However, their study was motivated by the false assumption based on previous findings that the cutaneous rabbit illusion does not cross the body midline (Geldard & Sherrick, 1972). Due to this misconception – which was identified by studies which reported consistent illusory sensations when the two locations of the stimulation were on different limbs (e.g., Patel, Ray & Manivannan) – the findings that show somatosensory activation have to be taken with a grain of salt. In a more recent study activation in the parietal lobe was observed, through brain imaging techniques, which is unsurprising since it is a key component in the pathway of tactile information processing (Lee et al., 2015). The limbic lobe was also activated, suggesting that tactile illusions may be considered a memory and recognition task.

Tactile stimuli are also subject to temporal biases – a touch can only be consciously detected as fast as the nerve conduction allows it; thus, the closer the touch is to the brain the shorter the time to "feel" it. This results in an interesting effect which is also employed by tactile illusions: if the ankle and the forehead of someone would be touched simultaneously, the latter would be perceived first, as it takes 50ms more for the touch on the ankle to reach the brain (Harrar & Harris, 2005).

In the literature, tactile illusions have been mostly studied regarding their practicalities for mobile and media platforms – such as enriching the movies and video games experiences, but also for driving and navigation aids (Israr & Poupyrev, 2011). Although it has been found that perception of the illusions is enhanced by adding visual feedback (Lee, Kim & Kim, 2012; Lee, Lee & Kim, 2013), other found supporting evidence showing that they can be perceived with only tactile feedback as well (e.g., Geldard & Sherrick, 1972; Patel, Ray & Manivannan, 2019).

Rendering audio to touch is challenging, and the tactile feedback has been mostly studied together with visual and/or auditive feedback (e.g., Boer, Cahill & Vallgårda, 2017; Florian et al., 2017; Mazzoni & Bryan-Kinns, 2016), although it has been used (e.g., Sharp, Bacon & Champoux, 2020; Yamazaki et al., 2018). Using tactile illusions to enhance the vibro-tactile musical experience is an emerging topic (e.g., Remache-Vinueza et al., 2022).

In this thesis, three spatio-temporal tactile illusions were used when rendering the compositions from audio to touch: phantom motion (Alles, 1970; Kirman, 1974) – a perception of movement, cutaneous rabbit (Geldard & Sherrick, 1972) – a perception of displacement, and funneling (Békésy, 1958) – a static sensation that can be used as an apparent change of location.

Phantom motion.

This illusion is known as phantom sensation, apparent tactile movement, tactile apparent motion, or phantom motion.

It refers to a simultaneous activation in two locations of actuators with modulated intensity to convey an illusion of movement between the two positions (Bellicha, Trujillo-Leon & Bachta, 2019; Kirman, 1974). The phantom motion is only perceived if the duration of the stimulus-onset asynchrony is just right – when it is too long the vibrations are sensed as discrete occurrences, and when it is too short, the vibrations are sensed as one occurrence (Lederman & Jones, 2011). Thus, consistent with the suggestions by Alles (1970), the phantom motion seems to come from the interaction between temporal and amplitude inhibitions.

This tactile illusion was consistently sensed “out of the body” (Bellicha, Trujillo-Leon & Bachta, 2019; Pittera, Obrist & Israr, 2017; Remache-Vinueza et al., 2022).

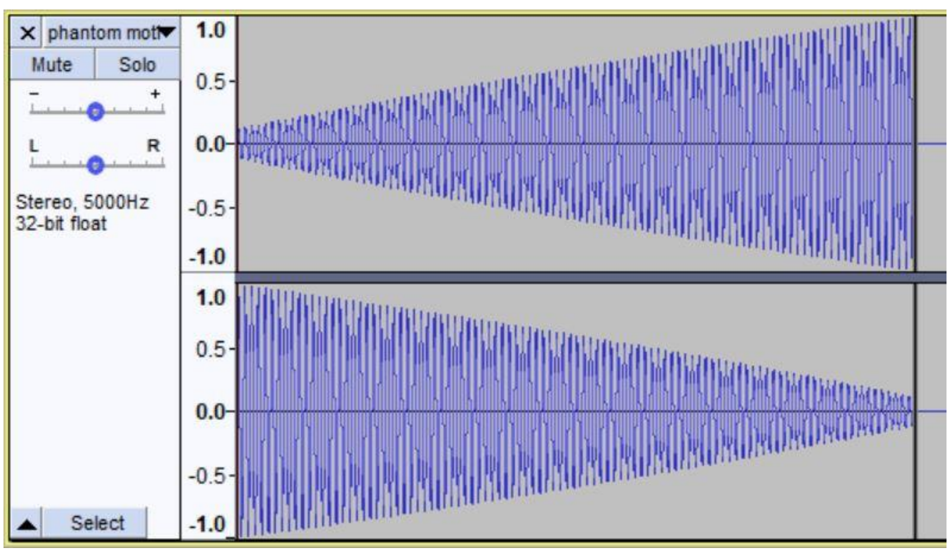


Figure 2.2.7.1 Signal of the phantom motion illusion as played in Audacity

Funneling.

Funneling (or “Illusory actuator”) refers to the simultaneous stimulation of two parts of skin with different amplitudes, which results in an error of localization of the sensation somewhere between the two original stimulation locations (Alles, 1970; Békésy, 1958).

Although funneling was originally discovered "on the body" (between two points on the same forearm; Békésy, 1958), for the purpose of this study, the extension known as "out of body" funneling illusions was used. The latter is similar to the former, with the exception that the phantom point is perceived externally (e.g., between two hands; Patel, Ray & Manivannan, 2019), in a location where there is no physical actuator.

The location of the illusory point can be controlled by changing the intensity and duration of the stimulation. By temporally modulating the amplitude of two points of stimulation and delivering successive funneling simulations at different locations, a "moving" directional sensation can be caused; this is also known as "apparent movement" (Israr & Poupyrev, 2011; Seo & Choi, 2010). Many tactile pattern systems use this technique for a richer experience than that provided with only one actuator (Lee, Kim & Kim, 2016).

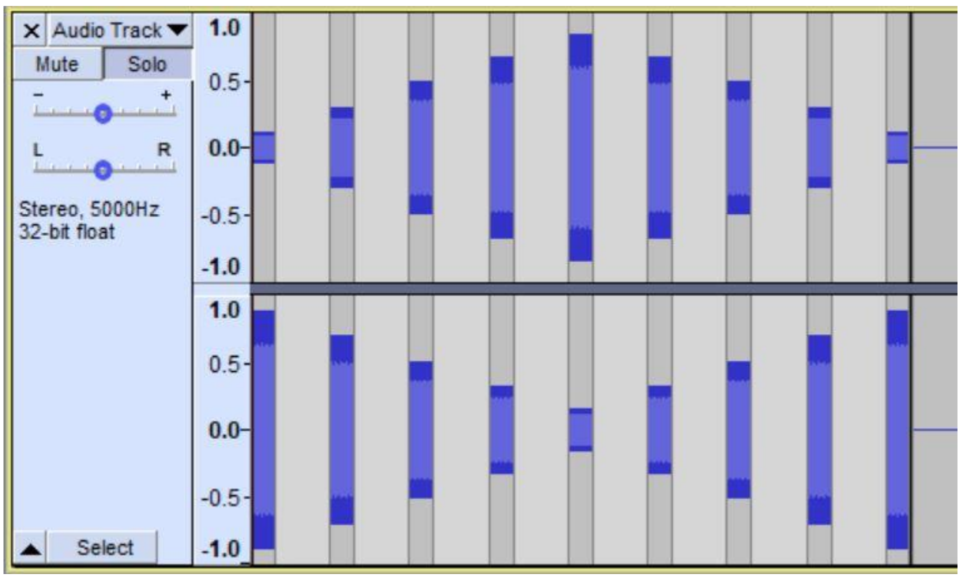


Figure 2.2.7.2 Signal for a succession of funneling illusions creating an apparent movement as played in Audacity

Cutaneous rabbit.

Discovered incidentally in 1972 and reminiscent of a hopping rabbit, this is how this illusion got its widely used name, although a more scientific term for it would be sensory *saltation* (Geldard, 1985). In this tactile illusion, two locations are stimulated successively, and the first stimulus feels like is shifting towards the second in the form of discrete "jumps" (Geldard & Sherrick, 1972). Perceived as a progressive movement of stimuli across the skin, it is created by sending short consecutive impulses at both locations, with short time intervals between.

It was originally believed that the sensation only occurs if the two stimulated locations are "on the body" (i.e., at two positions on the same patch of skin, such as on the same forearm); however, it has been found that the cutaneous rabbit tactile illusion is felt even if the stimulated skin areas are anatomically distinct – e.g., between the right and left arm, wrists or index fingertips (Eimer, Forster & Vibell, 2005; Miyazaki, Hirashima & Nozaki, 2010), if the actuators are kept relatively close.

Generally, the stronger the tactile stimuli, the easier it is to place it (Steenbergen et al., 2014). For the purpose of tactile illusions, and cutaneous rabbit specifically, however, a weaker stimulus is more beneficial – it allows for spatial and individual stimuli uncertainty (Tong, Ngo & Goldreich, 2016). This illusion is also subject to a temporal bias, which can be noticed through the attention shift to the expected location of the stimuli (e.g., the attention shifts to the position where the next stimuli is thought to occur; Kilgard & Merzenich, 1995). Additionally, the cutaneous rabbit could be based on an expectation for speed (Goldreich, 2007), due to the difference in temporal and spatial resolution of the skin.

For a more comprehensible examination of the cutaneous rabbit illusion, see Brooks & Trojan (2017).

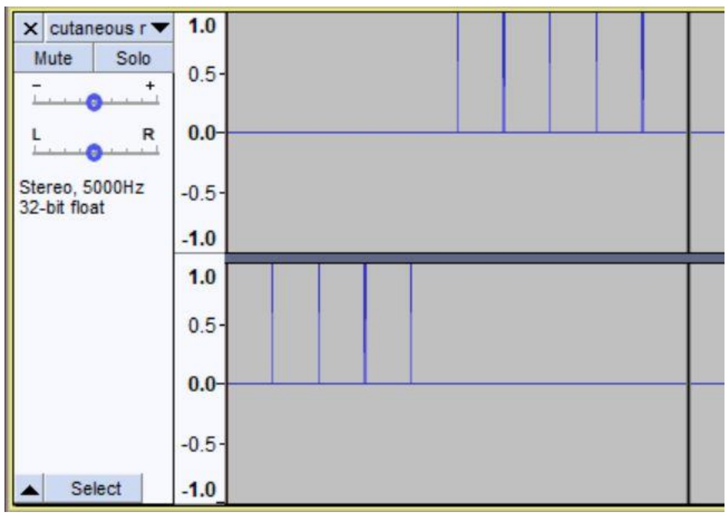


Figure 2.2.7.3 Signal for the cutaneous rabbit illusion as played in Audacity

Tactile illusions for vibro-tactile music.

Currently, there are no validated methods for rendering audio to touch while also considering the emotional content of music as a feature to be translated. A recently proposed algorithm considers tactile illusions when translating each note in the auditive stimuli, by assigning an appropriate illusion depending on the musical intervals and frequencies (Remache-Vinueza et al., 2022).

It is proposed that the directionality possible through the tactile illusions would enhance the dynamics of the resulting vibro-tactile composition. The pair of actuators can be treated as two speakers regarding the panning of the original music, and that is a possible association between audio-tactile stimuli. For example: the phantom motion may be used when conveying the idea of hands (or a bow) moving over the instrument while playing; and funneling to keep the rhythm and to locate a change in pitch (if the illusory sensation is located to the left and then to the right, we might believe that the first pitch was lower than the second).

In this thesis, the idea that tactile illusions can help transmit emotions through vibro-tactile stimuli is explored, making use of their possible associations with the form of movement, changes of direction and localization in the auditive stimuli.

3. Pilot Study

The goal of the pilot study was to determine which pair of actuators was the best to use for the main experiment. For this purpose, a group of experts in relevant fields tested the three tactile illusions with each pair. They were asked to consider which type of devices are superior regarding the clarity of the perceived illusions, and the level of comfort when holding them.

3.1 Methods

In this section the participants, material, apparatus and procedure of the pilot study are described.

Participants.

Ten experts in fields related to music technology and music cognition (3 women and 7 men) were recruited for this from the RITMO Centre of Interdisciplinary Studies in Rhythm, Time and Motion and from the Department of Musicology of Oslo University. One of the participants suffered from moderate hearing loss and tested everything with the hearing aid turned off.

Material.

Each expert tested three tactile illusions. Phantom Motion (PM; Alles, 1970; Kirman, 1974) or apparent movement, Cutaneous Rabbit (CR; Geldard & Sherrick, 1972) or saltation and Funneling (FUN; Békésy, 1958).

Apparatus.

Each expert tested the illusions on 3 different pairs of actuators, of which two are commercially available. Piezoelectric actuators were tested through the DRV2667EVM-CT Evaluation Module (EVM) kit (Texas Instruments, n.d.) from Texas Instruments Incorporated (www.ti.com). A LoSound engine based on an innovative voice-coil design was tested through the Basslet wearable subwoofers (Kickstarter, 2016) from Lofelt (www.lofelt.com). The last pair of actuators, named "hap-phones", was crafted at Universidad de Málaga in collaboration with Universidad Indoamérica and are based on a recoil-type vibro-tactile transducer proposed by Yao and Hayward (2010) put in a 3D-printed enclosure (see Remache-Vinueza et al., 2022).

Figure 3.1.1 The hap-phones, created after based on the design proposed by Yao and Hayward (2010)

Each of these 3 pairs of actuators were connected to the researcher's laptop to receive the appropriate soundwaves. The senders of the two Basslets were connected to the laptop through a Mini-Jack splitter – one 3.5mm Mini-Jack male connector plugged in the laptop and each Basslet sender plugged into one of the two 3.5mm Mini-Jack female connectors. These devices had integrated amplification. The Piezoelectric actuators and the hap-phones were connected first to a Lepy LP-2020A Class-D Hi-Fi Digital Amplifier with 3.5mm Mini-Jack cables. The amplifier was then connected to the laptop through a stereo 3.5mm Mini-Jack to Mini-Jack cable.

To prevent participants from hearing any external auditory stimuli, Beyerdynamic studio noise-cancelling headphones were tested, unconnected to any device.

Procedure.

Each session was structured as an open interview with no recording other than the researcher's notes. Participants were tested individually and gave oral consent for their feedback to be used in the paper. Although their identities were known to the researcher, they were kept confidential by only associating each response with a neutral ID. They were informed in the beginning that the goal of the session was to answer two questions:

- With which pair of actuators are the three illusions being felt the clearest?
- Which pair of actuators is the most comfortable to "wear"?

The three pairs of actuators were tested in an aleatory order among participants. The devices were held between fingertips as seen in the Figure below; the hap-phones were also tested strapped on the wrists. The set of three tactile illusions was presented in the same order for each pair of devices, PM, CR, and FN respectively. Each illusion was described before being played and presented either from right to left or the other way around; the experts had to determine the direction based on the vibrations. Each fragment was played in version 3.0.2 of Audacity® recording and editing software (2021) for Windows as a stereo .wav file on the researcher's laptop. See Figures 2.2.7.1-

3 for a visual representation of each illusion in Audacity. During the tests, the participants were not allowed to see the wave shapes of the input signal on the researcher’s laptop. In some cases, participants used noise-cancelling headphones to prevent them from hearing any sounds.

(a)  (b) 

Figure 3.1.2 (a) hap-phones held between fingertips and (b) strapped on the wrists as tested in the pilot study.

After experts made their judgement regarding which pair of devices they preferred for each question, they were allowed to see the wave shapes of the input signal and encouraged to discuss the experiment in a wider manner. The experts were tested individually, and each session lasted around 30 minutes.

3.2 Results

Basslets.

After the first five participants, a mistake was discovered regarding the cable connection between the Basslets and the laptop – by using a male to two stereo female Mini-Jack splitter the input signal was replicated as a stereo signal in both Basslets, making it impossible for the participants to feel the directionality of the illusions. The right splitter should have been a stereo male 3.5mm Mini-Jack to two **mono** female Mini-Jack, which would have allowed for panning the signal and for the right feel of the illusions. Therefore, the Basslets were not included for the rest of the experiment and their data was discarded, because it was not possible to acquire the right cable in time. The opinion regarding this pair of devices was that it was comfortable to use and that it had a very clear signal (due to its self-amplification), although this made them slightly numbing to use for extended periods of time. Two experts were of the opinion that it might have been the best pair of devices to use for the next experiment, were it not cabled wrongly.

Piezoelectric actuators.

Participants were divided in their opinions of these devices. Two experts felt that this pair had a mechanical response and a weight-feedback – it was heavier than the others and did not imply holding, just resting on the fingers, which combined with the weight gave it a more grounded feeling. On the other hand, three other experts felt that these devices were too big and distracting. Four participants could not identify the FUN illusion with this pair, and four could not identify the CR illusion. Three participants felt that the direction of the illusions was harder to identify correctly. Selecting the appropriate amount of amplification for these devices resulted in a high level of white noise and audible input signals from the illusions; therefore, participants were given noise-cancelling headphones to help them focus only on the vibro-tactile experience. One expert judged this pair to be the most comfortable (due to its size and weight) and the one conveying the clearest illusions.

Hap-phones.

This pair offered the clearest illusions while also being the most comfortable. Seven experts judged this pair of actuators to convey the best impression of movement, and all illusions could be felt uninterrupted as well as their directionality. Of these, two preferred the devices to be strapped to their wrists (see Figure 3.1.2 above) saying that it was more comfortable; however, in this case the participants required a higher intensity to feel the illusions properly which resulted in more audible tones. Three experts were of the opinion that holding the devices between each hand's fingertips was preferable, the pressure required for holding them giving them a clearer impression of the illusions, even if it was slightly less relaxing. The remaining two participants did not have a preference one way or the other. When testing each illusion, participants experimented with the distance at which to keep their hand – implicitly the actuators – and the best position was shoulder-width apart with the hands either supported on a table or resting on their thighs. The CR illusion was most sensitive to the distance between the devices: the illusory transition from side to side was not perceived anymore if they were too far apart or too close to each other. The PM illusion was the most permissive regarding the positioning of the hands. In most cases, there was no audible noise from the devices; even so, participants preferred to use noise-cancelling headphones, to make it easier to focus solely on the vibrations.

3.3 Discussion

In this experiment, ten experts in the fields of music technology and/or music cognition were asked to test three pairs of actuators with the purpose of determining which pair transmits the clearest illusions. The majority judged the hap-phones to be the best; the clarity of the signal made it easy to identify the illusions and their directionality as well as to differentiate between illusions. Therefore, this pair was used later for the main experiment, connected to the laptop through the amplifier. The other two pairs had great potential and further studies are encouraged to test their adequacy, especially through a direct connection through a stereo to mono splitter which seemed to sharpen the clarity of the signal. Especially the Basslets could be used to test similar vibro-tactile stimuli on the wrists, thanks to their watch-like design.

The hap-phones were also considered the most comfortable, their shape being easy to hold between the fingertips. Although they have the option to be strapped on the wrist as well, the perception of the illusions became muddled when tested as seen in Figure 3.1.2 (b) above. Compared to the Basslets which are made to be worn as a watch, the hap-phones are bulkier and the connection with the skin was not as definite. Since the vibrations were more subtle, an increase in intensity (volume) was requested, which resulted in more audible stimuli. When holding them between fingertips, participants put some pressure on the devices, which gave them a better feel of the vibrations. Because of this feedback, as well as information from previous literature which pointed to the fingertips as one of the most sensitive areas to vibro-tactile experience (Goldstein, 2010; Jones & Sarter, 2018; Purves et al., 2001), it was decided that in the main experiment the hap-phones were to be held as seen in Figure 3.1.2 (a). Additionally, shoulder-width distance between actuators seemed to be best for feeling all illusions clearly. From a placement point of view, participants were equally happy with holding the actuators in front of them on the table, on the chair armrests, or on their thighs.

In this experiment, the need to wear noise-cancelling headphones was also explored. Although the sound of the illusions was minimal at the intensity most needed to feel them, it became clear that higher pitches would be audible. Moreover, it was noted that the isolation provided by the studio-level headphones would be insufficient for the vibro-tactile compositions. Therefore, for the main experiment, earmuffs were provided, and all participants wore them.

Long periods of exposure to vibration are known to have a harmful effect on our sensory perception – e.g., numbness or tingling in the fingertips that can extend to the whole hand and then arm (Gerhardsson & Hagberg, 2019) – and even if the actuators give relatively low intensity stimulation, this was something several of the experts expressed concern over. In time, the fingertips would also loose sensation. Therefore, to avoid overstimulation, it was decided that the vibro-tactile compositions in the main study would be short and participants would have small breaks in between. The experts in the pilot study considered 30 minutes to be just right, and expressed their belief that more than that would be tiring for participants. In line with this, the main experiment lasted about 30 minutes.

4. Main Experiment

This experiment was designed to explore whether vibro-tactile music made of tactile illusions and rendered from music for the ear can carry emotional content embedded in those auditive musical compositions. For this purposes, already existing excerpts with proven emotional labels were rendered to vibro-tactile music and tested using the hap-phones.

4.1 Methods

In this section, the participants, material translation process, apparatus, and lastly, the procedure are described.

Participants.

Forty participants (19 women, 20 men and 1 other) between 18 and 60 years old (*M = 33.98, SD = 10.66*) with an average empathy score of *37.95 (SD = 9.69, with a minimum empathy of 12 and maximum of 54 out of a possible range of 0-56*) took part in the main experiment of this thesis. They were recruited from the Oslo and Bucharest universities and related institutes, as well as through the researcher's network. Of these, 38.2% were music-loving non-musicians, 16.4% were serious amateur musicians, another 16.4% were semi-professional musicians, 10.9% were amateur musicians, 9.1% were non-musicians, and another 9.1% were professional musicians – that is, 52.7% of the participants were musicians. A substantial effort was done to recruit people from Norwegian and Romanian associations for deaf or hard of hearing people. However, only 6 participants suffered of any type of hearing loss – 1 of mild, 1 of moderate, and 4 of profound hearing loss. Participants of the Pilot Study were also allowed to participate, since the vibro-tactile compositions at the core of the experiment were new to them and knowing the illusions from before presented no bias.

Anyone older than 18 and who understood English could volunteer to participate. If they wished to, participant could sign up on a separate list and enter a shuffle for a 200 NOK voucher. No other monetary compensation was offered, besides a selection of candy during the experiment.

Material.

The same three tactile illusions used in the Pilot Study were used in this experiment: the Phantom Motion, the Cutaneous Rabbit, and the Funneling. Additionally, eight vibro-tactile compositions were used, two per each emotion – happy, sad, scary and peaceful. These were selected from a previous study (Vieillard et al., 2008) and rendered from just-sound to just-vibration based on the process detailed below. Based on the results of the first experiment by Vieillard et al. (2008, p. 724), the fragments which were found to successfully express their intended emotion were used in the present study. The happy excerpts were G01 and G13, with a tempo of 112 and 120 Metronome

Marking (BPM), respectively. The sad excerpts were T08 and T13 with tempos of 40 and 48 BPM, respectively. For the scary fragments P09 and P11 were selected, with a 44 BPM tempo; and for the peaceful fragments A01 and A10 were used, with tempos of 60 and 80 BPM, respectively. The stimuli lasted 9.38 s on average (range: 5-15 s). Scores for the intended emotionality of each excerpt can be found in Appendix 2 of the original study (Vieillard et al., 2008). For the purpose of the present study, the happy excerpts were renamed into H1 and H2, the sad ones into T1 and T2 (from "triste"), the scary ones into S1 and S2, and the peaceful ones into P1 and P2 – respecting the order mentioned above.

The translation process.

Following the scores, the researcher played each musical excerpt on a Novation ReMOTE 49SL Compact keyboard connected directly to the researcher's laptop. The signal was recorded in Reaper: Digital Audio Workstation (DAW; www.reaper.fm) as a synth-based musical instrument digital interface (MIDI) file. The tempo of each piece was respected. The monophonic MIDI file was then put through an algorithm to create the vibro-tactile composition as a .wav file.

The monophonic MIDI files were rendered to vibro-tactile music compositions using the algorithm proposed by Remache-Vinueza et al. (2022). For this it is necessary to have only one note at a time in the melody, such that each note is then assigned a tactile illusion based on range and frequency criteria. The resulting vibro-tactile composition was saved as a stereophonic .wav file where the left-right panning was mapped on the left-right feeling in the illusions. See the picture below for an example of how the waveforms of two excerpts looks.

Apparatus.

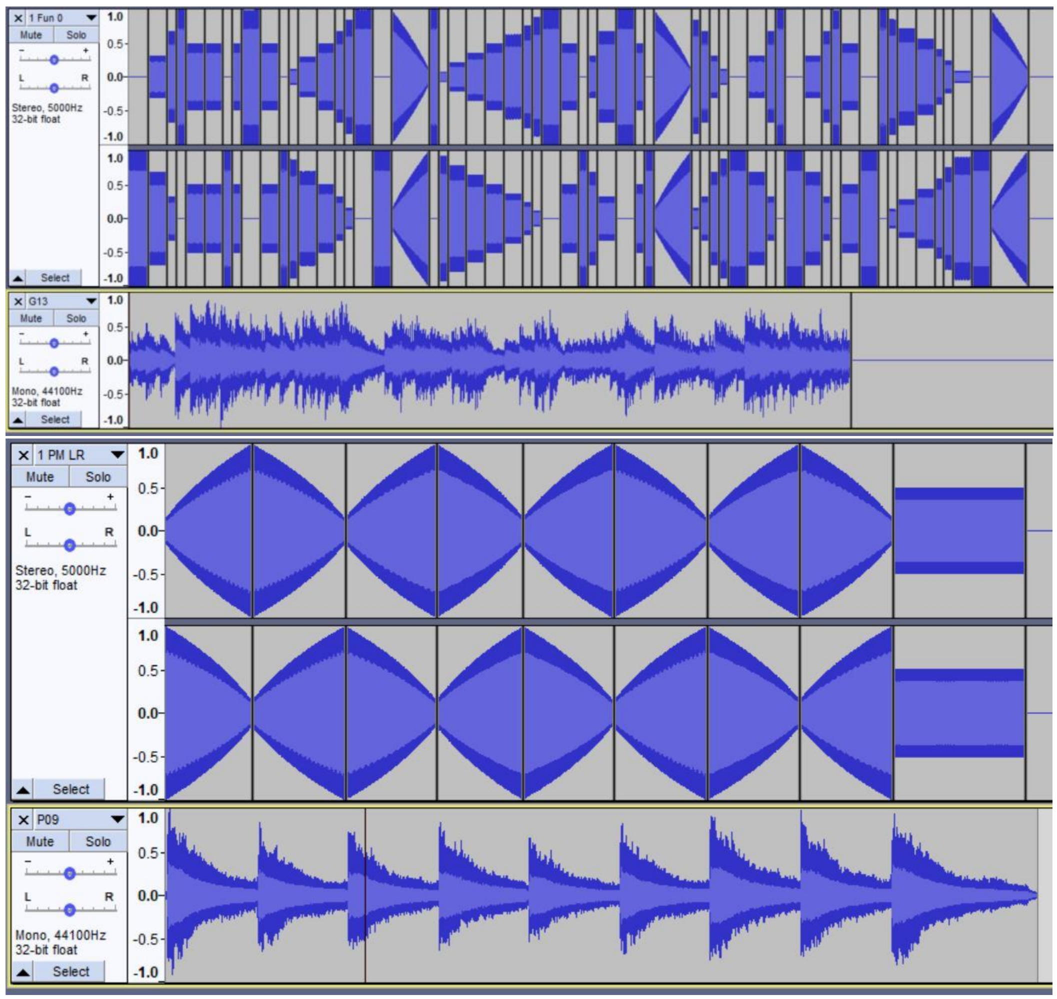
The actuators used for this experiment, the **hap-phones** were designed at Universidad de Málaga in collaboration with Universidad Indoamérica especially for conveying this type of tactile illusions, based on the suggestions of Yao and Hayward (2010). These devices were connected to a Lepy LP-2020A Class-D Hi-Fi Digital Amplifier with 3.5mm Mini-Jack cables. The amplifier was then connected to the researcher's laptop through a stereo 3.5mm Mini-Jack to Mini-Jack cable.

Protective earmuffs for shooting which reduce incoming noise with as much as 21dB were used for participants without hearing impairment. Additionally, noise-isolating earbuds were provided (to wear under the muffs) at a later stage. The deaf or hard of hearing participants were asked to turn off their hearing aids while the eight compositions were played.

Procedure.

The three tactile illusions and the eight compositions were saved as Audacity Project Files on the researcher's laptop. The illusions were presented in the same order: Phantom Motion, Cutaneous

Rabbit, and Funneling. The order of the excerpts was pseudo-randomized with the *random* function in Python 3 (Van Rossum & Drake, 2009), as a counterbalancing technique to avoid any order bias, fatigue or boredom bias. The sequences for each participant were saved in a table. For each participant, the researcher manually played the files in the right order. Each fragment was played in version 3.0.2 of Audacity® recording and editing software (2021) for Windows as a stereo .wav file on the researcher's laptop.



(a) (b)

Figure 4.1 A visual representation of the audio stimuli (bellow) which was rendered to vibro-tactile music using the algorithm proposed by Remache-Vinueza et al. (2022). (a) represents excerpt H2 (or G13 in Vieillard et al., 2008) and (b) excerpt S1 (or P09).

The experiment was structured around a questionnaire. Approval from the Norwegian Centre for Research Data (NSD, 2014) has been obtained regarding the anonymity of the data collection. This started with a page offering information about the study at the end of which participants were notified that the experiment is anonymous and that no personal data is collected. By pressing "next", they agreed to the terms and chose to participate. The questionnaire continued with some general questions – the participants' age, gender, musical expertise and level of hearing impairment. The "calibration" phase consisted of the presentation of the three tactile illusions as used in the Pilot Study, such that participants could learn to identify them later in the compositions. For each illusion, the researcher increased the intensity level until the participant confirmed that they felt it, and recorded the time. After this, the researcher made a note of the average intensity required for that participant and consequently played the vibro-tactile compositions at that level. The earmuffs were optional for this phase, as the sound level of the illusions was minimal and it was deemed more important to have a smooth communication between researcher and participant.

The main phase was the presentation of the eight compositions. Earmuffs (or hearing aids turned off) and isolating earbuds were required for this step. Participants were encouraged to keep their eyes closed to help concentrate exclusively on the sense of touch. Based on the findings of the pilot study, they were instructed to keep the actuators about shoulder-width apart, placed comfortably either on their thighs, the chair armrests or on the table.

Each fragment was played three times (with 3 seconds in between). They were encouraged to say if the intensity was too low and they could not feel the vibrations, or if they needed one more play-through, and in that case the researcher adjusted the volume and played it again. If they heard any sounds through the earmuffs, they had to say, and the researcher made a note of it. After each excerpt the participants had to answer four questions about its emotional content. They had to rate how pleasant the excerpt was from 0 (unpleasant) to 9 (agreeable), how stimulating it was from 0 (relaxing) to 9 (stimulating), to what extent the excerpt was happy, sad, scary, and peaceful (the participants had to give a score from 0 = entirely absent to 9 = entirely present for each emotion), and to what extent they experienced happiness, sadness, scariness, and peacefulness (giving scores from 0 = entirely absent to 9 = entirely present for each emotion). The researcher ensured that each participant understood the difference between rating the recognized and the felt emotions – the first being an intellectual judgement about the emotions found in the excerpt and the second a judgement about the intrinsic feelings experienced during the excerpt (the phrase "imagine that you're listening to a song that you know is sad, but it doesn't necessarily make you *feel* sad" was often used to clarify/exemplify the distinction). The same questions were repeated eight times, once for each excerpt.

Lastly, the questionnaire ended with 14 questions from the Interpersonal Reactivity Index Scale (Davis, 1980). Only the questions that are part of the Empathic Concern and Fantasy subscales were used (7 for each). After sending the results, the participants were informed that they could leave their email on a separate paper if they wanted an update about the study. A copy of the entire questionnaire can be found in Appendix 1. Each session lasted around 30 minutes and participants were tested individually in a quiet room.

At the end of the questionnaire, participants were asked if they were willing to answer one open question, conversationally. With one exception, all participants consented and spent an additional 5-10 minutes talking about it – i.e., if they experienced any associations during the vibro-tactile compositions and if so, which kind. The answers were recorded by the researcher and the participants gave oral consent for using some direct quotes in the paper. Their answers were kept confidential by only having them linked with their participant number; even in combination with the answers for the questionnaire, their identities were kept anonymous.

4.2 Results

In this section both quantitative – obtained through (statistical) analysis – and qualitative – obtained through responses to an open-ended question – results are reported. The qualitative results are briefly discussed as they are reported, while the quantitative results are discussed in section 4.2.2. At the end of this section, observations and notes taken by the researcher during the study about the limitations of the technical design are presented. Additional materials such as the raw data and the code used for analysis can be found in Appendix 2.

4.2.1 Quantitative results.

Two-way repeated measures ANOVAs

Firstly, in order to compare the ratings of different discrete emotions (happy, sad, scary, peaceful) as well as the type of rating (if the emotion was felt or recognized), eight two-way repeated measure ANOVAs were performed – one for each composition. In Figure 2.4.1.6 a visual summary of the data grouped per each felt-recognized emotion (happy, sad, scary, peaceful) in each excerpt, as boxplots, can be observed.

The data presented some extreme outliers (values above Q3 + 3×IQR or below Q1 - 3×IQR, where Q1, Q3 and IQR are the 1st and 3rd quartile, and the interquartile range, respectively). In each case, they were replaced with the 5th or 95th percentile value, in order to keep the intention of the rating, but with a less extreme value (e.g., if the value was above Q3 + 3×IQR, it would be changed with the value of the 95th percentile). Nearly each vibro-tactile musical composition had some outliers (values above Q3 + 1.5×IQR or below Q1 - 1.5×IQR), which were not considered troublesome and therefore were not removed (see Figure X).

With the exception of the data for felt-happiness of the excerpt P1, none of the data was normally distributed. Although the normality assumption was not met, no correction was applied to the data, due to the robustness of ANOVA and the small sample size. When checking the sphericity of the data, several vibro-tactile compositions did not meet the requirement; therefore, the p-values were corrected for sphericity using the Greenhouse-Geisser correction method, and only the corrected values being reported here.

A summary of which factors were significant for which excerpt can be seen in Table 4.2.1.1 below. With the exception of excerpts H2 and S2, for all other vibro-tactile compositions a significant interaction effect was found – i.e., there are differences between emotions that only occur when the type of rating was felt or only when recognized.

Table 4.2.1.1
Results of the repeated-measure ANOVAs for each excerpt for emotion and condition factors

	Factor 1: emotion	Factor 2: felt/recognized	Interaction
H1	F(2.26, 122.27) = 2.62	F(1, 54) = 15.98 *	F(2.58, 139.22) = 4.37 *
H2	F(2.13, 115.28) = 102.8 *	F(1, 54) = 2.66	F(2.12, 114.62) = 0.52
P1	F(2.51, 135.78) = 3.26 *	F(1,54) = 6.22 *	F(3, 162) = 6 *
P2	F(2.24, 120.83) = 19.27 *	F(1,54) = 9.58 *	F(2.45, 132.06) = 4.36 *
S1	F(1.95, 105.44) = 9.62 *	F(1,54) = 0.42	F(3,162) = 3.32 *
S2	F(2.04, 110.31) = 20.05 *	F(1, 54) = 2.36	F(3, 162) = 0.95
T1	F(2.39, 128.8) = 31.12 *	F(1, 54) = 1.96	F(2.49, 134.22) = 3.93 *
T2	F(2.04, 110.42) = 17.89 *	F(1, 54) = 7.25 *	F(3, 162) = 2.75 *

Significance level: * $p < 0.05$

Further, multiple paired t-tests were run to explore which pairs of emotions had significantly different scores under which condition (felt or recognized). P-values were adjusted with the Bonferroni multiple testing correction method. In the Table 4.2.1.2 below, the results of the paired t-tests can be seen. Using the mathematical symbols for “greater than” and “less than”, the direction of the mean differenced are shown (e.g., for excerpt P2, the ratings for happiness were significantly higher than the ones for peacefulness, sadness, and scariness, in the felt condition). Only the significant differences are reported here, for a higher clarity when interpreting the tables.

Table 4.2.1.2
Results of paired t-tests for the Emotion factor with an effect for felt/recognized condition
The greater and less than symbols indicate a higher or lower mean for the emotion on the left

	H1	P1	P2	S1	T1	T2
Felt:						
Happy – Peaceful			>*	<***	>****	>*
Happy – Sad			>****		>****	>****
Happy – Scary			>****		>****	>****
Peaceful – Sad	>**		>***	>***	>*	>**
Peaceful – Scary			>*	>**		
Sad - Scary						
Recognized:						
Happy – Peaceful		<*	>***	<****	>****	>***
Happy – Sad			>****		>****	>****
Happy – Scary			>****		>****	>***
Peaceful – Sad			>*	>*		
Peaceful – Scary				>**		
Sad - Scary						

Significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$

Additionally, paired t-tests were used to explore which condition had significantly different ratings for each emotion, meaningful for the interaction effect. The Bonferroni-corrected p-values can be seen in Table 4.2.1.3 below. Symbols are used in a similar way as before to represent the directionality of the mean difference – e.g., in excerpt P1 participants rated felt sadness as lower than recognized.

Tablet 4.2.1.3
Results of paired t-test of differences between felt/recognized ratings for each emotion
The greater and less than symbols indicate a higher or lower mean for the condition on the left

	H1	P1	P2	S1	T1	T2
Happy over felt/recognized			<**		<*	
Sad over felt/recognized	<***	<***	<**			<*
Scary over felt/recognized	<**		<*		<*	<**
Peaceful over felt/recognized						

*Significance level: * p < 0.05, ** p < 0.01, *** p < 0.001, **** p < 0.0001*

To explore the significant main effects of Emotion, pairwise comparisons between all emotions were calculated using Bonferroni-adjusted paired t-test. In this case, the emotional ratings were averaged between the felt and recognized conditions – i.e., only one score regardless of the condition was used in the analysis. A summary of the significant results, as well as their direction, can be seen in Table 4.2.1.4 below.

Table 4.2.1.4
Results of paired t-tests between emotions and felt/recognize ratings for all excerpts
The greater and less than symbols indicate a higher or lower mean for the emotion on the left

	H1	H2	P1	P2	S1	S2	T1	T2
Happy – peaceful		>****		>**	<****	>****	>****	>***
Happy – sad		>****		>****		>****	>****	>****
Happy – scary		>****		>****		>***	>****	>****
Peaceful – sad		>****		>**	>**		>*	>*
Peaceful – scary		>****			>**			
Sad - Scary								
Felt – Recognized	<***		<**	<***				<**

*Significance level: * p < 0.05, ** p < 0.01, *** p < 0.001, **** p < 0.0001*

One last paired t-test was used to determine whether there were statistically significant differences between the felt and recognized ratings of each excerpt (the data was not averaged). The p-values were adjusted using the Bonferroni method. The results can be seen on the last row of Table 4.2.1.4.

Two-way mixed measures ANOVAs

Several two-way mixed ANOVAs were performed to evaluate the effect of different binary variables on the average (felt-recognized) emotional ratings of participants. The between-subjects factors to be tested alongside the within-subjects factor of the type of emotion were: level of hearing loss (Figure 4.2.1.7), level of musicianship (Figure 2.4.1.8), and level of empathy (see the grids of boxplots for a visual summary of the data for each variable. Initially, they all had multiple levels, and empathy was a continuous variable. Due to the unequal sample size of each category, the level of hearing loss and musicianship were separated in only two levels. For this analysis, empathy was split into high and low empathy from the median score found in the data. Thorough the ANOVAs, the type of rated emotion continued to be significant (see repeated measures ANOVAs table for post-hoc paired t-tests).

The ANOVA run to explore any differences between hearing and non-hearing individuals regarding how they rated the emotions in each excerpt, yielded two significant interactions between hearing loss and Emotion – after the extreme outliers were removed as described in the section above – excerpts H1 (F(2.39, 126.69) = 6.73, p < 0.05) and T1 (F(2.14, 113.210 = 3.48, p < 0.05). Post-hoc pairwise comparisons adjusted with the Bonferroni method show that in excerpt H1, non-hearing participants rated positive emotions significantly higher in the happy-sad (p < 0.05), happy-scary (p < 0.01) and peaceful-scary (p < 0.05) pairs. In excerpt T2, hearing participants rated happiness significantly higher than the other emotions – i.e., happy-sad (p < 0.001), happy-scary (p<0.001) and even happy-peaceful (p<0.05). Post-hoc paired t-tests were also used to explore the effect of the main hearing loss factor. The adjusted results and their direction can be seen below both for the excerpts which had a significant interaction, and for two more which had a significant level of hearing effect in the ANOVA.

Table 2.4.1.5
Results of paired t-tests between hearing and non-hearing ratings for each emotion of the relevant excerpts. The greater and less than symbols indicate a higher or lower mean for the condition on the left

	H1	H2	T1	T2
Happy over hearing/non-hearing	<***			<*
Sad over hearing/non-hearing				
Scary over hearing/non-hearing	>*			
Peaceful over hearing/non-hearing		<*	<*	<*

*Significance level: * p < 0.05, ** p < 0.01, *** p < 0.001*

A two-way mixed ANOVA was used to examine the different emotional ratings for musicians and non-musicians. Two excerpts had a significant interaction after replacing the extreme outliers: H2 (F(2.15, 114.16) = 4.3, p < 0.05) and S1 (F(2.02, 106.86) = 7.41, p < 0.05). Post-hoc paired t-tests were run similarly as for the other ANOVAs, with adjusted p-values. Musicians rated excerpt H2 as less peaceful than non-musicians (p < 0.01), and excerpt S1 as more (p < 0.001). S1 was also rated as scarier by non-musicians (p < 0.05). In the Table 2.4.1.6 below, the differences between emotions and their directionality can be observed based on the musicianship level of the participants.

An ANOVAs was run to investigate whether individuals with high empathy rated emotions differently than those with low empathy. Only for excerpt H2 there was a significant interaction a difference when rating happiness between people with high empathy and low empathy (F(2.17, 114.97) = 3.26, p < 0.05), with higher empathy giving higher scores (p < 0.05). Figure X shows a boxplot with the distribution of the data before replacing the few extreme outliers. For both people with high and low empathy, the happiness rating was significantly higher than all the other (all had p < 0.001, except happy-peaceful for people with low empathy were p < 0.01). The peacefulness rating was significantly higher than the negative emotions for both people with high (p < 0.001 for both) and low empathy (p < 0.001 for sadness and p < 0.01 for scariness).

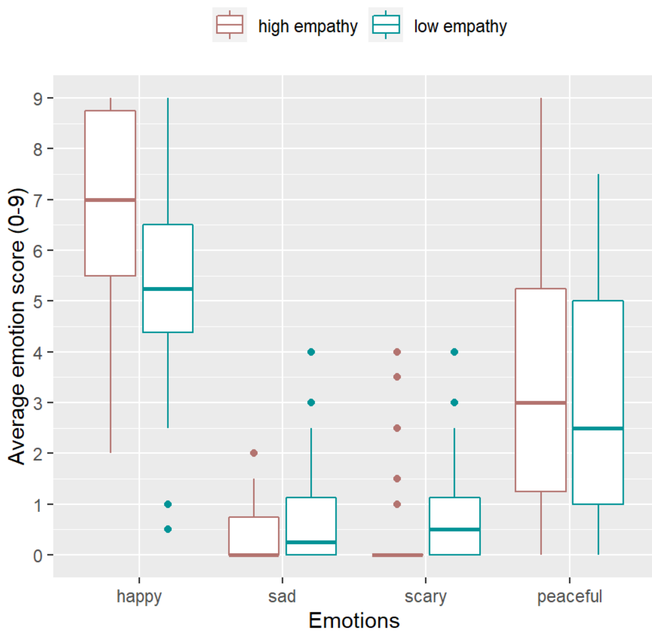


Figure 2.4.1.1 Scores given on average for each emotion based on the empathy of participants for excerpt H2.

Table 2.4.1.6
Results of paired t-tests between emotions for each level of musicianship. The greater and less than symbols indicate a higher or lower mean for the condition on the left

	H2	S1
Musician:		
Happy – Peaceful	>****	<****
Happy – Sad	>****	
Happy – Scary	>****	>*
Peaceful – Sad	>**	>****
Peaceful – Scary	>*	>****
Sad - Scary		
Non-musician:		
Happy – Peaceful	>**	
Happy – Sad	>****	
Happy – Scary	>****	
Peaceful – Sad	>****	
Peaceful – Scary	>****	
Sad - Scary		

*Significance level: * p < 0.05, ** p < 0.01, *** p < 0.001, **** p < 0.0001*

Other tests.

An independent sample t-test was run to evaluate, irrelevant of excerpt, how the level of musicianship was influencing the empathy scores of participants. For this analysis, empathy was kept as a continuous variable. Although a visual inspection suggests a slight trend towards musicians having higher empathy (see Figure X), there were no statistically significant differences (p = 0.118).

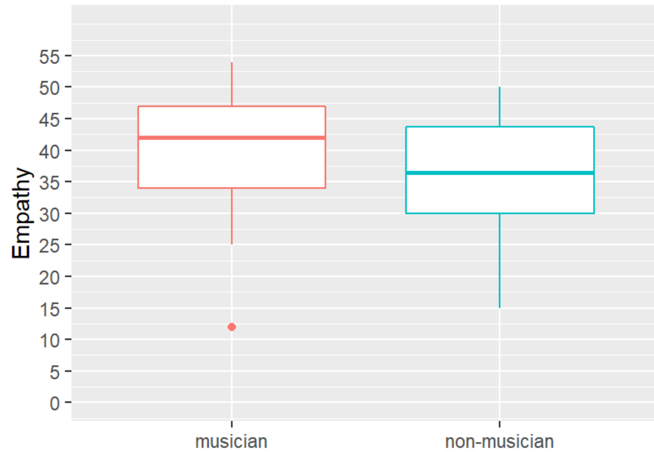
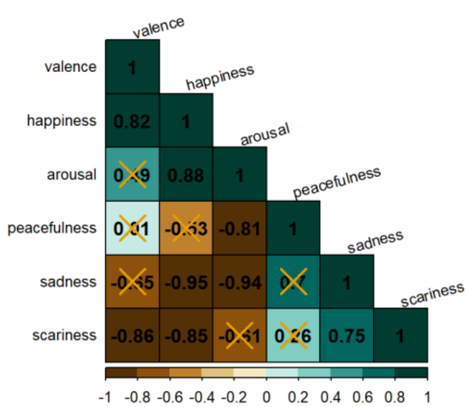
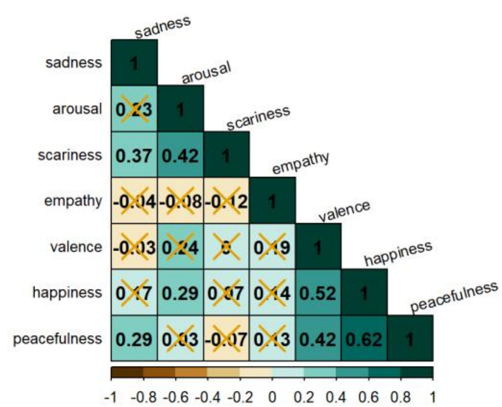


Figure 2.4.1.2 Empathy scores based on the level of musicianship of the participants.

Correlations between empathy, ratings for each emotion and valence-arousal scores were tested among participants (Figure 2.4.1.3 b), as well as correlations of emotions and valence-arousal scores among excerpts (Figure 2.4.1.3 a), to determine whether the scores given some are consistent with the others.



(a)



(b)

Figure 2.4.1.3 (a) Correlation between emotion ratings and valence and arousal scores among excerpts and (b) among participants (b).

A visual inspection of the scatterplot below shows a tendency for people with higher empathy to give higher scores for positive emotions (happiness and peacefulness) and lower scores for negative emotions (sadness and scariness). However, this trend is not supported by the relatively low correlation coefficients as seen in Figure 2.4.1.3 (b).

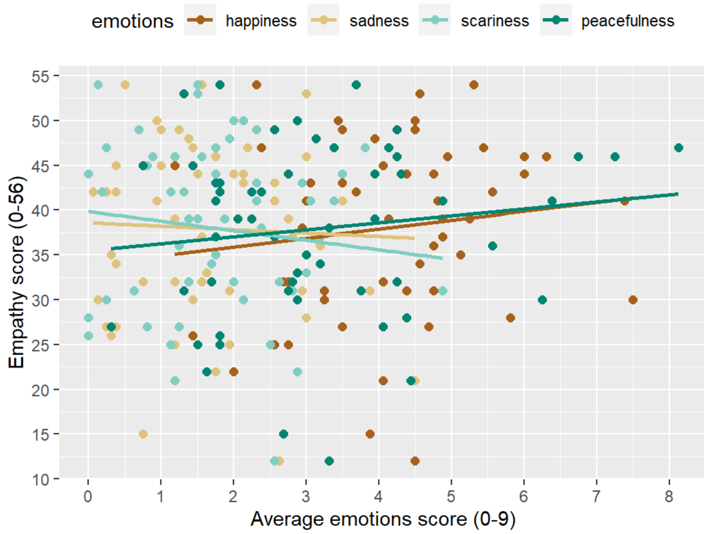


Figure 2.4.1.4. Average of emotional scores over empathy scores across participants. Regression lines for each discrete emotion are added over the scatterplots.

To visually compare the distribution of each vibro-tactile composition on the arousal-valence space with that of the audio excerpts used in Vieillard et al. (2008), an arousal-valence plot has been created. Instead of a localization of the excerpts with their corresponding intended emotion, it can be observed how all are clustered centrally and with a tendency toward stimulating and pleasant.

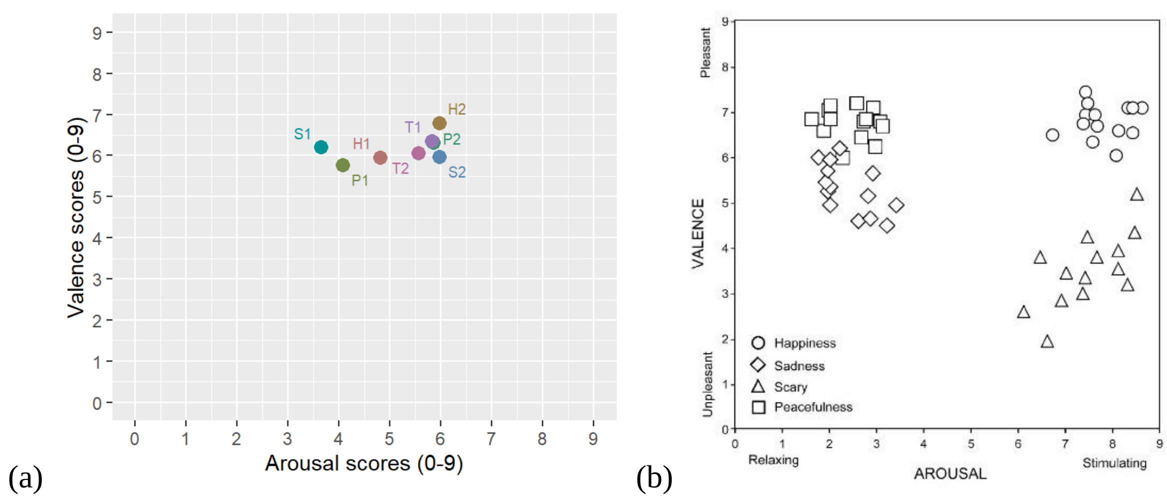


Figure 2.4.1.5 (a) Valence-arousal on average for the vibro-tactile excerpts used in this thesis (b) and valence-arousal scores for all audio excerpts, retrieved from Vieillard et el. (2008)

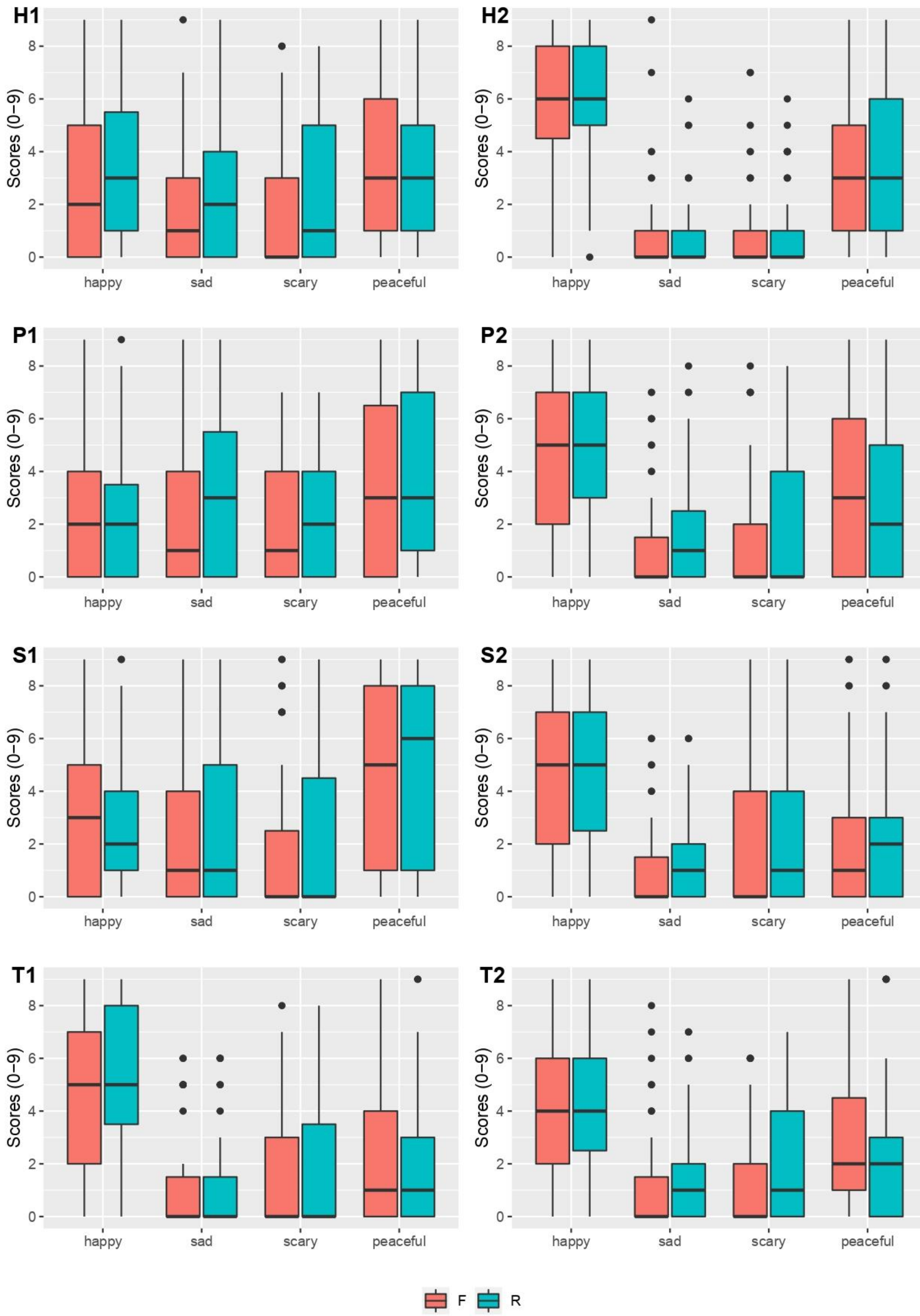


Figure 2.4.1.6 Scores given per excerpt on average for each discrete emotion based on the condition: F = felt and R = recognized.

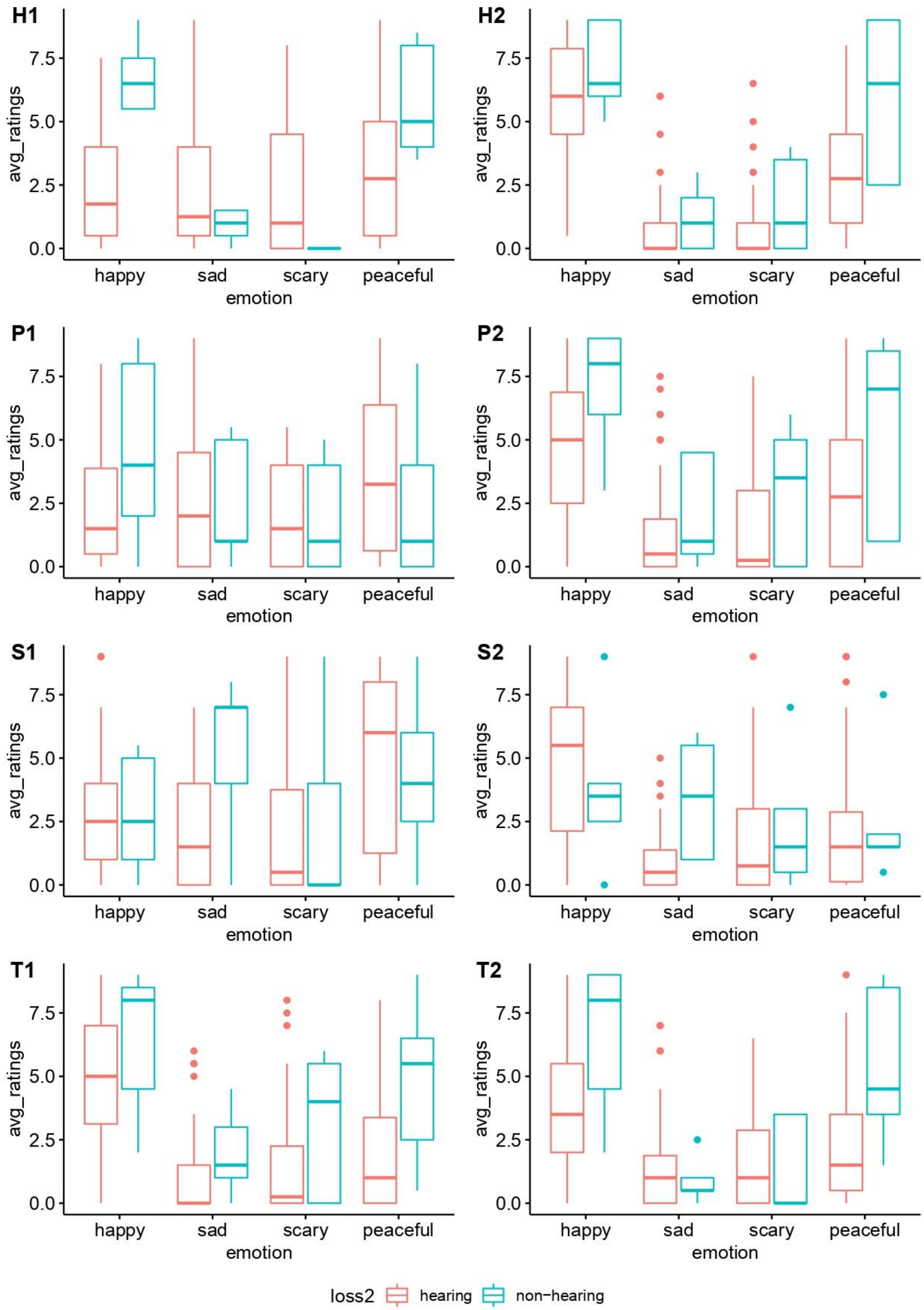


Figure 2.4.1.7. Scores given per excerpt on average for each discrete emotion based on the hearing loss level of participants.

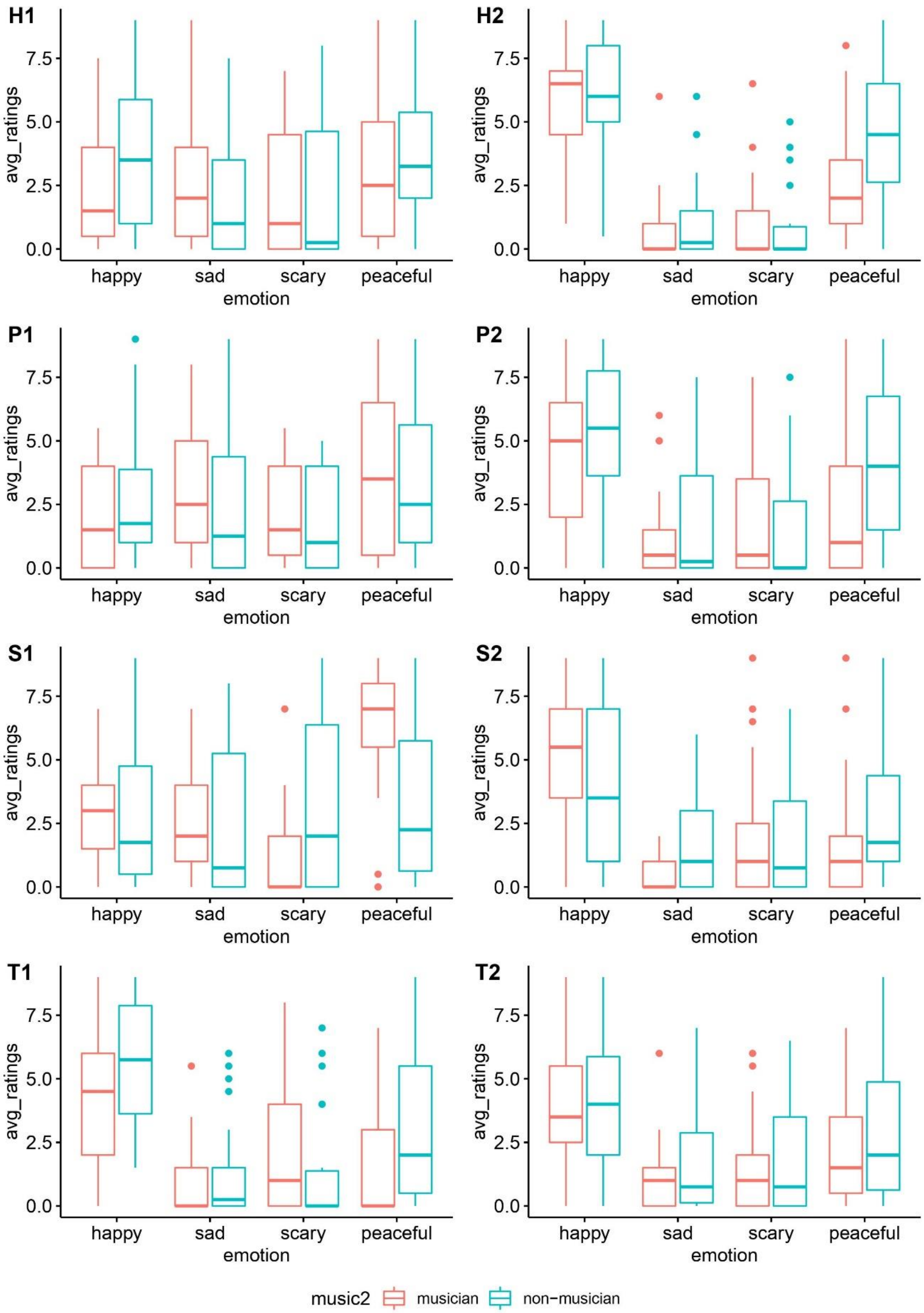


Figure 2.4.1.8 Scores given per excerpt on average for each discrete emotion based on the musicianship level of participants.

4.2.2 Discussion of quantitative results

Eight excerpts from Vieillard et al. (2008), two per emotion, were rendered to vibro-tactile compositions using the algorithm developed and tested by Remache-Vinueza et al. (2022), where a tactile illusion is mapped on each note of the original melody (see Figure 4.1 for an example of the waveforms before and after). They found that the vibro-tactile composition was perceived as happier and more peaceful, less sad and scary, and more agreeable and stimulating than the corresponding audio format of the same piece. This finding is supported by the results of the present study. As can be observed in Tables 4.2.1.2-4, the positive-negative pairs of emotions were consistently different in their ratings, with the positive emotion having the higher mean, which seems to indicate that participants rated significantly higher the happy and peaceful excerpts. In a few cases, happiness was rated even higher than peacefulness, which could be explained by the dynamicity of the rendered composition. It is unclear if they also rated lower the sad and scary ones when compared to the audio version of the eight compositions – to validate the findings in Remache-Vinueza et al. (2022), future studies should add the auditive stimuli in the experiment design and compare them to the vibro-tactile ones. We sugest that the vibrations were not too intense and they were a new experience for participants, which was approached with a curious and positive attitude, enhanced by the wearing of earmuffs which helped them focus on their sense of touch.

No large differences between the felt and recognized emotion ratings were found previously (Vieillard et al., 2008); however, in the present study four out of eight compositions (H1, P1, P2, T2) showed significant differences between felt and recognized ratings over all emotions ($p<0.01$ and $p<0.001$). All emotions were rated significantly lower when felt (see Table 4.2.1.3), except peacefulness which did not have a significant difference between conditions. This finding is consistent with music cognition literature (e.g., Kallinen & Ravaja, 2006), which hints toward people agreeing more about recognized emotions than felt, which is susceptible to more individual differences. None of the excerpts had a significant difference between sadness and scariness, which is in line with participants' feedback that it was hard to feel negative emotions since it was so agreeable overall (see Section 4.2.3 below for more details). Moreover, happiness ratings were higher than all the other for both conditions in three low arousal compositions (P2, T1, T2), while only for S1 peacefulness was rated higher than happiness ($p < 0.001$). Peacefulness was rated higher than sadness in several cases, which seems to align with previous findings where although these two emotions were close on the valence dimension, they were different (Vieillard et al, 2008). These differences between felt and recognized ratings might be explained by the fact that in the present study each participant rated both the felt and the recognized emotions, while in the study by Vieillard et al. (2008), different groups of participants rated the experienced and recognized emotions. Future studies would have to consider this inconsistence and design an experiment that could clarify if there are indeed any differences when asking individuals to rate emotions from these two perspectives.

Interestingly, in all but two compositions (H2, S2) significant differences between emotions' ratings were found depending on the felt or recognized condition, as hinted previously. The difference between felt negative and felt positive emotions was often significant, which might indicate that people experienced more intensely positive than negative emotions. Happiness ratings were higher than all others – suggesting that people are more willing to recognize happy feelings, or rather that happiness was easier to recognize due to the high dynamics and the general pleasantness of the stimuli; especially faced with a lack of tonal information. In two excerpts, P1 and S1, peacefulness was rated higher than happiness, which might be because of the tactile illusions used for rendering. This would have to be further researched.

After averaging over the felt and recognized ratings for each emotion, the potential effect of musicianship, hearing loss and empathy on them was explored.

Tentatively, considering the big sample difference (5 to 50), the differences between hearing and non-hearing participants were explored. In the current data, two excerpts had a significant interaction: H1 where non-hearing rated positive emotions significantly higher than negative, and T1 where hearing rated happiness higher than all others. Furthermore, non-hearing participants seemed to give higher happiness and peacefulness ratings, which suggests that non-hearing participants might have reacted more strongly to the high dynamics of the excerpts, or that for them the vibrations of the happy excerpts were closer to what they experience in a happy musical piece. Moreover, individuals with hearing loss rated happiness significantly higher than both sadness and scariness, which supports the idea that they differentiate better between positive and less positive (if not negative, because the corresponding valence scores were high) feelings based only on vibrations. Nevertheless, this can only be seen as a trend at this stage. Future studies should explore this with a better sample distribution.

When testing if the level of empathy influences the ratings given for each emotion, only one interaction was found, for excerpt H2. It seems to be the case that people with high empathy gave higher scores for happiness; however, both of them and individuals with low empathy rated happiness and peacefulness higher than the other emotions. This is a tentative result which should be explored further – perhaps controlling for the types of tactile illusions used in the compositions and their dynamics. Tempo could be a good confounding variable to consider, as H2 was the excerpt with the considerably higher tempo than the rest (120 BPM).

The differences between musicians and non-musicians over several variables were explored. Only two excerpts (H2 and S1) showed a significant difference in emotional ratings based on the participants' musicianship level. Musicians rated peacefulness different than non-musicians in both cases – lower for H2 and higher for S1, which might suggest that they were more attuned to the rhythm and tempo of the pieces (H2, with a higher tempo and more dynamic tactile illusions, was rated less peaceful than S1, with a low tempo and very "wavy" illusions). Interestingly, S1, originally a scary audio excerpt, was identified and rated as scarier by the non-musicians ($p < 0.05$) – this might indicate that the musicians got "tricked" by the smooth, sweeping tactile illusion representation, while the non-musicians understood its underlying dissonant tones better. This tentative finding could be explored further, perhaps while comparing their reactions to audio-tactile, tactile only and auditory only stimuli.

Based on some previous findings (Cho, 2021), it was expected for musicians to have higher empathy scores than non-musicians. However, this was not the case in the present study, where the difference existed, but was not significant (see Figure 2.4.1.2). There are some potential reasons for this, which should be considered in future studies. Firstly, due to uneven sample distribution, the musicianship variable had to be converted from six levels (see section 4.1 where participants are described based on their musicianship level) to only two, which might have impacted the findings. It might be the case that the empathy is correlated with the number of years of instrument practice, or with the number of years of performing in front of an audience, in which case, a more detailed description of musicianship is necessary. Secondly, the Interpersonal-Reactivity Index used to measure participants' empathy score originally has two additional subscales which were not included here due to time constrains and lower relevance. It is important to consider the relation between empathy and musical emotions more thoroughly before deciding if only subscales or the whole scale should be included in a study. Moreover, there were no significant correlations between the empathy scores and the ratings for each emotion or valence and arousal scores among participants. However, a visual inspection of the scatterplot in Figure 2.4.1.4 shows a slight tendency for people with higher empathy to give higher scores for positive emotions and lower scores for negative emotions; thus, this is a trend worth considering.

Lastly, in this part of the experiment, participants gave a score for the valence and arousal of each composition. It was expected that these scores would be consistent with the ratings for the discrete emotions – such as: a higher rating for happiness would mean high valence and high arousal, higher rating for scariness would mean low valence and high arousal – which was indeed the case. To explore the overall pattern of how participants rated their experience, correlations between mean ratings were analyzed. After averaging over excerpts, it was found that happiness ratings were correlated positively with high valence and high arousal, that peacefulness and sadness correlated negatively with arousal, and that scariness correlated negatively with valence. Additionally, sadness and scariness were correlated positively (which can also be seen in a lack of significant differences between the two during the ANOVAs), and happiness was correlated negatively with both sadness and scariness. Overall, participants seemed to rate the emotions in a consistently. Averaging over participants, it was found that higher scores for valence were associated with higher scores for both positive emotions, and higher arousal scores with happiness and scariness. Moreover, high sadness ratings related to high scariness and peacefulness ratings as well, and high happiness with high peacefulness. These findings are in line with previous literature where it was found that ratings for discrete emotions are consistent with their valence-arousal dimensions (Eerola & Vuoskoski, 2011; Vieillard et al., 2008).

The eight compositions used in the present study were rendered from the excerpts used in Vieillard et al. (2008). As seen in Figure 2.4.1.5, they found that happy excerpts were in upper half for both valence and arousal, peaceful excerpts were in the upper half for valence, but in the lower half for arousal, scary excerpts were in the middle-low for valence, but upper half for arousal, and that sad excerpts were in the upper half for valence (slightly lower that peaceful excerpts), but lower half for arousal. The scores for the equivalent vibro-tactile compositions were not similar, and could be said to be just where the others were not. All excerpts received mid-high scores for both dimensions. This is consistent with the findings from Remache-Vinueza et al. (2022) where the tactile condition had a significant increase in valence and arousal from the audio condition. It does seem to be the case that tactile stimuli are overall perceived as pleasurable. The results hint towards the complexity of translating emotional expressivity through different musical features, from the auditive to the vibro-tactile dimension.

Interestingly, the excerpt with the highest tempo (120 BPM in H2) was also the one perceived as the most stimulating. However, the sad and scary excerpts with tempos between 40-48 BPM were very close behind, with excerpts T1, T2, and S2 being perceived as more stimulating than excerpt H1 which had a tempo of 112 BPM. S1 (44 BPM) was perceived as the least stimulating, even with a slightly higher tempo than T1 (40 BPM) which is not surprising considering that it consisted almost entirely of PM illusion, which was regarded by most participants as the most relaxing and calming of the tactile illusions. The peaceful excerpts were divided: P2 (80 BPM) was considered the second most stimulating, which is understandable considering the high dynamics of the illusions; while P1 (60 BPM) was almost two points lower on the scale, close to H1 (112 BPM), which is predictable considering their very similar waveforms and distribution of illusions. See Figure 4.1 for a visual observation of the waveshapes of each excerpt in vibro-tactile form. Although it was expected that the arousal scores would be significantly higher for all vibro-tactile excerpts due to the physical stimulation present in the study, this was not the case; in this study, it seems that the scores were somewhat lower while still in the mid-upper half of the scale. In future research, it should be tested if the order in which the excerpts were played influenced significantly the ratings for valence-arousal and discrete emotions.

4.2.3 Qualitative results discussed

Perhaps the most interesting qualitative findings are based on the open-end question asked conversationally by the researcher at the end of the experiment – i.e., if they experienced any sort of associations during the vibro-tactile music compositions. Out of the 55 participants, 41 experienced associations. Of the remaining 14, 6 participants considered the experience abstract and unrelatable, 2 thought the experience was "a bit musical, although abstract", 5 focused on deciphering the emotional content based on the rhythm (e.g., "faster rhythm felt happier"), and the last one was focused on judging the quality of how the tactile illusions had been utilized in the compositions to transmit emotions.

Of the people who experienced associations, they could be categorized into musical and imaginative associations. 18 participants only experienced musical associations, 11 only imaginative, and 12 both. Musical associations were described as movie or video games' soundtracks (e.g., heartbeats or steps in horror movies before something bad happens, or the association with holding a controller with haptic feedback while playing video games), ringtones ("like the old Nokia ringtones"), tiny Christmas tree lights with sound, ambient or meditation music, "musique concrète", lo-fi, synthetic or electric music, and even church music (bells and organ). For all of these especially rhythmical characteristics of percussive instruments were felt. Fantastical associations referred to (childhood) memories and/or daily life situations such as: feeling cradled and rocked from side to side; being by the sea/ocean side, hearing the waves and feeling the wind (mostly regarding the continuous phantom motion illusion); the ambulance alarm; dancing music ("felt like I was dancing a waltz under the stars"); being in green fields full of flowers; feeling "summer vibes"; being in a busy pub or night club; skipping down the road "on a bright summer day"; driving a car and feeling its vibrations. All participants suffering from hearing loss considered the vibro-tactile compositions as reminiscent of music and could recognize and feel emotions.

Interestingly, music-loving non-musicians experienced slightly more musical and/or fantastical associations compared to the non-musicians, and, as expected, musicians experienced more musical associations. All individuals who suffered from hearing loss were music-loving, and with one exception, experienced both or only musical associations.

Additionally, some participants commented on the research idea and/or the experiment design. The musicality of the compositions was considered to be percussive and not melodic, with a focus on dynamics but very little to no tonal information. It was hard to get a handle on the fine-grained emotions – rather than happy, sad, scary or peaceful, feelings of “liveliness”, “mellowness”, “calmness”, “startlement”, “unease”, “heaviness” would be better suited to describe the compositions. This comes as no surprise considering the somewhat closely clustered scores for valence and arousal. The need for a test trial was mentioned, to help understand the task. Participants felt that they got used to the compositions and to identifying their emotional responses the longer they were exposed to them. The directionality and transitions felt similar to listening to stereo music through headphones and hearing in the middle. Rhythmic intensity was correlated with the musicality level of the excerpt (“more rhythm – the more it seems music”). The excerpts using the sweeping, wave-like tactile illusions were much more peaceful than the faster, more impulsive illusions which were perceived as more energetic; a finding that is supported by the valence-arousal graph compared to the original tempo. In the beginning, the emotional judgement was just about the fragment itself, whereas later on in the experiment there seemed to be more of a comparison between fragments. Individuals suffering from hearing loss were especially delighted by the experience and mentioned how much this could help them with the spatiality and directionality of sounds. Overall, participants agreed that such vibro-tactile compositions have potential to be enjoyed as “music for touch”, especially for non-hearing individuals, and especially if they would be longer than a few seconds. The study was considered a pleasant and excitingly new experience, that did not overstimulate the senses, but rather inspired a new musical perspective – a couple of participants even said it felt like “a massage for the fingertips”.

4.2.4 Technical design limitations

During the experiment, several things were noted down by the researcher about the participant response. One of these was the intensity at which participants seemed to feel each illusion. Phantom motion and funneling were felt at 15-40% of the amplifier’s volume (which is correlated with the intensity of the vibrations), while the cutaneous rabbit required 20-45%. Because of this difference, the vibro-tactile compositions were played at 20-50% volume, depending on each participant’s sensibility. It was not possible to record with accuracy this value. There was no noticeable difference between the hearing and non-hearing participants, although the non-hearing participants tended to be more sensitive to vibrations (i.e., had a lower threshold for attuning to touch) and to require less volume – even so, they were less likely to hear anything with a higher intensity, which is perhaps why 2 of them asked for volume up to 55%. An interesting comment made by one of the participants is worth further consideration – the intensity necessary for each participant to feel and differentiate between vibrations might be related to the hardness of their palm skin. Individuals doing constant manual labor, climbing, craft work, or playing string instruments like bass guitar might have thicker and tougher skin on their fingertips and palms, which in turn might require higher intensity for the vibrations. Future studies should explore this possibility, in order to better understand how to tailor this new experience to the needs of people.

In the planning phase, recording of the necessary time to feel each illusion was desired: increasing the volume with one bar (about 10%) every 5 seconds. In practice, however, it quickly became clear that the measurement was not reliable, as participants did not always understand the instructions from the beginning, and it was often inevitable to start the “calibration” again. Nevertheless, it seemed that the phantom motion illusion required the least time to be felt ($T = 7.15s$ on average, and 19 participants felt it immediately), followed by funneling ($T = 8.24s$ on average, 9 participants felt it immediately) and lastly the cutaneous rabbit illusion ($T = 8.73s$ on average, and only 2 participants felt it immediately).

After the pilot study it was noticed that unplugged noise-cancelling headphones made for a recording studio environment were not sufficient in blocking out the sound from the actuators. That is why, for the main experiment, protective earmuffs meant for the shooting range were used. Although they proved better at isolating the residual sound from playing the vibro-tactile music compositions, higher pitches were still perceivable, even at the lowest perceivable intensity. More specifically, parts of the happy and peaceful (H1, H2, P1 and P2) excerpts were consistently heard by participants (some heard something during all of four compositions, others only during one, two, or three of them). After collecting data from 40 participants (of which only 2 hearing individuals did not hear anything during any of the compositions), noise-isolating earbuds were procured. Following participants were instructed to use them under the earmuffs, with successful results. Of the remaining 15 participants only 3 hearing individuals still heard something from the happy and/or sad excerpts, which supports the decision to use both earbuds and muffs in the future.

5. General discussion

In this section, the main results of both the pilot study and the main experiment are discussed in the light of existing literature. The conclusion and recommended future work are presented at the end. Below the research questions are restated:

RQ 1. Are voice-coil actuators purpose-built based on literature indications effective in transmitting accurate tactile illusions?

RQ 2. Do ratings of felt and recognized emotion differ in vibro-tactile music?

RQ 3. Are tactile illusions a meaningful and consistent way to transmit emotional information present in musical stimuli?

RQ 4. Are individual differences such as empathy, hearing loss level, and musicianship level influencing emotional ratings?

RQ 5. Are valence and arousal scores consistent with the ratings of their discrete counterparts?

RQ 6. Does vibro-tactile music evoke associations, and if so what kind?

5.1 Discussion of results based on the research questions

Broadly, the goal of this thesis was to explore the emotional response of individuals to vibro-tactile music. For this, eight musical excerpts from Vieillard et al. (2008), two for each emotion (happy, sad, scary, peaceful) were chosen based on how well people recognized and felt the intended emotion. The excerpts were then rendered from audio to vibrations through a recently proposed algorithm by Remache-Vinueza et al. (2022), which uses tactile illusions as a resource for translating musical characteristics such as tempo, loudness, melody, pitch in a meaningful way. For this process, three illusions were used: two discrete (funneling and cutaneous rabbit) and one continuous (phantom motion). The rendered signal was transmitted to a pair of actuators and used panning in a similar fashion to a pair of headphones, to make use of the space between actuators. For this to be effective, the tactile illusions and their directionality had to be clearly perceived.

In the pilot study, ten experts from the music cognition and music technology fields tested two types of actuators to decide which pair of actuators was better for this task. A pair of commercially available piezoelectric actuators and a pair of voice-coil actuators based on the design proposed by (Yao & Hayward, 2010) were tested. The latter, named “hap-phones”, were judged to convey the clearest tactile illusions and were the most comfortable to hold between the fingertips. Therefore, based on the results of the pilot study, the hap-phones were used to convey the eight vibro-tactile stimuli in the main experiment. This also answers RQ1, specifically that the voice-coil actuators built based on a literature-proposed design conveyed clear tactile illusions. The results of the pilot study tentatively suggest that they might be better than commercially available options; however, a more in-depth study is necessary to verify this finding.

The main experiment was designed to help understanding the emotional response individuals have to vibro-tactile music. Considering the inconsistencies in literature regarding felt and recognized emotions, and the efficiency of different ways of measuring emotions, this thesis integrated both a distinction between felt and recognized emotions in the categorical measurements (as ratings for happiness, sadness, scariness and peacefulness in both conditions) and a continuous measurement (valence and arousal ratings based on the circumplex model; Russell, 1980).

Previously, no large differences were found between the felt and recognized emotional ratings of the auditive excerpts (of which eight were selected to use here; Vieillard et al., 2008), with even a slight trend toward felt emotions rated higher than recognized. In the present study, however, a significant difference was found in four excerpts. Excerpt peacefulness (which was not significantly different between conditions), all other emotions were rated significantly lower when felt than recognized (RQ 2). This is consistent with previous findings which suggest that people agree more when rating the perceived emotional content of a musical piece than when judging their evoked feelings, which is more susceptible to individual differences (Kallinen & Ravaja, 2006). This inconsistency with Vieillard et al. (2008) where felt emotions were rated higher than recognized might be explained by the experiment design – they used a between-subjects design, while in the present study each participant gave ratings for all conditions.

The differences between felt negative and felt positive emotions was often significant, suggesting that people experienced positive emotions more intensely. Regarding the specific emotions, happiness ratings were higher in both conditions for the excerpts intended to have a low arousal (peaceful and sad). In one case, peacefulness was higher than happiness (for S1). This is interesting considering the distribution of tactile illusions in these excerpts – the ones where happiness was perceived as higher used more discrete illusions like funneling, while S1 used only the phantom motion continuous illusion. Peacefulness was rated higher than sadness in some cases, consistent with previous findings which found that the two emotions differ in their ratings although they are close on the valence dimension (Vieillard et al., 2008), as seen by the consistent high peaceful and high sad ratings. Sad and scary ratings did not differ, and were actually positively correlated, which is supported by the participants feedback that the experience overall was pleasant, and that it was hard to feel or identify negative emotions in the stimuli. Sad, scary and peaceful excerpts used a more blended distribution of tactile illusions.

A tendency to recognize high dynamics as happy and low dynamics as peaceful can be observed in the data, especially without tonal information. If the excerpt used both discrete and continuous illusions, there was a tendency towards high ratings for positive emotions. The rhythm and intensity of the vibrations seemed to also be related to higher ratings for happiness. Overall, these findings suggest that the type of illusions (discrete or continuous) influenced the emotional response to the vibro-tactile music (RQ 3).

To answer RQ 4, the effect of hearing loss, empathy and musicianship on emotional ratings was explored separately.

The most notable difference between hearing and non-hearing participants was that the latter tended to rate positive emotions higher than negative and to recognize better between positive and less positive emotions. They seemed to react more strongly to the dynamics of the excerpts, which might be because the vibrations of some excerpts were closer to what they experience usually when they encounter a known happy piece. These results tentatively suggest that hearing and non-hearing individuals differed in their emotional response to vibro-tactile music. This is an relevant finding for the topic of this paper, but more research is necessary before drawing a definite conclusion.

Only a provisional effect of the level of empathy was found for the emotional ratings. Just in excerpt H2, individuals with higher empathy gave higher scores for happiness. This could be because this was the excerpt with the highest tempo (120 BPM), or because of its arrangement of tactile illusions (it had high dynamics with a lot of funneling). This finding should be explored further, as it is unclear at this stage whether empathy is an individual characteristic influencing the ratings of emotions found in vibro-tactile music.

Musicians and non-musicians differed in their emotional ratings only for two excerpts (H2 and S1). Interestingly these two excerpts might be the ones that differ the most in terms of dynamicity and arrangement of tactile illusions: H2 has a high tempo (120 BPM), and is created mostly with funneling and few short phantom motions for emphasis, while S1 has a low tempo (44 BPM) and contains phantom motions exclusively. Musicians rated peacefulness lower for H2 and higher for S1, compared to non-musicians who did the opposite. These results might be explained by a closer attunement of the musicians to the rhythm and tempo of the excerpts, even with a lack of tonal information. Tentatively, this finding suggests a difference between non-musicians and musicians in their emotional response, which could be based on the recognition of musical aspects in the tactile stimuli. Although it was hypothesized that musicians would have higher empathy than non-musicians, which might be an underlying mechanism influencing their ratings, secondary results only show a slight trend in this direction, without a significant effect.

Consistent with previous findings (e.g., Vieillard et al., 2008; Vuoskoski & Eerola, 2010), the valence and arousal scores were consistent with the ratings of the discrete emotions (RQ 5). Among participants, higher valence scores were associated with higher scores for both positive emotions (happiness and peacefulness), and higher arousal scores with happiness and scariness, as expected. Among all excerpts, happiness was correlated positively with both valence and arousal, peacefulness and sadness negatively with arousal, and scariness negatively with valence. Therefore, in the case of music for ears as well as music for touch, measuring emotional response with both categorical models (the ratings of discrete emotions) and continuous models (the dimensional circumplex model) is effective. Interestingly, when comparing the plotting of the means of each excerpt on the valence-arousal dimensions, all were clustered in the mid-upper half of both axes, almost in the exact space where there were no excerpts in the Vieillard et al. (2008; see Figure 2.4.1.5 for a better visual understanding). A possible explanation for this is the novelty effect of the stimuli which might have led to a sort of confusion in ratings, as well as a lack of already-there baseline for what would be a relaxing or stimulating vibro-tactile musical piece (participants often mentioned how difficult it was to give a valence-arousal score without a baseline, i.e., an idea of how a stimulating or unpleasant vibro-tactile composition would feel like, especially in the beginning).

Lastly, through an open-ended question addressed after the questionnaire it was assessed whether participants experienced any associations during the vibro-tactile music, and if so which type. Almost 75% (41 of 55) of the participants experienced musical (N = 18), imaginative (N = 11) or both (N = 12) types of associations (RQ 6). Musical associations ranged from soundtracks and ambient music, to "musique concrète", synthetic sounds and church music. Imaginative associations referred to (childhood) memories as well as daily life situations – e.g., being by the ocean side and hearing the waves and the wind blowing (mostly for the excerpts with an arrangement with more continuous phantom motion illusions), dancing, skipping down the road "on a bright summer day", or being in a busy pub or nightclub. Interestingly, non-musicians who love music experienced more associations than non-musicians, and musicians experienced more musical associations. Non-hearing participants were music-loving, and with one exception, experienced both or only musical associations. These results open up interesting aspects for future studies, such as individuals' imaginary capabilities as a potential factor that influences the perception and rating of musical emotions.

Overall, participants considered the experiment a pleasant ("like a massage for the fingertips") and exciting experience by, or despite, its newness, that inspired them to consider new musical perspectives. The participants that suffered from hearing loss considered it highly entertaining and reminiscent of music with a lot of potential in the future, especially for helping them perceive spatiality and directionality in sounds. There was a consensus regarding the difficulty in identifying fine grained emotions (e.g., instead of discrete emotions, they felt "liveliness", "mellowness", "startlement", "unease").

5.2 Limitations and future work

Perhaps the most important limitation of this thesis was the utilization of Musical Instrument Digital Interface (MIDI) files when rendering the excerpts from audio to vibrations – the excerpts from Vieillard et al. (2008) were played by me on a keyboard and recorded in Reaper through a synthesizer effect. That removed a lot of the subjectivity gained by recording an actual performance (as opposed to generating and playing them electronically as done in the original study). To substantiate, some participants considered the vibro-tactile music "synthetic". Future work using vibro-tactile music rendered from audio could use other musical stimuli, perhaps from existing songs. The difficulty with this suggestion is that the translation algorithm only works with monophonic MIDI files at this stage (as it is assigning a tactile illusion for each note), and already-existing songs are rarely available in this format.

This thesis explored the response to vibro-tactile music. Arguably, people suffering from hearing loss have a heightened sense of touch. A deeper exploration of the differences between hearing and non-hearing people was desired. However, the sample of participants collected for the main experiment included only 5 people with moderate or profound hearing loss. It was, thus, not possible to draw reliable conclusions regarding their differences in perceiving vibro-tactile music. Future studies should specifically focus on comparing these two populations with equally distributed samples.

Moreover, due to the relatively small sample size (55 participants in total), several effects were only trending in a certain direction. For a better understanding of emotional responses – which is a subjective and personal topic in itself – a bigger sample would yield more significant and general results. The musicianship level was considered in the context of capabilities of extracting emotional information from music; however, due to the unequal sample distribution it was necessary to reduce the levels to just being or not being a musician, based on people's own judgements. This might have resulted in lost effects, which would come to light in a better distributed sample. The influence of musical background could also be considered in future studies, to explore whether the longer one had a relation with music the more vibro-tactile musical associations are experienced and the bigger the difference in their emotional response.

Empathy was considered a potential factor in explaining individual differences between participants in their emotional ratings. Only two out of four subscales of a well-used measuring tool (Davis, 1980) were used due to time constrains. Potential findings based on a more thorough empathy score, as well as potential differences between the subscales were lost in the current data. Future work could focus on exploring this, but also other individual characteristics with a potential in influencing one's response to vibro-tactile music.

The emotional response to vibro-tactile music was explored through quantitative measurements, as well as through an open-question. Initially prompted by my curiosity and interest in participants' opinion about the whole idea of the study, the qualitative component of the main experiment was insufficiently considered or structured. Future work should consider better-designed qualitative explorations of the potential of the vibro-tactile music to evoke emotions and associations.

An intriguing consideration for future studies is to explore the differences between vibro-tactile music made from scratch and the one rendered from audio. The associations between tactile illusions and their emotional expressivity should be more systematically studied, and then applied to "composing" vibro-tactile music. Ultimately, in the context of tactile music for non-hearing individuals, the goal is to create a methodology for them to be able to compose and enjoy music for touch in a similar way hearing participants enjoy music for ears.

5.3 Conclusion

In this study, the voice-coil actuators based on a design proposed in literature were found to convey the clearest illusions. A pair was consequently used to explore the emotional response to vibro-tactile music rendered from audio excerpts using a recently proposed algorithm that assigns tactile illusions for each note. Categorical and continuous models were used to measure emotional response. Several differences were noted between ratings of felt/recognized emotions, hearing and non-hearing participants, musicians and non-musicians. Musical and imaginative associations were also experienced by the participants in most cases. Overall, irrelevant of the intended emotion, nearly all excerpts were considered happy, and a few peaceful, suggesting a bias towards rating vibro-tactile as pleasant, which is consistent with participants' opinions.

This thesis could be considered as a stepping stone towards more research combining the fields of musical haptics (music technology) and music cognition, specifically regarding the study of emotions in vibro-tactile music.

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Appendix 1

This is a copy of the questionnaire used in the study.

GENERAL

What is your gender? Female/Male/Other

What is your age? … (number)

Do you suffer from any type of hearing impairment? If so, what level of impairment do you suffer from?

- no hearing loss
- mild hearing loss
- moderate hearing loss
- severe hearing loss
- profound hearing loss
- I prefer not to answer.

Which title best describes you?

- Non-musician
- Music-loving non-musician
- Amateur musician
- Serious amateur musician
- Semiprofessional musician
- Professional musician

EMOTIONAL RESPONSE

For each vibro-tactile excerpt, provide ratings for each of the four emotion labels, based on a 10 point scale where 0 means that the emotion was absent and 9 that the emotion was present.

To what extent was this excerpt…?

HAPPY
0 …………1 ……. 2… …………………………….. 9
(absent)…………………………………………..(present)

SAD
0 …………1 ……. 2… …………………………… 9
(absent)………………………………………..(present)

SCARY
0 …………1 ……. 2… …………………………… 9
(absent)………………………………………..(present)

PEACEFUL
0 …………1 ……. 2… …………………………… 9
(absent)………………………………………..(present)

To what extent did you experience …?

HAPPY
0 …………1 ……. 2… …………………………… 9
(absent)………………………………………..(present)

SAD
0 …………1 ……. 2… …………………………… 9
(absent)………………………………………..(present)

SCARY
0 …………1 ……. 2… …………………………… 9
(absent)………………………………………..(present)

PEACEFUL
0 …………1 ……. 2… …………………………… 9
(absent)………………………………………..(present)

VALENCE AND AROUSAL

For each vibro-tactile excerpt, rate the valence and arousal on a 10 points scale as follows.

How pleasant was this excerpt?
0 …………..….1 ……. 2… ……………………………… 9
(unpleasant)………………………………………..(agreeable)

How stimulating was this excerpt?
0 …………..….1 ……. 2… ……………………………… 9
(relaxing)………………………………………..(stimulating)

INTERPERSONAL REACTIVITY INDEX

The following statements inquire about your thoughts and feelings in a variety of situations. For each item, indicate how well it describes you by choosing the appropriate letter on the scale at the top of the page: A, B, C, D, or E. When you have decided on your answer, fill in the letter next to the item number. READ EACH ITEM CAREFULLY BEFORE RESPONDING. Answer as honestly as you can.

ANSWER SCALE:

A	B	C	D	E
DOES NOT DESCRIBE ME WELL				DESCRIBES ME VERY WELL

1. I daydream and fantasize, with some regularity, about things that might happen to me.

2. I often have tender, concerned feelings for people less fortunate than me.

3. Sometimes I don't feel very sorry for other people when they are having problems.

4. I really get involved with the feelings of the characters in a novel.

5. I am usually objective when I watch a movie or play, and I don't often get completely caught up in it.

6. When I see someone being taken advantage of, I feel kind of protective towards them.

7. Becoming extremely involved in a good book or movie is somewhat rare for me.

8. Other people's misfortunes do not usually disturb me a great deal.

9. After seeing a play or movie, I have felt as though I were one of the characters.

10. When I see someone being treated unfairly, I sometimes don't feel very much pity for them.

11. I am often quite touched by things that I see happen.

12. I would describe myself as a pretty soft-hearted person.

13. When I watch a good movie, I can very easily put myself in the place of a leading character.

14. When I am reading an interesting story or novel, I imagine how I would feel if the events in the story were happening to me.

Appendix 2

Additional materials and a link to the MCT Blog where a blog post about the thesis will be posted can be found at https://github.com/alenaclim/mct-thesis-tactile-music