Politecnico di Torino

ASSESSMENT OF THE USAGE OF TACTILE FEEDBACK IN REMOTE MUSIC TEACHING

Degree in Telecommunications Engineering

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FINAL PROJECT

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Ackonowledgment

To my parents, because everything I have and everything I am is thanks to them. My successes are also theirs.

To my aunts for their unconditional support. Especially to my aunt Maribel, for whom I chose the degree that today I am completing thanks to all the confidence she has placed in me from the beginning.

To the Public University of Navarra. Above all, for the friends who have become a fundamental part of my life. With special mention to the one who is my life partner, for trusting me more than I ever will and for always having the words I need.

To all that the city of Turin has given and taught me.

Last but not least, I would like to thank my supervisor Cristina and her PhD student Matteo for all their help, affection, and availability from the very first moment. Without them this work would not have been possible. Thank you for making me feel at home 1200 km away from my own.

Real progress happens only when
the advantages of a new technology
become available to everybody.

Henry Ford

Abstract

Inclusion and accessibility are becoming increasingly important in our society in the present day. At the same time, in recent years we have seen how technological advances have completely taken over our daily lives and how humanity is unable to live in a world without them. Fortunately, the world is increasingly evolving towards more inclusive practices and technology is helping, among many other goals, people with hearing impairments to live experiences that were previously unimaginable.

Contributing to this, this thesis aims to find ways, if it is possible, to present music for deaf and hard of hearing people through tactile feedback. To achieve this goal, it is essential to find out how people establish multisensory relationships between colors, textures, images, vibrations, etc. and sounds.

Having gathered all this information, an interface has been developed using the TanvasTouch device, thanks to its ability to create textures and haptic effects on its touch screen. This application aims to improve the musical experience of hearing-impaired people.

Keywords

Haptics, vibrotactile feedback, inclusion, accessibility, disabilities, music, deaf and hard of hearing, musical experience, multisensory perception, TanvasTouch, waveform, tactile perception, touch screen.

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1. Introduction.

Nowadays, inclusion and accessibility are becoming increasingly important in our society.

On one hand, social inclusion, according to [1], is the process of improving the terms on which individuals and groups take part in society by enhancing the ability, opportunity, and dignity of those disadvantaged based on their identity.

On the other hand, accessibility, the ability to access, is the design of products, devices, services, etc. to be used by people with disabilities: enabling this way access for them.

At the same time, in the last few years we have seen how technological advances have fully taken over our society. We are now unable to live in a world without television, mobile phones, computers or even the internet. Neither are we able to live without music, as it is something we use in our daily lives, whether for running, travelling, enjoying with friends or alone. Indeed, it also forms part of our culture and can bring back memories of our childhood.

It is the above that leads to the development of this thesis. Taking advantage of the knowledge provided by the degree in telecommunications engineering, concepts such as wave analysis, programming, image, and sound processing, etc. can be combined to achieve the desired goal. Fortunately, we have today all the knowledge of all these technologies that can facilitate the inclusion and accessibility of people with disabilities. The world is evolving towards more inclusive practices and technology is helping deaf people to live experiences that were previously unimaginable.

The final project I am presenting here was developed during my one-semester stay at the Politecnico di Torino thanks to the Erasmus scholarship. This university has lent to me all the necessary material to carry out this project.

I have also had the help of the music conservatory teachers Chiara Nicora and Piera Bagnus, who have provided me with documents of interest for the development of my thesis as well as relevant information.

1.1. Objectives.

This work aims to know how to present music for deaf and hard of hearing people by tactile feedback, providing inclusion and accessibility to people with hearing disabilities. To achieve this, the TanvasTouch device, see Chapter 4.1, has been used thanks to its ability to create textures and haptic effects on its touch screen.

To this end, an in-depth study on how to present music for these people has been made. For this reason, it is essential to know what is considered music and how people interpret it, considering some discrepancies that may exist between people without disabilities in this context. Fortunately, the existence of a significant body of scientific literature on such topic has made this easier, all of which will be referred to throughout the thesis.

Another main objective is to find out how people make relationships between colors, textures, images, vibrations, etc. and music. In this way, this thesis will try to find a way for a hearing-impaired person to feel what a non-hearing-impaired person feels when listening to music thanks to the knowledge of that relations.

After gathering all this information, an interface has been developed for the TanvasTouch device, which aims to improve the musical experience for people with hearing impairments based on the relationships between instruments, sounds, colors and textures. This application has been designed according to the results obtained by means of a questionnaire, the outcome of which is shown in Chapter 5. Results and discussion.. This form was made in order to find out how people associate music to colors, images, smells, taste and touch feelings.

2. State of art.

To begin to develop this thesis, first it is necessary to know the existing literature on the subject to be dealt with. Examples of references used are experiments with tactile feedback or techniques for visualization of music for deaf people. In this chapter, the literature necessary for the elaboration of this work will be presented.

2.1. Conveyance of musical information through the sense of touch.

In this section, some studies based on the conveyance of musical information through the sense of touch will be analyzed. However, only the most important aspects will be included here. This was a good starting point for the development of the project because it provided useful information about the topic.

According to [2], where it was investigated how input voltage waveform affects our haptic perception of electro vibration on touch screens, people are more sensitive to square wave stimuli than to sinusoidal stimuli for fundamental frequencies below 60 Hz, this is due to the frequency-dependent electrical properties of human skin and human tactile sensitivity. In addition, the Pacinian is the primary psychophysical channel in the detection of the square wave input signals tested in this study.

The effect of frequency levels on the ability of humans to perceive vibrotactile stimuli as sounds at the index fingertip was studied by [3]. This paper concludes by saying that the optimal audio-tactile integration frequency range is 200-390 Hz.

A method whereby Fourier series spectral analysis can be employed to describe physical surface characteristics is described in [4]. The results presented suggest that a bandlimited Fourier series provides an accurate representation of small-scale surface details.

The transfer of information through a single vibrator at the fingertip has been studied by [5]. In a first experiment, the discrimination of an octave-step frequency change at the midpoint was investigated and it was concluded that temporal cues are more important than spectral cues in this task. In a second experiment, subjects were required to perceive changes in a sequence of stimulus elements. This experiment concludes that it is more appropriate to transmit suprasegmental information on a time scale of a few hundred milliseconds rather than segmental information on a time scale of several tens of milliseconds. In addition, an important consideration is the effect of the location of stimulation: the wrist is a common choice for tactile aids, rather than the fingertip. Perception at the wrist is currently being investigated: Initial results suggest that, if the level of stimulation is increased to compensate for the lower sensitivity of the wrist, the perception of sequences through the glabrous skin of the lower wrist is similar to that of the fingertip.

The article [6] defines a touch rendering algorithm to simulate 3D geometric features on touch screen surfaces from the frictional forces between the user's finger and the touch screen.

A study on the subjective magnitude of vibration was conducted by [7] to determine the growth of sensation as a function of stimulus intensity, establish contours of equal subjective magnitude and compare, over a wide range of frequency and intensity, the psychophysical methods of direct scaling and intensity matching.

In thesis [8], psychophysical experiments were conducted with hearing-impaired and non-hearing-impaired participants to determine vibrotactile detection thresholds at the middle fingertip and sole of the foot, as well as to evaluate relative and absolute vibrotactile musical pitch perception. This thesis concludes that no differences in perception at the middle fingertip were found between normal and hearing-impaired participants in the range 32.7 Hz 1046.5 Hz. An optimal and safe dynamic range has been estimated to vary between 12 and 27dB in the range 65.4Hz to 523.3Hz. In addition, the forefoot and heel could use a dynamic range similar to the fingertip.

Based on the use of an ultrasonic touchscreen, the tactile perception of the change in friction is investigated in [9]. The objective of this study is to investigate the relationship between our tactile perception of the change in friction and the underlying contact mechanics during sliding. Psychophysical experiments were conducted to evaluate human tactile perception of friction change for rising friction (RF) and falling friction (FF). For a sliding finger, subjects' psychometric curves for rising friction (RF) and falling friction (FF) were almost identical, whereas they perceived the change in friction for FF only when they gently pressed their finger on the surface without sliding, as in key presses. On the other hand, when the gliding experiment was repeated with stimulus levels significantly higher than the detection threshold level, RF was perceived more strongly than FF. These results suggest that the factors affecting our tactile perception of friction change for sliding are different from those for non-sliding. Furthermore, finger speed is shown to have little or almost no effect on our tactile perception of the change in friction. However, subjects' perception was affected by transition time and normal force: as transition time increased, the strength of their perception decreased.

The human capacity for vibrotactile frequency discrimination has been compared directly for glabrous and hairy skin regions in [10]. In contrast to the detection task, for which there are marked differences between the different skin sites, discriminative performance was remarkably similar in hairy and glabrous skin. The increase in magnitude of the Just Noticeable Difference (JND) or Δf, for frequency discrimination from ~5 Hz at a standard frequency of 20 Hz to values of ~25 Hz at 200 Hz suggests that there is a deterioration in discriminative performance as a function of increases in frequency.

Study [11] concludes that humans can distinguish between different waveforms through vibrotactile stimulation only when presented asynchronously at a fundamental frequency of 160 Hz. The performed experiment confirmed that humans can distinguish between pure sinusoidal and complex waveforms with non-sinusoidal periodic shape containing odd (square) and odd and even (saw) harmonic content at a given frequency.

Apart from the papers mentioned, there are other relevant aspects which should be commented:

- In the case of vibrotactile systems, the range of response frequency is 20Hz-1000Hz lower than the range of the auditory system which oscillates between 20 Hz and 20000Hz.

- The Weber-Fechner law, [12], states that "the smallest discernible change in the magnitude of a stimulus is proportional to the magnitude of the stimulus". The Weber ratio appears in some of the papers related to this topic.

- The frequency discrimination capacity depends on the frequency that is being transmitted.

- Loudness of sound depends on amplitude of vibrations.

- [13] is a video of an example of a haptic device: VibGrip++: Haptic Device Allows Feeling the Music for Hearing Impaired People.

2.2. Haptic feedback experiments.

In this section some haptic feedback experimental setups will be listed. These prototypes or devices can be used to present music for deaf and/or hard of hearing people, therefore, they can be replicated or simply helpful in achieving the project's objective.

[14] presents a method to present tactile sensations by generating vibrations via irradiating sound waves of various frequencies and amplitudes on a plate. In the Image 1 and the Image 2 the device configuration and the prototype device can be seen.

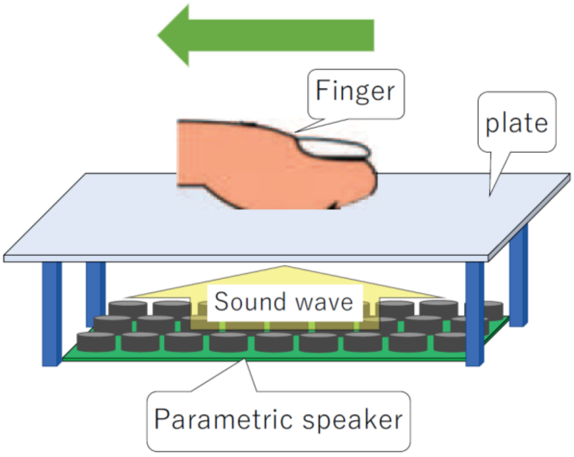

Image 1. Device Configuration. *Extracted from [14].*

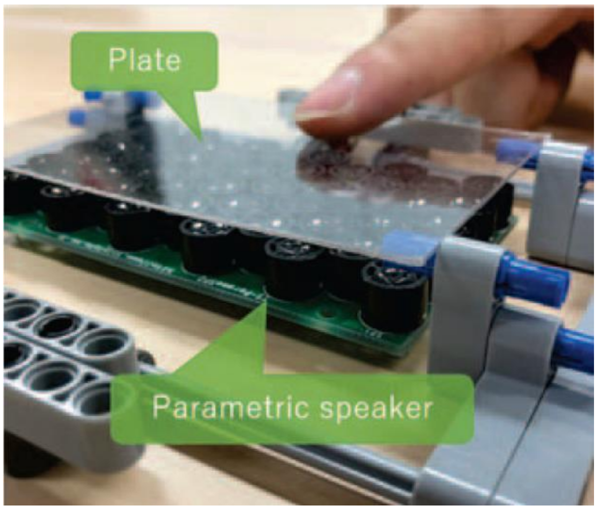

Image 2. Prototype device. Extracted from [14].

The prototype device consists of a parametric speaker and a plate, the plate will vibrate thanks to the sound waves produced by the speaker. When the vibrated plated is traced with a finger, a tactile sensation will be presented by a vibration stimulation to the skin.

To measure this a laser light and a camera are necessary. The laser beam shall be applied to the surface of the plate while the sound waves are radiated, then the reflected light will be projected onto the screen and photographed. The reflected light in each image will be tracked and a fast Fourier transform will be performed to determine the plate's vibration frequency peak.

In the Chapter 6.2. Future work this method will be the basis for the proposed work.

Apart from this experiment, many other possible configurations can be found to achieve the same goal: to present music through the haptic sense. In brief, some of them will be discussed below.

[15] proposes a device, see *Image 3*, whose vibration system is an eccentric mass DC motor with a cuff system built for wrist level clamping.

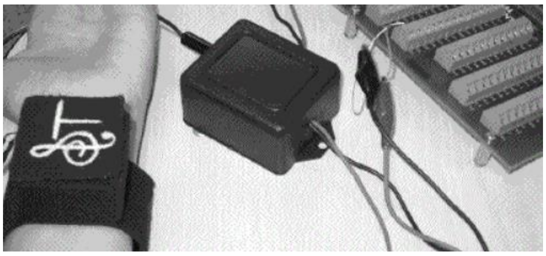

Image 3. Vibrotactile audition system.Extracted from [15].

In [16] a prototype of a spherical surface where localized haptic feedback is generated is described. It is covered with actuators and a sensor. This can be seen in the *Image 4*.

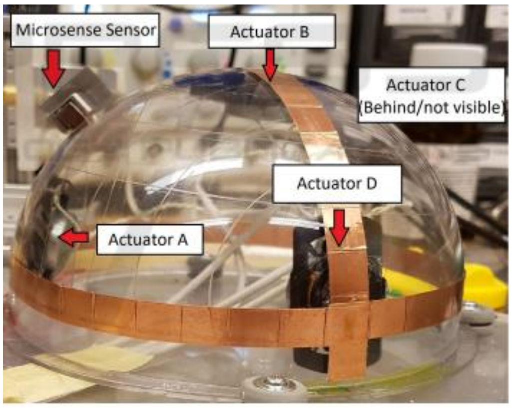

Image 4. Spherical surface with localized haptic feedback.Extracted from [16].

Another alternative is to create tactile feedback without direct contact with the skin, through acoustic radiation pressure as [17] explains. This is based on ultrasound haptic devices.

According to [18], a chair, see *Image 5*, can be used to transmit musical information through the haptic sense. In the mentioned paper the design and evaluation of this haptic chair is included.

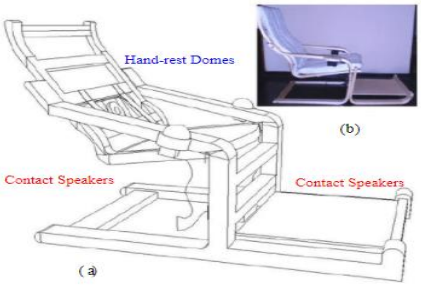

Image 5. Haptic chair. Extracted from [18].

The [19] article is about a belt, the Feelbelt, which is being sold to enhance the virtual reality experience.

In [20], a single and multi-finger vibrotactile device is built that takes the tactile feedback signal from an experimental virtual reality haptic setup developed in the Unity 3D environment.

2.3. Music visualization techniques.

Apart from the techniques mentioned above, all of which are related to the sense of touch, visualization can also be useful in presenting music for people who cannot hear. In this section, the papers on this topic analyzed for this thesis will be described.

The paper [21] presents a music visualization prototype, called ViTune (see *Image* 6), which enhances the musical experiences of the deaf and hard of hearing community thanks to the usage of an on-screen visualizer generating effects alongside music.

This study tries to give an answer to the following question: "How might we create an inclusive, effective, and viable visualization system of music for the deaf and hard of hearing?". For this, they considered the feedback given by members of deaf and hard of hearing community.

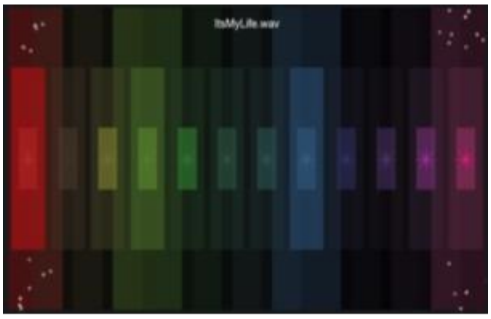

Image 6. Example of music visualization by ViTune. Extracted from [21].

Paper [22] introduces BufferBeats, a toolkit for creating multimodal experiences for streaming services, so people with hearing loss can enjoy online streaming music consumption (nowadays the central way for people to play music). This tool is necessary because of the presence of the Digital Rights Management anti-piracy encryption which restricts the access to audio data which is required to create multimodal experiences for music streaming. Throughout the paper, a way to overcome technical obstacles to develop a multimodal music streaming experience for deaf and hard-of-hearing music consumers is demonstrated.

Music presented by the softwares which we use daily, for example Spotify or Apple Music, has non-auditory interfaces such as lyrics or music videos. However, modalities like haptics or vibrations, which allow accessibility for the deaf, do not appear in these softwares.

Subtitles can also be useful for the visual content to aid the enjoyment of the music. Interestingly, technological advances, such as captioning, are welcome as they are not perceived as intrusive by deaf people (like a cochlear implant would) but adjust the environment to their needs. The study [23] discusses, among others, the font and size, the number of lines or the position on the screen that subtitles should have so that deaf people can enjoy the musical experience more. This is not only true for music but also for plays, for example.

3. Background.

The purpose of this chapter is to provide information on existing knowledge about deaf and hard of hearing communities, as well as describing how music is present in our lives and its significance in our society. In addition, haptic technology and its advantages for the deaf community are also described.

3.1. Hearing losses.

According to [24], hearing loss is considered one of the most common forms of disability around the world. It can appear at different periods across the life span and for several reasons for example: genetic factors, infections, collection of fluids in the ear, chronic diseases, exposure to loud sounds…

The three types of hearing loss are the following:

- Conductive. The sound is blocked or cannot get into the ear as the result of excess earwax, colds, injuries to the ear.

- Sensorineural. Sounds can get into and travel through the ear, but the sound cannot be perceived because of an issue with the cochlea or the auditory nerve.

- Mixed. Having both conductive and sensorineural loss.

Normally, a person has hearing loss in a range of frequencies, especially at high ones. Although, it is possible to experience hearing loss only at certain frequencies.

3.1.1. Disabilities.

In accordance with [25], a disability is any condition of the body or mind that makes it more difficult for the person with the condition to do certain activities and interact with the world around him/her.

There are many types of disabilities, being the auditory one the one which concerns this work. This group includes deaf and hard of hearing people, which will be mentioned further on.

It should be considered that deaf and hard of hearing people constitute a very diverse group:

- Deaf people do not hear anything and communicate only by gestures. They consider themselves to be part of a linguistic and cultural minority. Deaf people are not able to hear and/or to make meaning of anything they might perceive as sound.

- Those with hearing impairments may not hear some frequencies but can have a spoken conversation and may need hearing aids or implants. They have some limited ability to hear music.

In conclusion, the diversity of the group of deaf and hard of hearing people is better reflected in their preferred method(s) of communication, which may include spoken language, sign language or both.

All that has just been said is important to develop devices or algorithms for the deaf and hard of hearing communities because they may not be the same depending on the degree of auditory disability of the user.

3.1.2. Prevention.

Although in some cases hearing loss may be present at birth, in many cases it is also due to preventable causes. Unfortunately, more and more people are suffering from hearing loss due to the excessive music consumption in terms of volume and exposure time. Throughout the thesis the importance of the sense of hearing in our lives is mentioned, therefore, it is important to reflect on bad habits in order to avoid them and to take care of our auditory system.

According to [26], inadequate exposure to noise, noise pollution or infections are some of them. Some methods to prevent hearing loss are as follows:

Avoid loud noises, loud environmental noises such as the sounds of construction sites or vehicle traffic, which can be one of the causes of hearing losses.

It should be kept in mind that using headphones for long periods of time and at high volume can cause hearing loss. Nowadays, there is growing concern about the damage caused by using headphones to play music. It is always recommended to adhere to the "rule of 60". That is, do not listen to music at more than 60 decibels for more than 60 minutes.

High volume levels of electronic devices such as televisions, music players or mobile phones can affect hearing in the long term. It is recommended to avoid exceeding the volume levels suggested on the data sheet of each electronic device.

3.2. Music.

Reflecting on how music is present in our lives, one can see how it is something that we use in our daily lives. Indeed, from the time we are little we live with music, so it is something we all have grown up with. For example, it is impossible to imagine a film without a soundtrack: this way it would be "silent" and unable to convey any emotions.

Moreover, music is part of a country's culture. In many cultures, music is an important element of people's way of life, playing a fundamental role for example in religious rituals, in ceremonies as graduations or weddings and in social activities such as dancing.

3.2.1. Definition.

Everyone knows how music makes us feel, and we know what we enjoy while hearing it, but expressing it through words is a complex job. In addition, imposing a single definition is difficult because people's opinions differ about what music is. Sound is by no means an intangible phenomenon.

For [27], music is a collection of coordinated sounds. And, making music is the process of putting sounds and tones in an order, often combining them to create a unified composition.

Besides that, music can be defined as a form of communication. An example of this might be sending a message or to expressing ideas and emotions.

3.2.2. Music properties.

As previously mentioned, it is not easy to find a global definition of music. However, musical properties are helpful to describe and build music in an objective way. This section will define some of the most important properties, but they are not the only existing ones. According to [24]:

Tone is a discrete musical sound.

Pitch is what gives listeners the sense of a tone's relative position in the musical scale.

Timbre allows a listener to easily distinguish between the sounds of different instruments even when they play together.

Loudness relates to the physical amplitude of the tone.

Tempo is the overall pace or speed of the piece.

Rhythm is the way that the durations of a group of notes fit together into larger units.

Reverberation is the sense of how far the source of the sound is.

Harmony is the relationship between the pitches of different tones.

Melody is the main theme of a musical piece.

3.2.3. Music for deaf and hard of hearing people.

This section includes a collection of findings drawn from [24]. These are the followings.

Deaf people like loud bass more than sounds with high pitch because it coveys vibration; using bass sounds is born from the premise that as their vibration frequency is slower than high-pitched sounds, it allows us to "feel" it through the body and play a little more. When assessing visualization tools for deaf/hard of hearing (D/HH) community, visualizations of tonality, harmony, pitch change, timing, instrumentation present, and beat/rhythm information were too complex and not appreciated by most of the subjects. Aesthetic and entertainment elements are strongly preferred over information elements. However, some knowledge of how to interpret the visualization is needed or the information is not able to be fully appreciated. D/HH viewers are not so interested in how accurately the visualization represents the music, but how entertaining the representation is. Indeed, non-D/HH music consumers listen to music for entertainment, not for analysis.

Nowadays there are concerts dedicated to the D/HH community where music is played very loud so that D/HH people can feel the produced vibrations, in addition to the show given by the concert performers. Some hearing aid users often disconnect their hearing aids so as not to damage their ears. It is a very enriching experience for them. The concert shown in *Image 7* is one organized by DJ Martin Garrix so that people with hearing problems could enjoy the concert. The environment was equipped with speakers that emitted low frequencies, a player system attached to the body so that the vibrations of the songs made them feel the music and special platforms to feel the rhythm, as well as some visual elements such as water and screens that transmitted movement, they managed to transmit the music that the DJ was playing in his session. After the experience, some of the attendees commented that music is not only heard through the ears, as they could feel it with their whole body.

Image 7. Example of a concert for deaf people.

3.2.4. Haptic technology.

Haptic technology allows music to be "heard" through the skin. An example of this can be seen in the *Image 8*. There are different levels of deafness and therefore different ways of enjoying music. Deaf people who use technical aids, such as cochlear implants or hearing aids, can hear the music and the lyrics. However, people who do not use technical aids can only feel the vibrations produced by the music through their body. Being this last point, what haptic technology is based on.

Image 8. The vibrations of the music, passing through a special platform, are felt through the body. (Università Ca'Foscari Venezia).

The paper [28] is a good starting point to study about the haptic technology. This document is a review on the technology and methods to achieve music transmission through the sense of touch. Currently, haptic music players have been developed to give people with hearing losses the opportunity to experience music. This study aims to compile the methods and technologies used to render musical information through vibrotactile stimuli.

Some aspects to highlight about the above-mentioned study are the following:

There are frequency limits between which vibrotactile stimuli are perceived. These values are from 0.3 Hz to 1000 Hz. Furthermore, depending on the part of the body with which the stimulus is being accessed and the intensity of the vibrations, the best perceived frequency will be different.

Another concept to consider is spatial resolution. This again depends on the part of the body where the stimulus is being elicited. The study concludes that for the hands and lips the spatial resolution is 10 mm, which is four times lower than for the back.

Depending on the type of music to be played, rhythmic patterns may have more presence in a specific frequency band, so one way to enhance vibrotactile rhythmic information is to use filters. An example of this would be that in jazz music the bass or drums often mark the rhythmic baseline, so a low-pass filter can be used to cut the high frequencies and enhance the bass tones that carry the rhythm.

Tone discrimination is not constant and is frequency dependent. The JND between the tones varies with frequency. This means that if the frequency increases, the JND between the tones also increases.

Pitch can be related to touch using tactile metaphors. It is known that it is possible to associate tactile metaphors such as sharpness, roughness, softness, weight, warmth and wetness, and musical characteristics such as pitch, loudness, timbre, and their combinations. An example of this would be: "higher pitches can be described as sharper, rougher, harder, cooler, drier and lighter than lower pitches". For all these reasons, tactile metaphors can be of special value for the hearing impaired.

The practical representation of melody, property of the music described in the Chapter 3.2.2. Music properties., can be achieved from the spatialization of frequencies in different parts of the body varying on time. It is possible to discriminate intervals with frequency changes of about 8 Hz, but this value depends on the location of the vibrotactile stimuli. Apart from this, the study concludes that the tactile resolution for pitch discrimination is lower than that of the auditory resolution.

Timbre, property of the music described in the Chapter 3.2.2. Music properties., is based on the spectral content of audio signals, so tactile representation is challenging. However, it is known that individuals can recognize the timbre of audio signals rendered from musical instruments only with vibrotactile stimuli. In addition, the sense of touch can recognize the waveform of the signals. This recognition ability can be used as a tool to represent timbre as vibrotactile texture.

Vibrotactile loudness, property of the music described in the Chapter 3.2.2. Music properties., explained in a subjectively explained way, is a variable that corresponds to the distance at which the skin is displaced by stimuli. Its tactile representation can be simple, as it can be directly mapped to the intensity of the actuators. This representation can be improved by adding visual feedback in the form of varying light brightness.

In addition to the above, the study [29] states the following. On one side, it affirms that after a cochlear implant only about 15% of adults enjoy listening to music and about 70% are disappointed. It also claims that frequency discrimination for implanted listeners, although worse than for normal-hearing listeners, is better than for haptic stimulation. Moreover, people with congenital deafness (hearing loss which is present at birth) have better tactile sensitivity than people with normal hearing.

3.2.5. Relating music to graphic elements and textures.

Based on what has been mentioned in the previous sections and thinking about how to prepare an experience like the one a non-hearing-impaired person has when listening to music, it is possible to think about a multisensory experience. That is, combining visual and haptic representation of music.

The Chapter 2.3. Music visualization techniques. contains references to studies on music visualization. However, there is no stipulated definition on how to relate visual and multisensory content to music. Therefore, a questionnaire needs to be prepared to find out how people associate sounds with colors, images, smells, tastes, textures, etc.

The details of the above questionnaire and the results obtained will be described in the Chapter 5. Results and discussion.

3.2.5. Teaching music remotely to deaf people.

Teaching music to deaf people is a really difficult task, which becomes even harder when performed remotely (web-mediated or online teaching), thanks to the support of information and communication technologies. It is enough to imagine how to explain to someone who is not able to hear something that, supposedly, can only be perceived by the sense of hearing. The purpose of this section is to list some ideas, drawn from two separate studies, that might be helpful in achieving this.

The thesis [30], defines a Networked Music Performance (NMP) as a musical performance where musicians located at different physical locations, interact over a network, feeling as if they were in the same room.

In its second chapter, relevant literature for the design of networked music performance scenarios and experiments is framed. The most relevant part of the chapter is summarized as follows:

It has been shown that latency values in the range of 20 – 60 ms degrade the quality of the performance. However, remote music teaching is not affected by the latency as much as remote music performance.

The use of Ambisonics[1] techniques have been explored to provide expressive and congruent environments in network music applications.

JackTrip, [31], is the application developed by the SoundWIRE research group, to support bi-directional music performance.

LOLA, [32], is based on low-latency audio/video acquisition hardware, optimized to transmit audio/video contents through a dedicated network connection. The main drawback is that the application is not open source and not serviceable for generic network connections.

The DIAMOUSES, see thesis [33], project provided a scalable architecture for both synchronous and asynchronous musical interactions.

MusiNet, [34], is a project involved a network architecture consisting of different clients and a server that can manage audio/video and additional information (textual data). Spatial audio was also considered in the system.

Leaving aside the above, the presence experience is composed by the following three major groups of constructs:

1. The spatial-constructive and attention facets of the experience of being there are respectively operationalized into spatial presence (emerging relation between the mediated environment as a space and the user's own body) and involvement components (user's active engagement and focused attention).

2. The coherence of the scenario is reflected into the perceived realness (reality judgements with respect to the meaningfulness and coherence of the scenario), and predictability components.

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[1] *Ambisonics is a method of sound field coding. This is achieved with the complete system of recording, synthesis, and presentation of spatial sound (360-degree 3D audio: the feeling that the sound is coming from several points).*

3. The quality of the system's technology is distilled into the two components of the interface awareness, that is distraction factors, and the quality of immersion.

Besides that, the focus on smart education and, consequently, on smart pedagogy has recently become a new trend, and the field of music teaching and learning is no exception.

As [35], today's teachers must be equipped not only with content and pedagogical knowledge, but also with technological knowledge. *Image 9*, shows a diagram of how technology helps to achieve pedagogical objectives in the field of music.

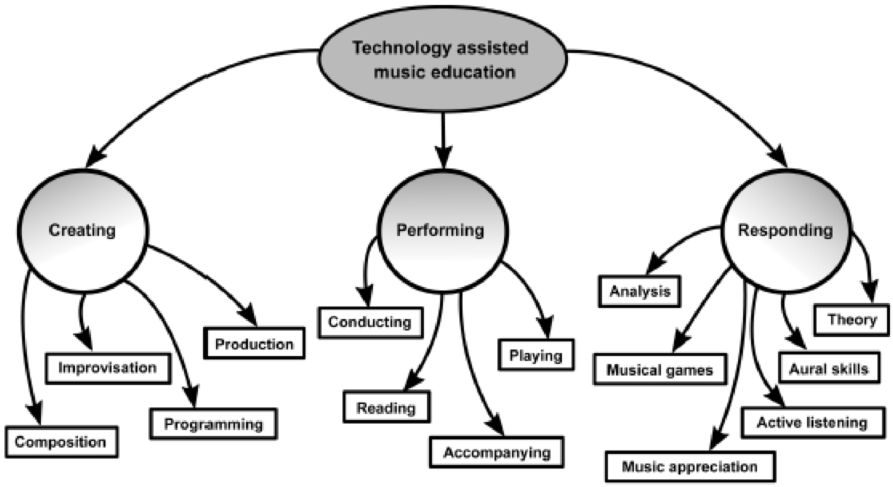

Image 9. The multi-level graphical representation of the pedagogical goals axis. Extracted from [35].

Being able to use technology effectively requires not only an understanding of technology itself, but also of effective pedagogical approaches for using that technology in a particular content area.

4. Designing an interface to convey musical timbre and grain to deaf and hard of hearing students.

As stated in [36], the experience of music is multi-modal, it is perceived not only through hearing but also through touch thanks to the effects of a combination of low frequencies and high amplitudes that impact, penetrate, and resonate in the body. In this essay, the concept of “sonic grain” is introduced. "Sonic grain" enables a cross-modal mapping of texture between the microstructures of sound and material surface.

High granularity sounds have rapid sonic impacts, which may sound like a sequence of discrete attacks, a cluster of smaller sounds, or something "noisy" with sonic interference. In contrast, low granularity "soft" sounds have little surface fluctuation or have regular pitch fluctuations with smooth transitions. Most soft sounds have a clear tone emanating from a sustained vibration, while coarse-grained sounds tend to have an indeterminate pitch and tend to arise from percussive impacts.

The similarities in microstructure lead to an understanding of grain as a perceptual phenomenon that works across sensory modalities, suggesting that tactile, auditory, and visual experiences of texture are not only comparable, but also intertwined and concretely interconnected. This can be seen in the way in which the grain of sound can provide information to the listener about the texture and physical state of the objects used to produce it.

Once the concept of "sonic grain" has been defined, it can be better understood how the interface that has been designed can transmit music through the sense of touch. In the next chapter, Chapter 4.1. TanvasTouch device., the device that has been used to design the application is introduced. Then, in Chapter 4.2. Developed interface., the developed interface and how it has been arrived at is presented.

4.1. TanvasTouch device.

The TanvasTouch device creates textures and haptic effects on its touchscreen. It can be seen in *Image 10*. Its main advantage is the ease with which the user can design haptics. Moreover, it can be done infinitely: it is limited only by the imagination.

Image 10. The TanvasTouch device.

TanvasTouch represents an entirely new software-defined interaction layer that provides tactile feedback localized to the user's fingertip. Like any user interaction technology, the haptic surface of TanvasTouch must be designed carefully if it has to be practical and comfortable. As mentioned above, this device is an extremely flexible asset for user experience design.

TanvasTouch technology solves two specific classes of haptic feedback problems on touch screens. On the one hand, locating: Finding tactile features on an otherwise featureless surface. And, on the other hand, operating: Dynamically adjustment of a parameter by user movement.

Haptics are designed using a simple image-based metaphor. These are integrated via APIs, and then rendered in real time thanks to the TanvasTouch Engine.

The TanvasTouch API documentation [37] provides information to develop programs in the .NET software design platform. In this case, .NET uses the C# programming language.

In the Appendix I the first steps to design haptics are explained.

4.1.1. Example of the use of TanvasTouch device.

To understand how it works and what the TanvasTouch device consists of, when installing the TanvasTouch SDK, an example of a rotary knob will be available in the default folder: "*C:\Program Files\TanvasTouch SDK\API\.NET\examples\hapticknobwpf*". Fortunately, all the code has comments to make it easier to interpret.

In addition, the tutorial [38] briefly explains, based on the example, how the device works. This guide describes how to take advantage of TanvasTouch's surface haptic feedback to solve real world feedback problems and deliver an overall excellent user experience in the context of a surface haptic control knob. The final presentation can be seen in the *Image 11*.

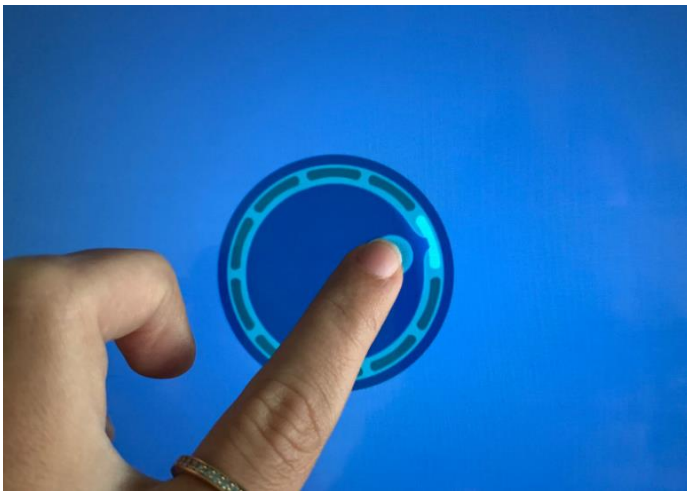

Image 11. Rotary knob presented in the TanvasTouch device.

The Appendix II. Haptic knob example., details the content of the haptic knob example and analyses the code to ensure its correct interpretation. It might be useful to, for example, develop more complex designs.

4.1.2. How to overlap graphic images with haptic ones.

The most difficult part of designing textures with the TanvasTouch device is making the graphic image overlap with the haptics. This means that what is being touched corresponds to what is being seen. Unfortunately, the documentation provided, [37], has not been helpful in achieving this.

This problem stems from the coordinate system that the device uses to place images on the screen. By default, visual coordinates are used. However, the dimension and position of the TSprite, which is the on-screen haptic object, must be defined in the screen coordinate system.

To achieve the above, the size and position of TSprite must match the size and position of the graphic image multiplied by the dpiScale. The dpiScale represents the screen scale of the Tanvas device. For example, if the screen zoom is 125% the dpiScale value will be 1.25.

Apart from this, another aspect to note is that the coordinates in the screen coordinate system are relative to the main screen. That is, the point (0,0) will be the top left corner of the main screen.

If a second screen is added, as it happens when the TanvasTouch device is connected, the coordinates of what is presented on this second screen will be relative to the main screen. For example, if the second screen is placed to the left of the main screen, as in the *Image 12*, the coordinates on the horizontal axis will be negative for everything displayed on the second screen.

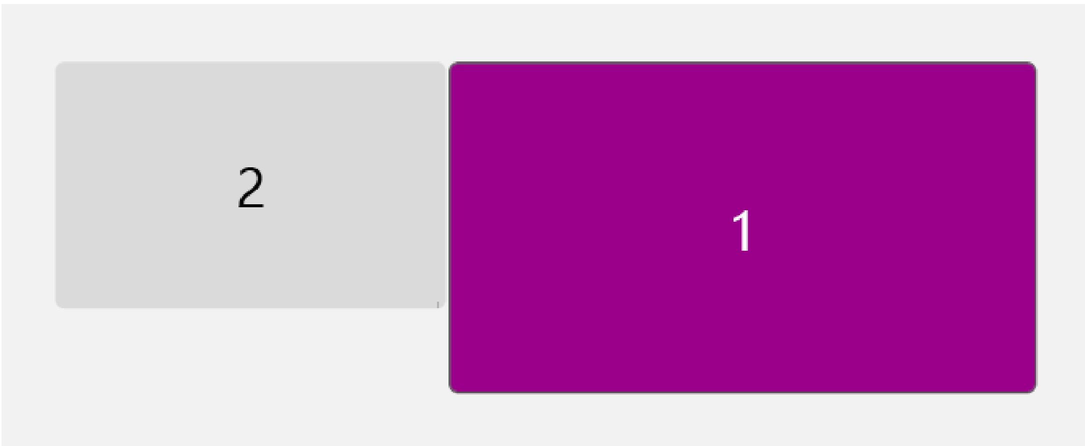

Image 12. Second screen (2) placed on the left of the main screen (1). This is shown in the computer's dislay configuration.

4.2. Developed interface.

Applying all the knowledge mentioned throughout this thesis, an interface has been developed to present sounds in a multisensory way. The TanvasTouch device, detailed in the previous chapter, has been used because of the flexibility it offers in designing haptic images.

All the code employed has been developed in the "Visual Studio" environment using the C# programming language. In addition to the library "TanvasTouch.WpfUtilities" which contains WPF utilities, which allow the development of interaction interfaces, for use with the TanvasTouch .NET API.

The proposed solution offers to display images of instruments together with a haptic image that has been designed according to the results of a questionnaire carried out to find out people's multisensory perception of timbre, see Chapter 5. Results and discussion..

The screen has three different pages. Selecting which of the three pages will be displayed is possible via the menu on the left of the screen, see *Image 13*. Each page is divided into four sections. In *Image 13*, they correspond to the square parts and are colored in yellow, blue, pink, and green. In each of these sections, after having selected one of the pages via the left menu, an instrument will be displayed. This instrument will be accompanied by a button to play an audio that corresponds to a piece played by the instrument itself. The haptic image designed based on the qualities suggested by that audio will also appear. When designing this haptic image, the shapes, textures, and colors that people most often relate to the audio played will be considered; this has been extracted from the questionnaire detailed in Chapter 5. Results and discussion., as mentioned in the previous paragraph.

Image 13. Interface without having pressed any button.

Page one, see Image 14, shows the following four instruments: harp, piano, tenor saxophone, and violin. Page two, see Image 15 for its part, displays the instruments: harpsichord, eardrum, guitar, and accordion. Lastly, page three, see *Image 16*, presents: flute, horn, hurdy gurdy and trumpet.

Image 14. Page one of the interface.

Image 15. Page two of the interface.

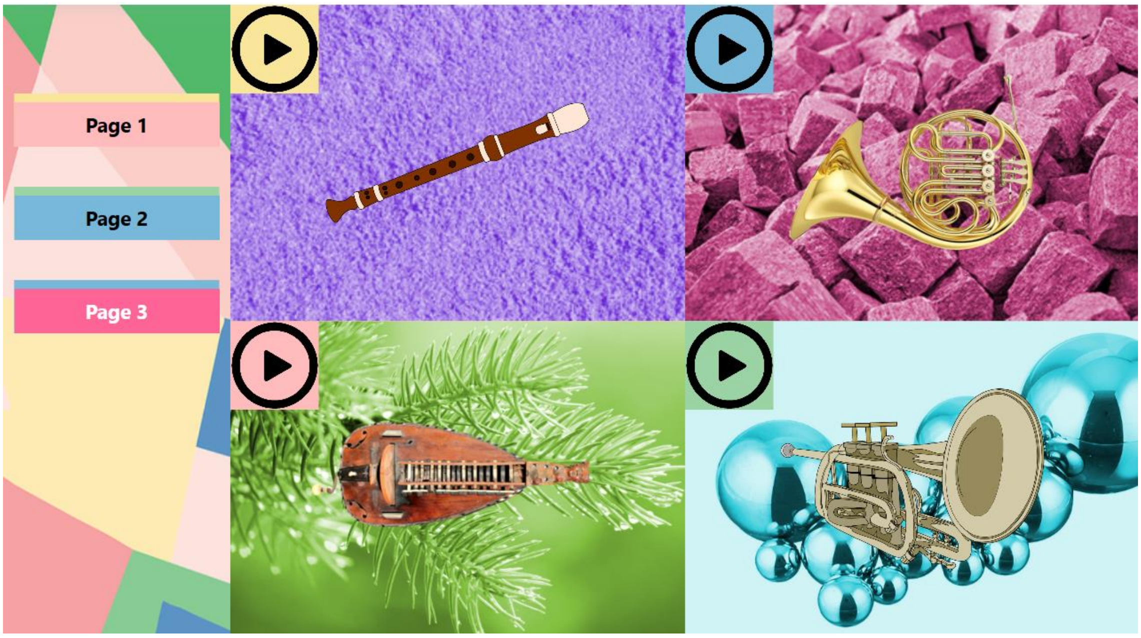

Image 16. Page three of the interface.

The idea of this interface is to make navigation simple and intuitive. Therefore, it only has buttons to choose the page to display and buttons to play audios of each instrument.

The user should be able to perceive the timbre not only through the sense of hearing, which is the intuitive way to do so, but also through the sense of touch and sight. In this way, the application will be useful for presenting music to deaf and hard of hearing people.

The code, audios and images that compose the interface are available in the GitHub repository [39].

One thing to consider is how the haptic images have been designed. As mentioned above, they have been designed based on the results of a survey. However, these images shown on the interface do not really correspond to the haptic image. The haptic image is the visual image but converted to black and white. The TanvasTouch device creates textures from black and white images, with white being the roughest part and black the smoothest. In this way, different textures can be created. Knowing this, it is interesting to increase the contrast of the haptic images to perceive more noticeable textures. Inverting the images is also a good idea if you want to swap the parts of the texture to be emphasized. In addition, if the background does not contain relevant information, it should be black so that you do not feel anything when you run your finger over it.

The latter is the case in *Image 17*, where the background and the gaps between the spheres are set in black so that the texture would be completely smooth.

Image 17. Example of a haptic image with black background.

An example of changes in the contrast of the image can be analyzed for with *Image 18*. In this image the contrast is very low, so you will hardly be able to tell the difference between touching a brick or the gap between them, and the brick will not look very rough. However, by increasing the contrast, as in Image 19, you can easily distinguish between the bricks and the hollows and when you touch the bricks it will be more like a real situation because the texture will be much rougher.

Image 18. Image of bricks with low contrast.

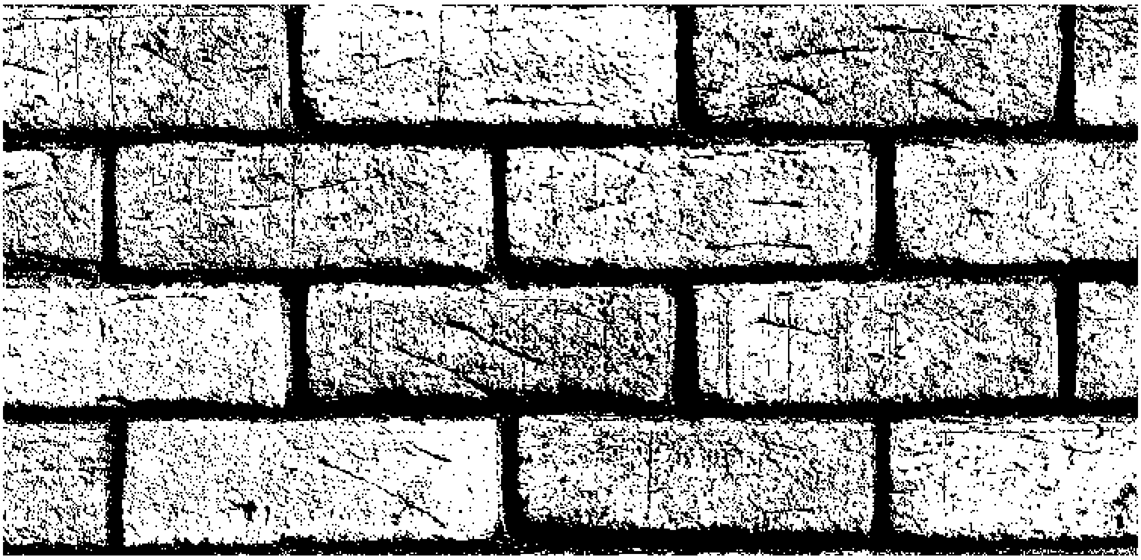

Image 19. Image of bricks with high contrast.

5. Results and discussion.

In order to find out how people perceive timbre in a multisensory way, a questionnaire has been carried out, available in [40].

The questionnaire has twelve questions (six in the shortened version). In each question you are asked to listen to an audio twice, as shown in *Image 20*, and once you have finished playing it, seven questions will appear with a structure as shown in *Image 26*. These seven questions ask you to choose between one and three of the available options. The aim is to select the most appropriate attributes for the taste, smell, color, light, texture, shape, and quality that the audio played suggests to the person taking the questionnaire.

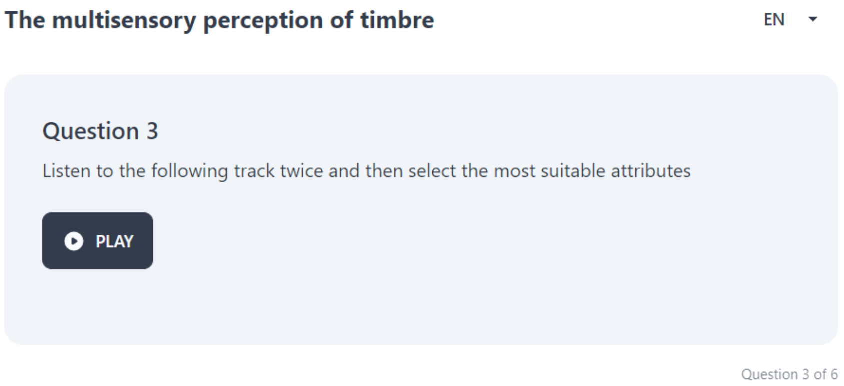

Image 20. Structure of the questionnarie. Play the audio to be analyzed.

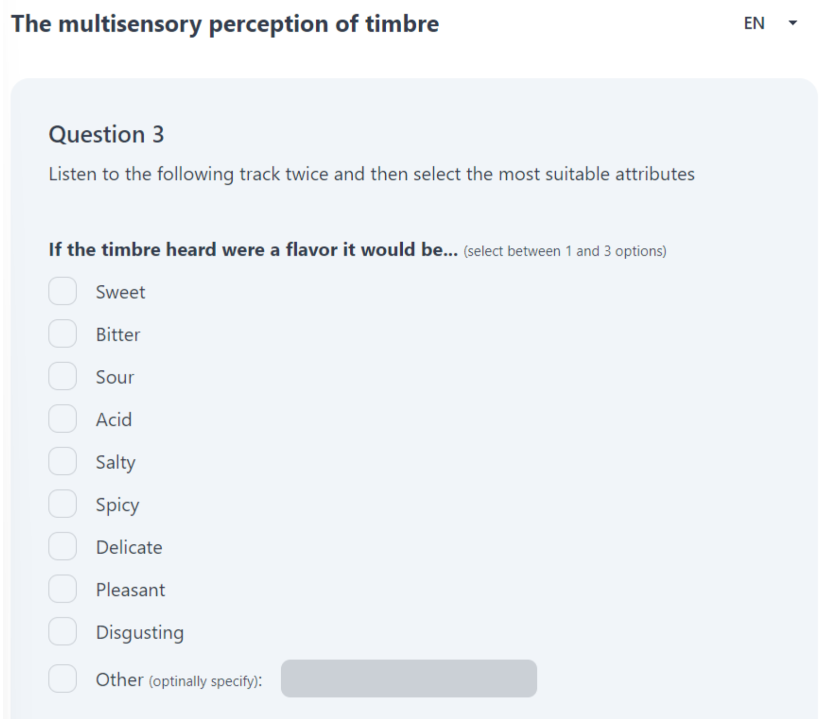

Image 21. Structure of the questionnaire. Selecting suitable attributes.

All the results obtained can be found in Appendix III. Outcomes of the questionnaire: multisensory perception of timbre.. In this appendix, graphs for each sensory quality (taste, smell, color, light, texture, shape, and quality) for each of the twelve audios are reported. These audios can be found in the "assets" folder within the GitHub repository [39]. Each audio corresponds to each of the following instruments: harp, piano, tenor saxophone, violin, harpsichord, eardrum, guitar, accordion, flute, horn, hurdy gurdy and trumpet. The same audio excerpts are also played-back through the interface, by pressing the button "Play" (see images 14-16).

Although the survey has not concluded with clear results for all categories, the most voted answers have been mixed to obtain haptic images. For example, the audio played by the harp is mostly associated with the colors yellow and white, with sunlight and warmth, and with round, curved, small and spherical shapes. Combining all these attributes we can design a haptic image based on bubbles, as they have the mentioned properties. It is important to keep in mind that the haptic image is the same as the displayed image but converted to black and white and increasing its contrast to better feel the reliefs. In addition, the visual image will be colored according to the color and light results obtained. The image designed can be seen in *Image 22*.

Image 22. Image designed for the audio played by the harp.

Another example of an image created from the survey results is that of the audio played by the harpsichord. This audio is associated by the colors black and brown mostly, the light it relates to is dazzling and cold so it will be colored with dark brown. Furthermore, it is associated with sharp, irregular, and penetrating shapes reminiscent of the shape of a cactus. With all this the image created to represent this sound in a visual way is the *Image 23*.

Image 23. Image designed for the audio played by the harpsichord.

The interface developed, see 4.2. Developed interface., has been based on the results obtained in this questionnaire. The design of this interface has been influenced by these outcomes when designing the haptic images displayed for each audio. The audios played in the application are the same as those included in the questionnaire.

Although only the results relating to textures, colors, lights, and shapes have been used in the interface, the categories of quality, taste and smell may be useful in future work in this area.

To show the interface in action, how it looks like and how it is used, a video has been hosted on YouTube to make it even better. This video is available at [41].

6. Conclusions.

This chapter has two main objectives, dedicating a section to each of them.

On the one hand, one of the objectives is to summarize the entire contribution made with this thesis.

On the other hand, to hint at future work. In this section, it is presented an experiment based on the analysis of sound-induced vibrations, which is being carried out at Politecnico di Torino by Cristina Rottondi and Matteo Sachetto.

6.1. Conclusions extracted.

We can conclude this thesis by saying that it has been proven that it is possible to perceive sounds not only through the sense of hearing. This is of great interest in terms of making music perceptible to everyone, including the hearing-impaired community. In addition to confirm that sounds can be perceived not only by the sense of hearing, a prototype application for doing so has been presented.

An interface has been developed, see 4.2. Developed interface., to present sounds not only through the sense of hearing, but also through the sense of sight and touch. This interface has been developed to run on the TanvasTouch device, see 4.1. TanvasTouch device., which offers tactile feedback on its touch screen. This device is used thanks to its capacity to design haptic images.

Since sound is not only presented through the sense of hearing, the usage of such interface can be proposed to deaf or hard of hearing subjects. In this way, inclusion for people with hearing disabilities can be achieved, as it has been envisioned at the beginning of the thesis. This is thanks to the new technologies available today, in addition to the knowledge that the degree in Telecommunications Engineering provides. A few years ago, it would have been unthinkable for deaf people to be able to enjoy music. Thanks to all the existing literature and the advancement of technology, it is not unreasonable to think that at some point in the future a deaf person will be able to feel the same way as a person without hearing loss when listening to music.

All the literature that constitutes the present thesis is fundamental to understand how to present music without the sense of hearing being present. Vibrations and the sense of touch are the main path that is proposed. Since, when we are exposed to a sound we can feel the vibrations in our body, as it can be experienced, for example, at a concert.

Conclusions can also be drawn from the questionnaire administered to gather multisensory associations with sounds. Although no clear winning answers were obtained, as it is difficult to objectively relate sounds with colors, tastes, smells, qualities, textures, etc., in most cases two or three properties emerged as the most chosen. However, in most cases, these three properties can be combined because they are similar and can be used to create content. An example of this is the images designed for each of the audios presented in the three pages of the interface, which combine several of the properties of sound to present it in a visual way.

6.2. Future work.

Based on the study [14], an attempt will be made to design a setup for presenting music for the deaf and hard of hearing people. Being the vibrations emitted by a parametric loudspeaker, see *Image 24,* and measured on an aluminum plate, see *Image 25*, the fundamental part of this configuration. The main idea of this work is to make it possible to feel music when touching the lamina. For the design of this device this thesis may be used as a reference.

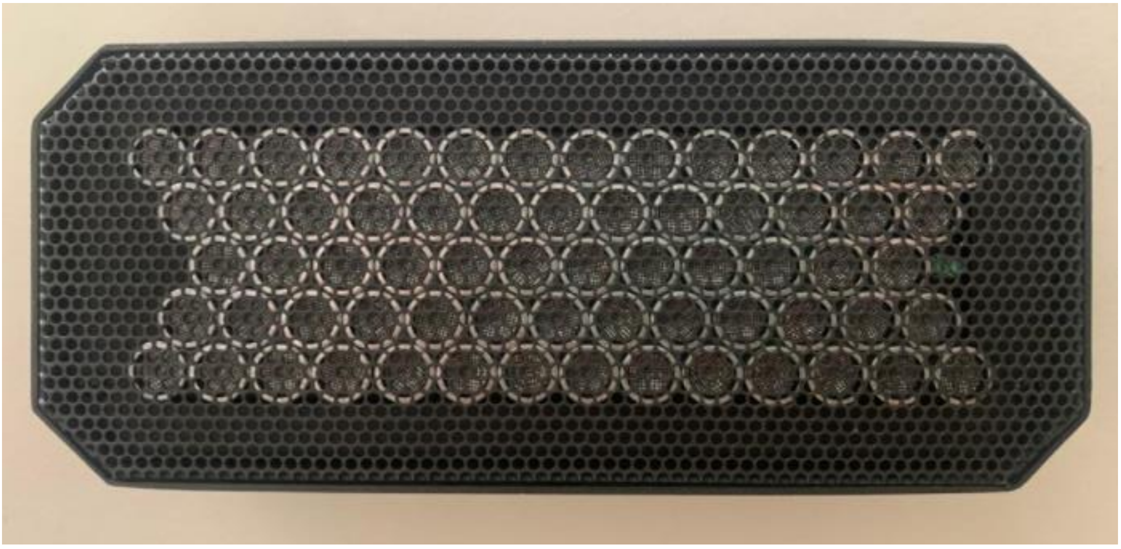

Image 24. The parametric loudspeaker.

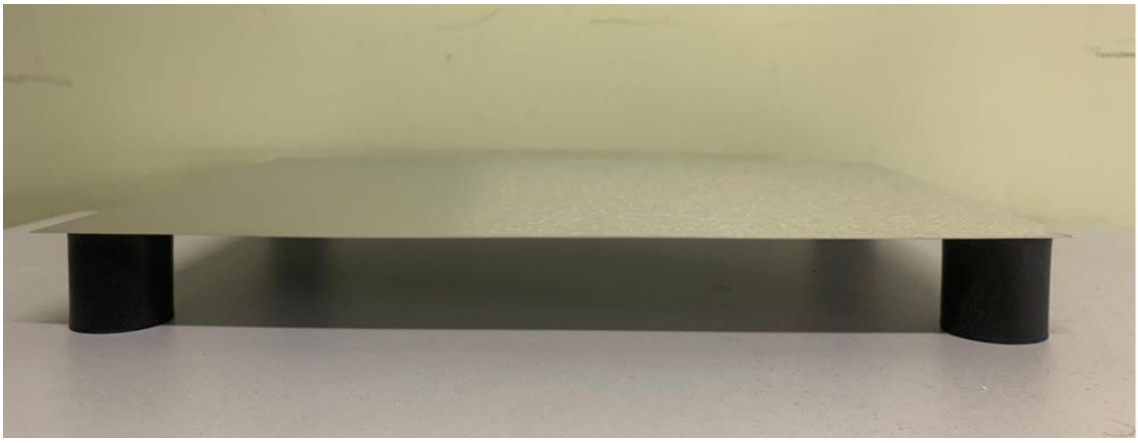

Image 25. The lamina.

In contrast to what has been developed in the present thesis, in this work objective results will be obtained. For this purpose, a laser and a receiver will be used to transform the displacement of the plate, due to the action of the parametric loudspeaker, into voltage. This transformation will be analyzed by the "Volt Data-logger". This way, a sound-induced vibrations analysis will be carried out.

The displacements will be measured with respect to a reference point, which will be the unstirred plate, and will represent how the plate is moved vertically by the action of the vibrations produced by the ultrasonic waves emitted by the loudspeaker. The displacements can be either positive or negative, depending on whether the plate is raised or lowered with respect to the reference point.

Parametric loudspeakers deliver directional audio so that sound can be localized in a specific area while maintaining silence elsewhere. These speakers can produce waves with frequencies ranging from 500 to 20000Hz. Higher frequency waves have a shorter wavelength, so they produce more directional sound than a conventional speaker system (this diffuses audible sound more than parametric systems due to the longer wavelengths it uses). All this implies that the vibration generated by the parametric loudspeakers at the point where they are aimed is very pronounced. Therefore, this is the type of loudspeaker used for this experiment, as the aim is to get the most vibration out of the lamina so that it can be better felt by touch.

The parametric loudspeaker is placed close to the plate. The laser will be placed together with the receiver on top of the plate at a distance of approximately 15 cm. For this purpose, a metal support will be used, which will also allow these two devices to be moved both horizontally and vertically. In this way, it will be possible to choose the point on the plate from which measurements are to be taken.

Apart from that, this thesis could be a good starting point for future work lines based on presenting music in a multi-sensory way.

An example of the latter are the results obtained about how people perceive timbre multisensorially, extracted from the questionnaire detailed in the Chapter 5. Results and discussion.. These findings could be used in any study which requires knowledge of the relationship between sounds and other qualities unrelated to the sense of hearing.

At the same time, the bibliography included in this thesis is a great source of information and a fundamental basis for developing any study in this field.

In addition, the developed interface, defined in the Chapter 4.2. Developed interface., can also become an example for presenting music in a visual and haptic way for any application to be developed. Special emphasis is placed on the choice of its layout: displaying the images with a colored background and the image associated with the haptic feedback. It is important to consider that the results of the questionnaire carried out, see Chapter 5. Results and discussion., had a strong influence on the design of the interface, being these the ones that defined how to relate colors and haptic feelings with each sound.

Appendix

Appendix I. Create a new application in TanvasTouch.

In this appendix the first steps for developing an application for the TanvasTouch device are defined.

1. **Create a new Project** in Visual Studio. It is necessary to have .NET 5.

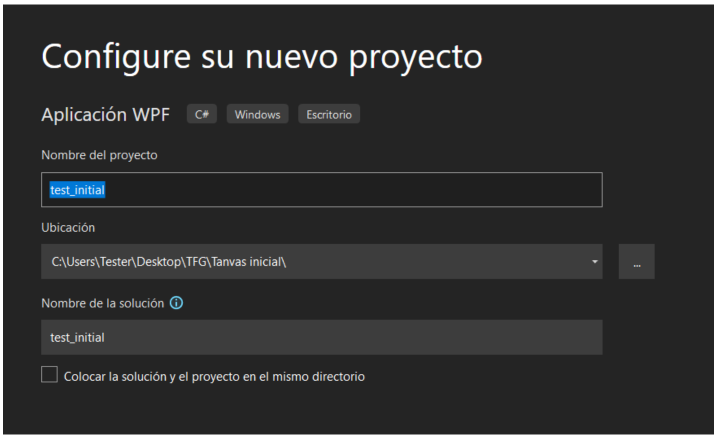

Image 26. Create a new project in Visual Studio.

2. **Run the application** by clicking the start button. Then, a window (Main Window) will appear.

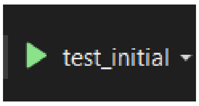

Image 27. Start button.

3. Set the **platform target to x64** (test_initial>properties).

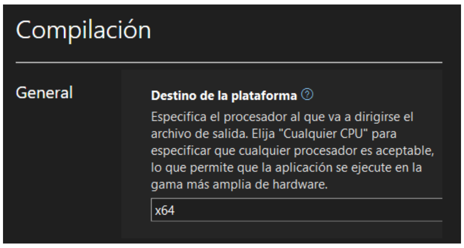

Image 28. Set platform target to x64.

4. **Import the TanvasTouch API** (NuGet package) into the project. *Tools > NuGet Package Manager > Manage NuGet Packages for Solution.*

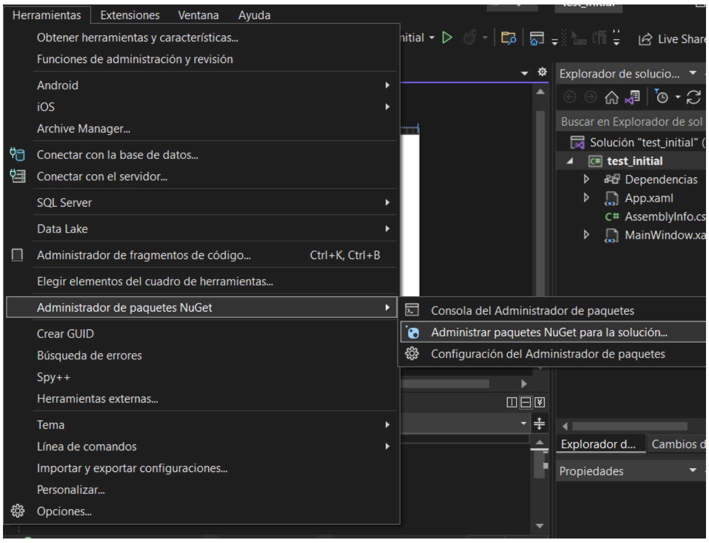

Image 29. Import the TanvasTouch API.

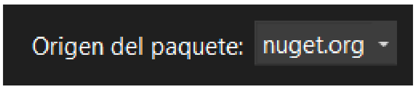

Image 30. Set the Package source to nuget.org.

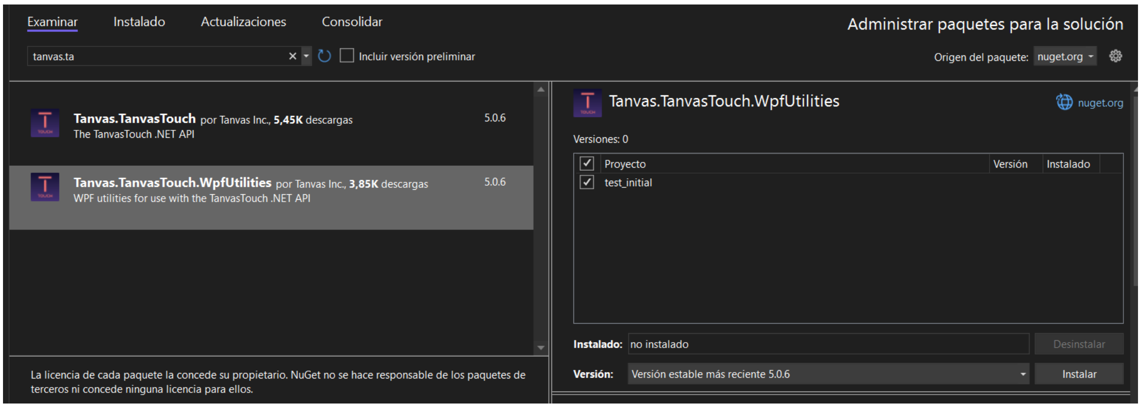

Image 31. Install Tanvas.TanvasTouch.WpfUtilities.

5. **Add the Hello Tanvas assets** to the project.
   a. In MainWindow.xaml set the window size:

   b. Create a new folder with the picture and the haptic map. Change the **build action** for the two files to **resource through its properties.**

   c. Add the following code in MainWindow.xaml:

```
<Grid>
       <ImageSource="Assets/HelloTanvas_visual.png" Width="1024"
       Height="738"      Margin="0"      VerticalAlignment="Top"
       HorizontalAlignment="Left"/>
</Grid>
```

6. **Initialize the API**

   a. Import the TanvasTouch .NET API classes in MainWindow.xaml.cs.

```
using Tanvas.TanvasTouch.Resources;
using Tanvas.TanvasTouch.WpfUtilities;
```

   b. Add this code to MainWindow's constructor:

```
public MainWindow()
{
       InitializeComponent();
       Tanvas.TanvasTouch.API.Initialize();
}
```

7. Add code to create haptic resources.

a. Add an event handler for the Loaded event in MainWindow.xaml. (Write this after the width and height and before the grid label).

```
Loaded="Window_Loaded">
```

b. Add the following fields to the MainWindow class:

```
public partial class MainWindow : Window
{
        TSprite mySprite;
        TanvasTouchViewTracker viewTracker;
        TView myView
       {
              get
              {
                   return viewTracker.View;
              }
         }

          public MainWindow()
```

c. Implement Window_Loaded inside MainWindow.xaml,cs:

```
public void Window_Loaded(object sender, RoutedEventArgs e)
{
        viewTracker = new TanvasTouchViewTracker(this);

        var                  uri                  =                 new
Uri("pack://application:,,/Assets/HelloTanvas_haptics.png");
        var mySprite = PNGToTanvasTouch.CreateSpriteFromPNG(uri);

        myView.AddSprite(mySprite);
}
```

8. Verify that your app is communicating with the TanvasTouch Engine.

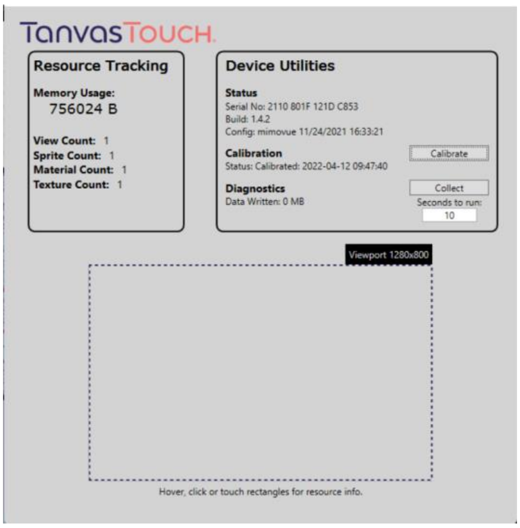

Image 32. Verify that your app is communicating with the TanvasTouch Engine.

9. Test your app.

Click on the start button at the top of the screen. The window will be displayed on the TanvasTouch Dev Kit display and so you can run your finger across the surface to feel the haptics.

Appendix II. Haptic knob example.

This Appendix will attempt to analyze the haptic knob example in detail to understand how it works. To be able to study the code properly, the content of each of the most important files necessary to run the example will be discussed below.

<u>MainWindow.xaml</u>

This file is responsible for defining the window to be displayed. For example, it includes the initial positions of the different images and sets the window size.

The showed images are in the folder "assets". Inside this folder are two other folders: "background" and "nub". In the *Image 33* and *Image 34* it can be seen the content of these folders: different images are used to achieve a dynamic effect when the user interacts with the TanvasTouch device. Also, it is fundamental to distinguish between haptic and graphic images.

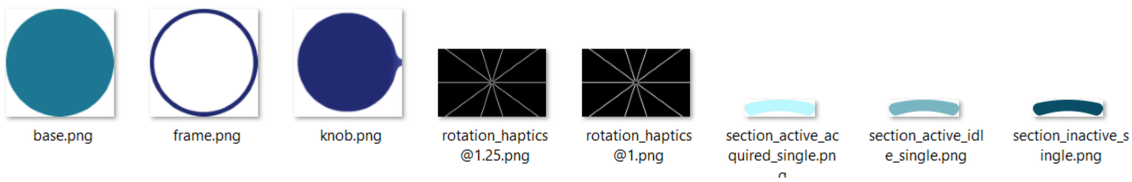

Image 33. Haptic knob project's background folder.

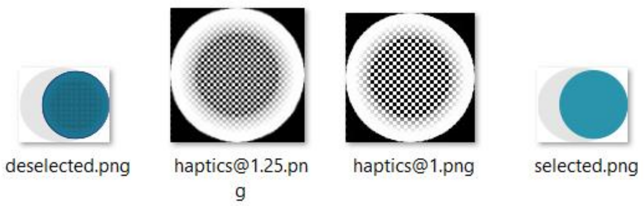

Image 34. Haptic knob project's nub folder

In this file also the canvas elements[2] "KnobCanvas", "KnobRotate" and "KnobNub", which are mentioned throughout the entire code, are defined.

<u>MainWindow.xaml.cs</u>

First, the code checks if the TanvasTouch engine has been initialized. Once it has been verified that this has been done correctly, it creates the "HapticKnob" (designed in the "HapticKnob.cs" file) element.

Also, this file has a method in charge of displaying the "selected" or "deselected" image. This will be dependent on the "acquire" state of the knob:

[2] *This type of element can be used to draw graphics, make photo compositions or even animations.*

when this state changes, this delegate will be called. This means that when the knob is pressed by the user one image is displayed and when it is released a different image will be shown. These images are "NubSelected" and "NubDeselected", defined in the "MainWindow.xaml" file.

HapticKnob.cs

It could be the most important, and complex, part of the code because it contains, for example, all the functions that allow the application to be dynamic and make the graphic image correspond to the haptic one.

Here the "HapticKnob" element is defined as the same time as their properties and methods. The methods that this part of code has are:

- `CalculatePointAtAngleAndDistance`

It returns a point for the given angle and distance from the center of the knob.

- `ComputeAngleFromPoint`

This function will calculate the angle around the circle, given the point that is passed. Importantly, the point must be relative to the KnobCanvas itself.

It will return an angle measured in Radian.

- `SetKnobAtAngle`

This method will fix the knob at a given angle (in Radian) of rotation.

- `KnobAcquired`

When it is determined that the knob has been acquired, it will be tracked along with the user's touch.

- `KnobReleased`

It will be called when the knob has been released.

It uses the "AutoLerp" function (defined in "AutoLerp.cs") which will interpolate a floating value from one value to another.

- `CreateSectionMark`

This will create a unique section mark - these are the marks (the "lights") around the circumference of the knob.

- `CreateActiveSectionMarks`

This will create the active section markers around the knob. The idea is that only one marker is "on" at a time, and that it changes as the user turns the knob. This method creates the images and animations, and places them in position (hidden). As the knob is turned, the corresponding marker (active section) will light up, see the Image 35.

Image 35. Illuminated marker.

- `AlignNubHaptics`

It aligns the nub haptics with the nub element. It needs the method "PointToHapticView", which will be explained later.

- `AlignRotationHaptics`

Called to align the TanvasTouch TSprite "as it turns" with the knob. The center of the sprite should be aligned with the center of the knob. Again, it needs the method "PointToHapticView".

- `SetupHaptics`

Call to configure the haptics. This will create a view for the controller, along with the two sprites for the haptics. It will be called once the window has been loaded.

- `TeardownHaptics`

It is responsible for cleaning everything (remove).

- `CreateHapticSprites`

Determines the size of the texture to use. Only DpiScaleX is used because it corresponds to DpiScaleY.

Windows suggests only 100% and 125% zoom, so this application provides textures for those two zoom levels.

It uses the function "CreateSpritFromPNG" which creates a TSprite with a TMaterial that contains a TTexture created from the PNG at a URI.

- `KnobWindow_Loaded`

This must be called when the window containing the knob has been loaded, so that it can be initialized with all the UIElements existing.

It uses the functions "SetupHaptics", "CreateActiveSectionMarks" and "SetKnobAtAngle", which were previously mentioned.

- `KnobWindow_Unloaded`

Called when the window is unloaded, it uses the "TeardownHaptics" method to remove everything.

- `KnobWindow_ContentRendered`

It uses the functions "AlignRotationHaptics" and "AlignNubHaptics" when the window's content has been rendered to make sure the haptics align with the visuals.

- `KnobWindow_DpiChanged`

- `LerpUpdateCallback`

While the knob is returning to the center of the section this function is called and then it makes a call to the method "SetKnobAtAngle".

- `WindowTouchDown`

Called when a touch down happens anywhere in the window. If the touch is close to the nub ("KNUB_ACQUIRE_RADIUS_PIXELS" from the center of the nub) then the knob will be acquired.

To get this, it finds the center of the knob and where the touch happened (each of them relative to the window) and if this function considers that these points are close enough it will call the function "KnobAcquired".

- `WindowTouchMove`

It will be called when the touch has moved anywhere in the window. If the knob had been acquired, then it will be rotated to match the touch thanks to the function "SetKnobAngle".

- `WindowTouchUp`

It is called when the knob is released (touch-up), then it uses the function "KnobRealesed".

- `WindowTouchLeave`

It releases the knob. Again, it uses the function "KnobReleased".

- `WindowSizeChanged`

It will be called in case the window changes its size. It uses the function "KnobReleased" because there are some touchscreens which are multi-touch and it´s impossible for the window to be resized while the user is acquiring the knob.

- `WindowLocationChanged`

It will be called in case the position of the window changes. Again, because there are some touchscreens which are multi-touch and it´s impossible for the window to be resized while the user is acquiring the knob.

Also, the "FrameworElementHapticsExtensions" element (it is possible to have more than one objects in the same file because C# has the namespace concept) is defined. This class has the method "PointToHapticView" which is made to return a Point in a TView system by a given point in the coordinate system of a Visual. The mentioned method uses the "PointToHapticView" function to compute this.

The above is very important because the location of the specified client point doesn´t correspond with the screen coordinate system, so if this function is not used the graphic image would not correspond with the haptic one.

Appendix III. Outcomes of the questionnaire: multisensory perception of timbre.

This appendix shows the results of the survey conducted to find out how people perceive sound in a multisensory way. The questionnaire asked people to listen to an audio twice and then select between one and three adjectives for attributes such as taste, smell, color, light, shape, quality, and texture suggested by the audio played.

The results are presented using two different types of graphs. On the one hand, with stacked bar plots and, on the other hand, with confusion matrices. In this way, the results can be easily analyzed visually.

The first type of graph, the stacked bar one, corresponds to the Image 36 to Image 42. This graph is a useful method to study the results visually, even if the way of doing it is not precise, it can be a useful tool to draw general conclusions.

The second type of graph, the confusion matrix, corresponds to the images between Image 43 to Image 49. The confusion matrix is a useful method to analyze the results objectively and accurately. This matrix shows all the percentages of occurrence of the different attributes. These values can be used to carry out any other mathematical study.

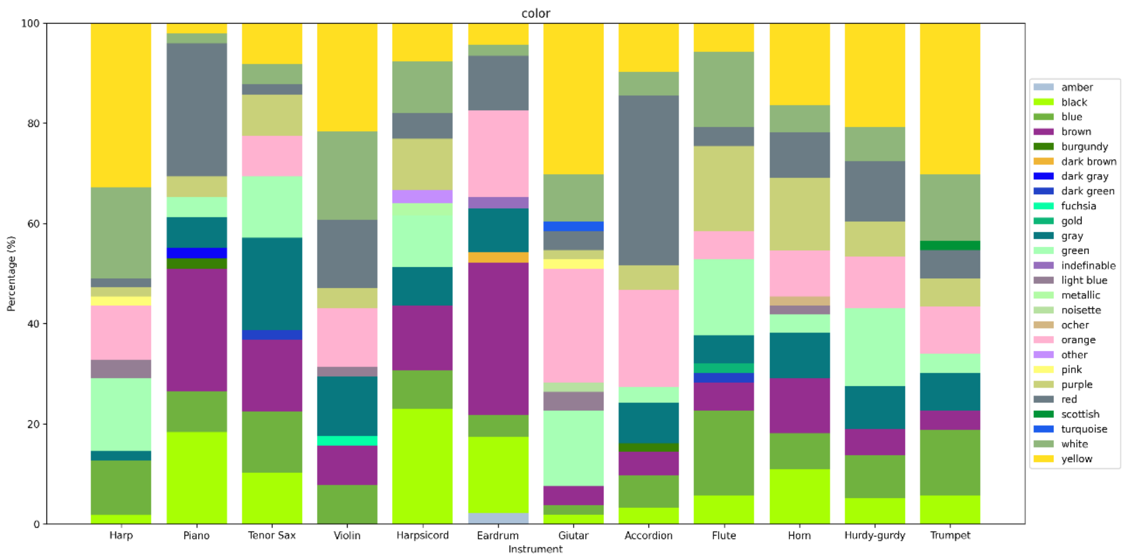

Image 36. Stacked bar plot. Color property.

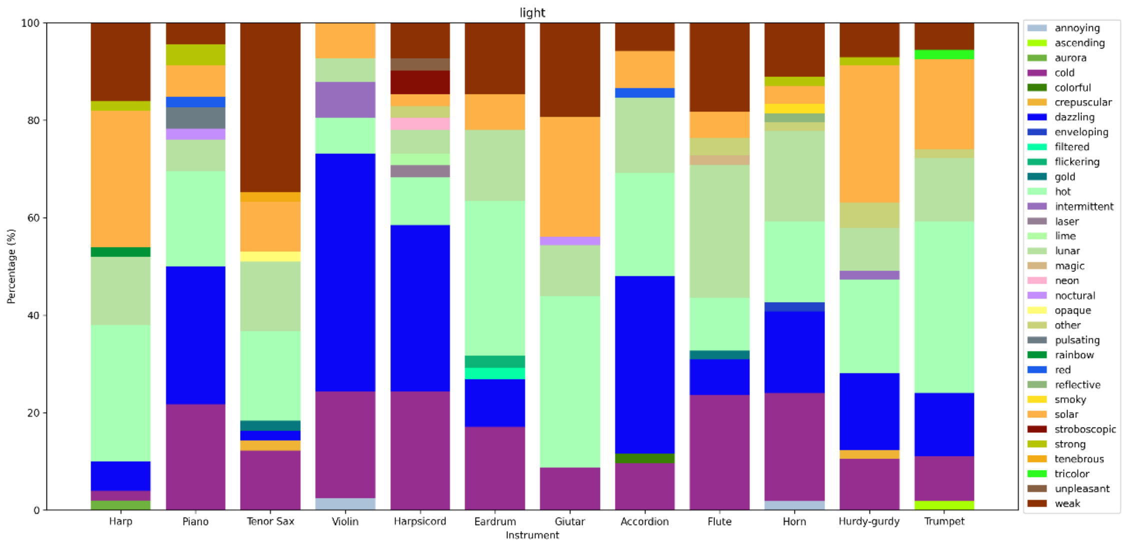

Image 37. Stacked bar plot. Light property.

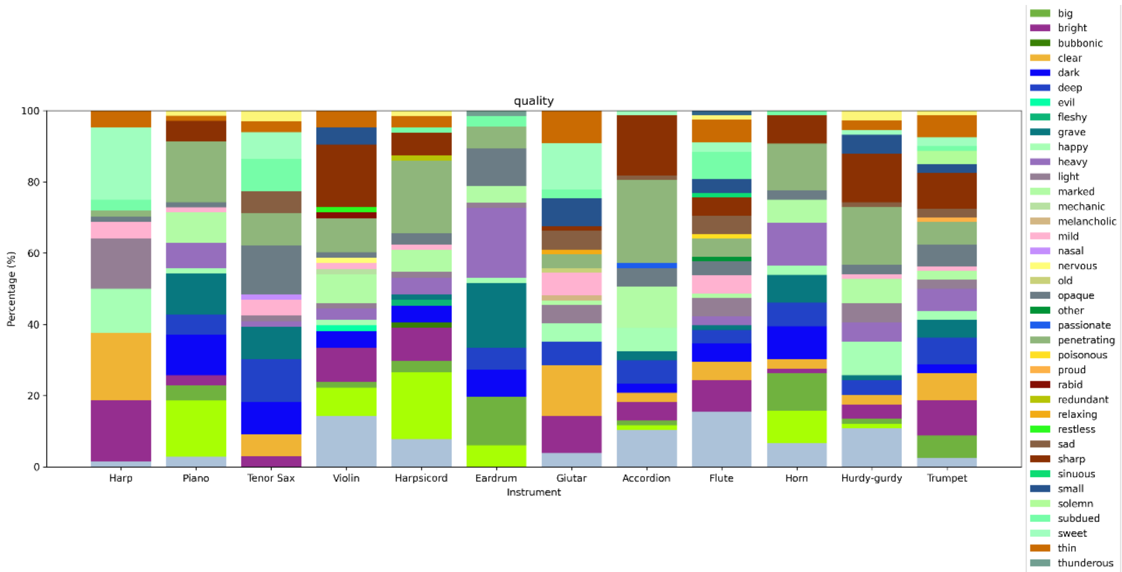

Image 38. Stacked bar plot. Quality property.

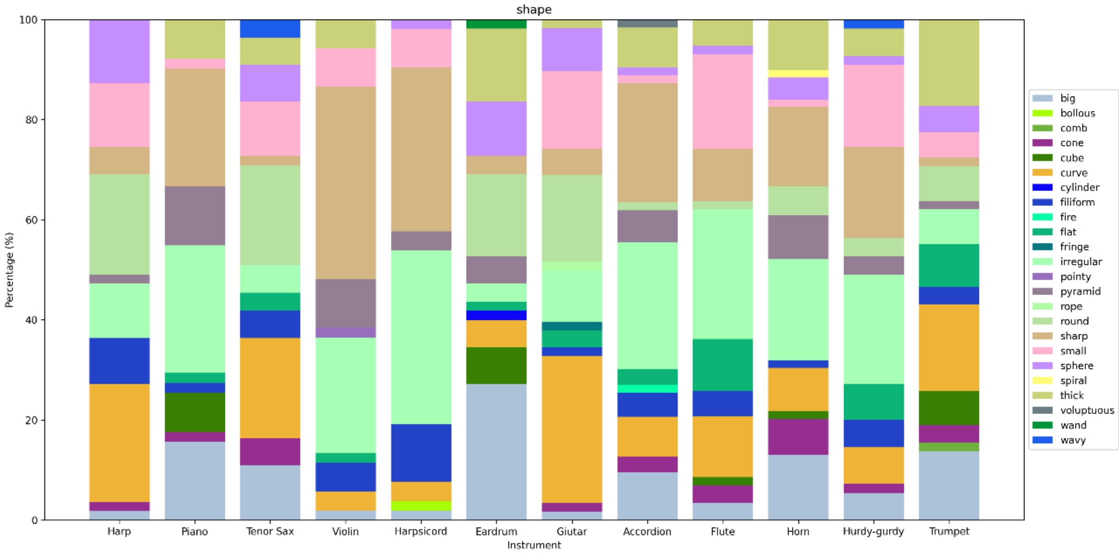

Image 39. Stacked bar plot. Shape property.

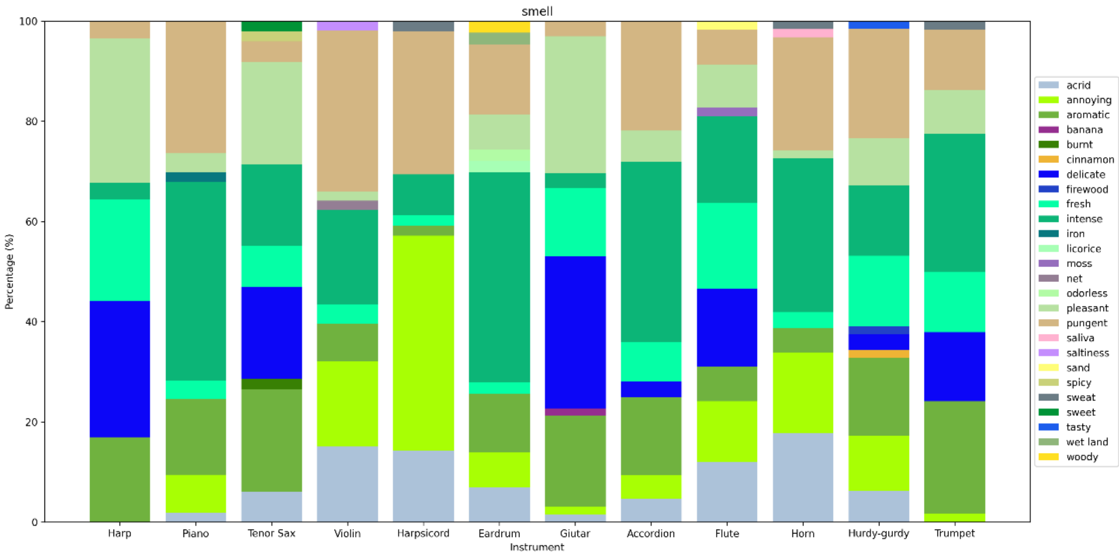

Image 40. Stacked bar plot. Smell property.

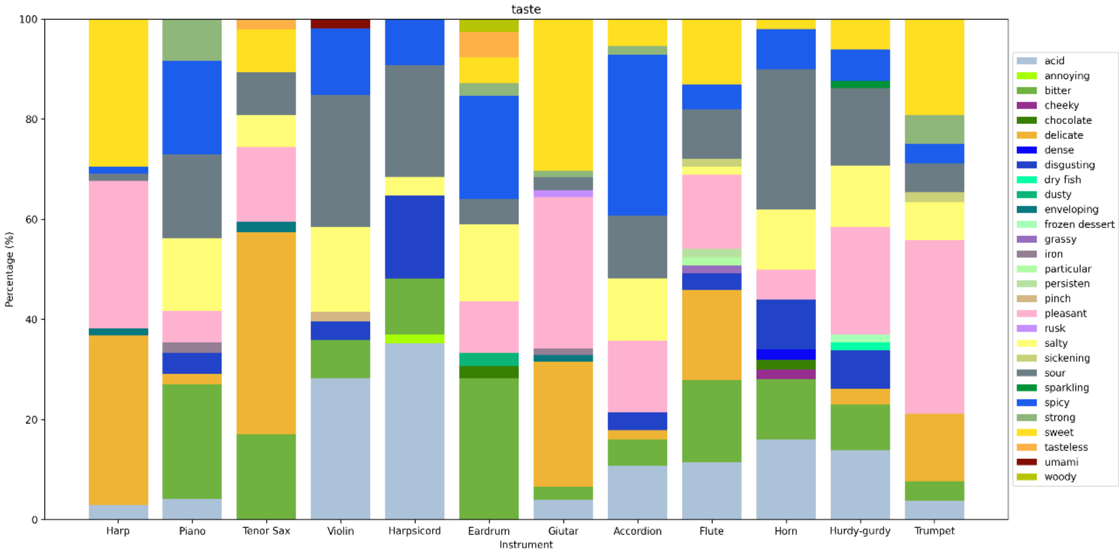

Image 41. Stacked bar plot. Taste property.

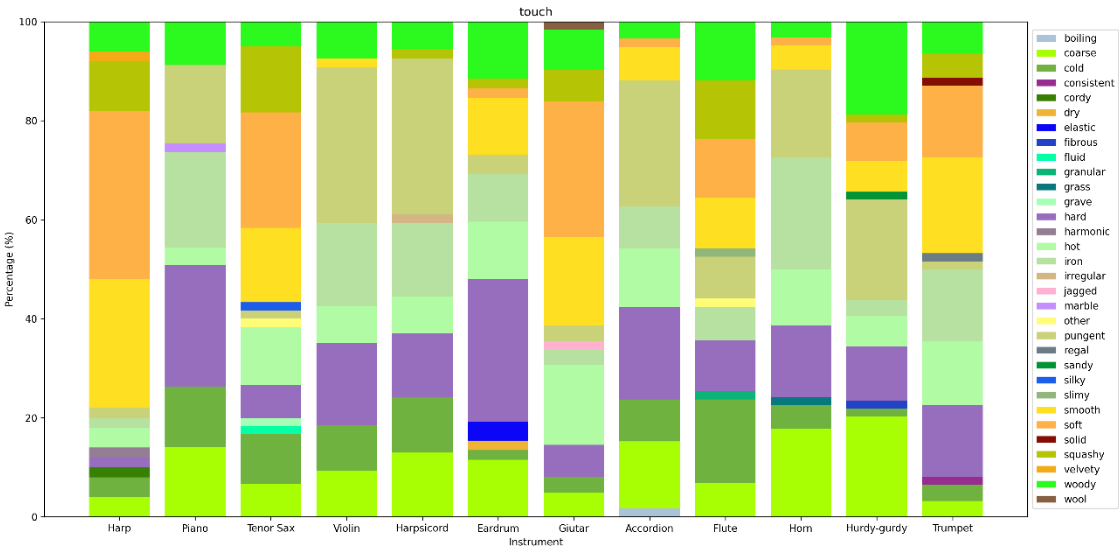

Image 42. Stacked bar plot. Touch property.

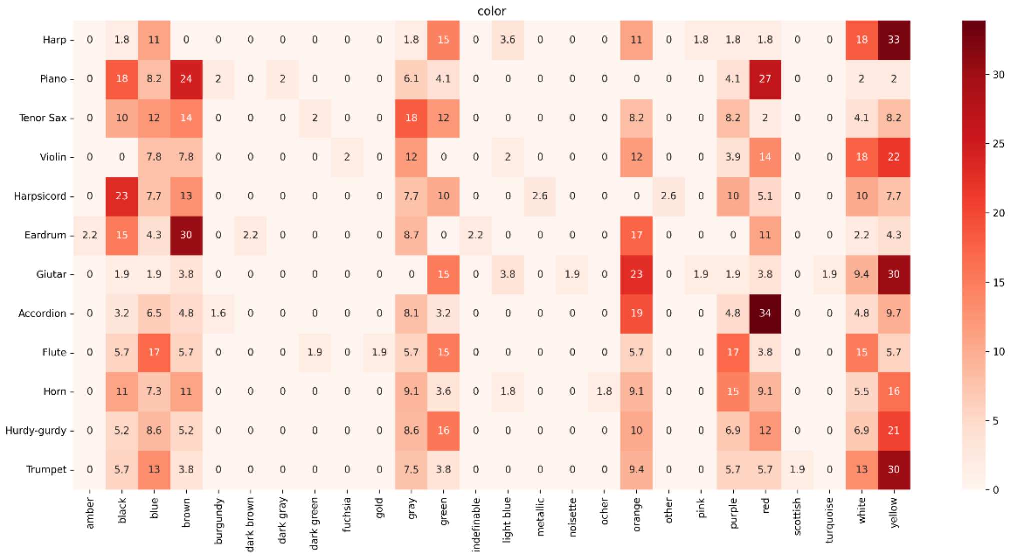

Image 43. Confusion matrix. Color property.

Image 44. Confusion matrix. Light property.

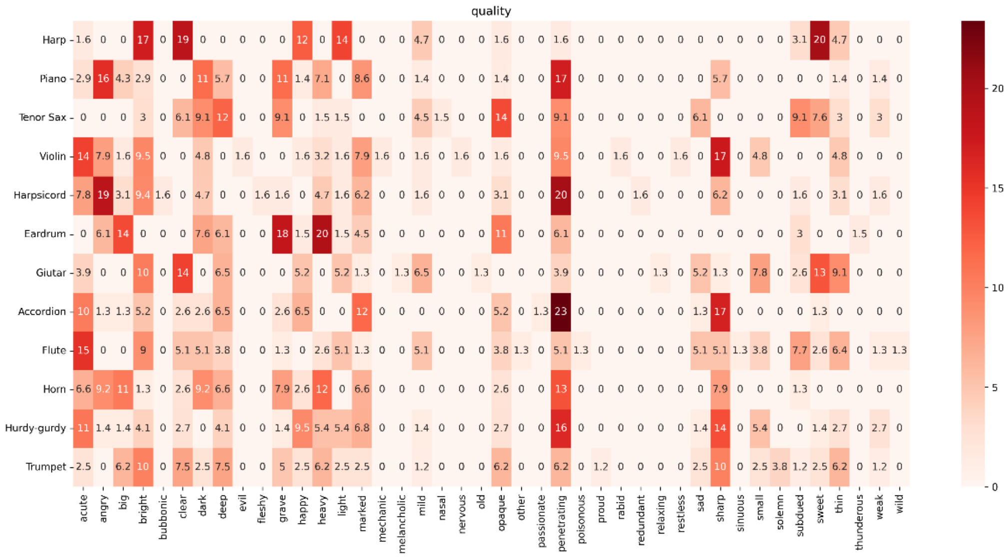

Image 45. Confusion matrix. Quality property.

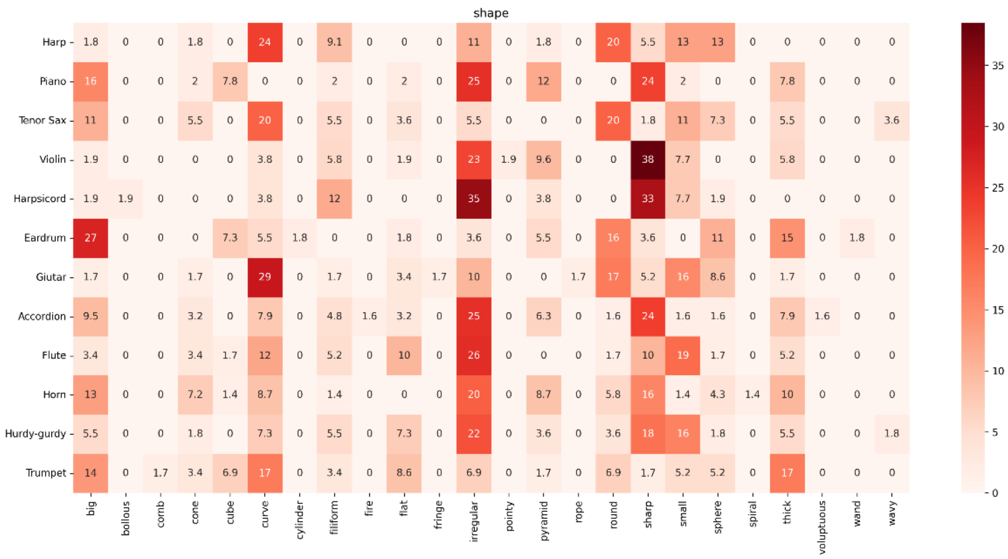

Image 46. Confusion matrix. Shape property.

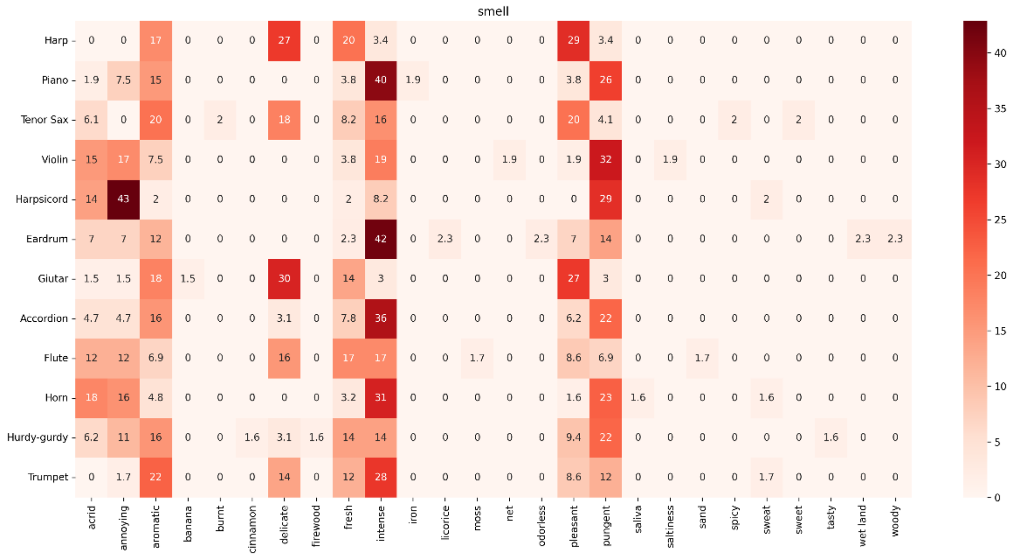

Image 47. Confusion matrix. Smell property.

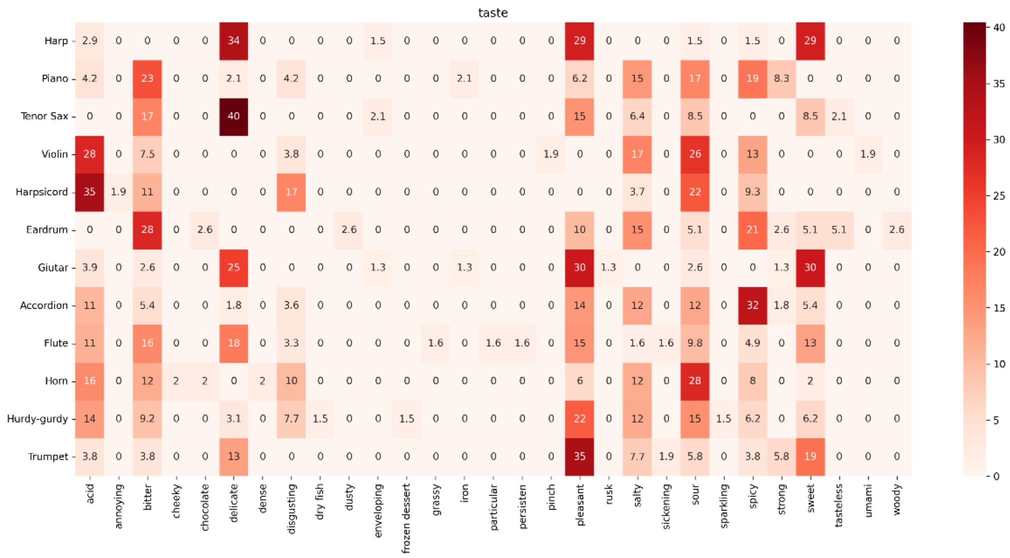

Image 48. Confusion matrix. Taste property.

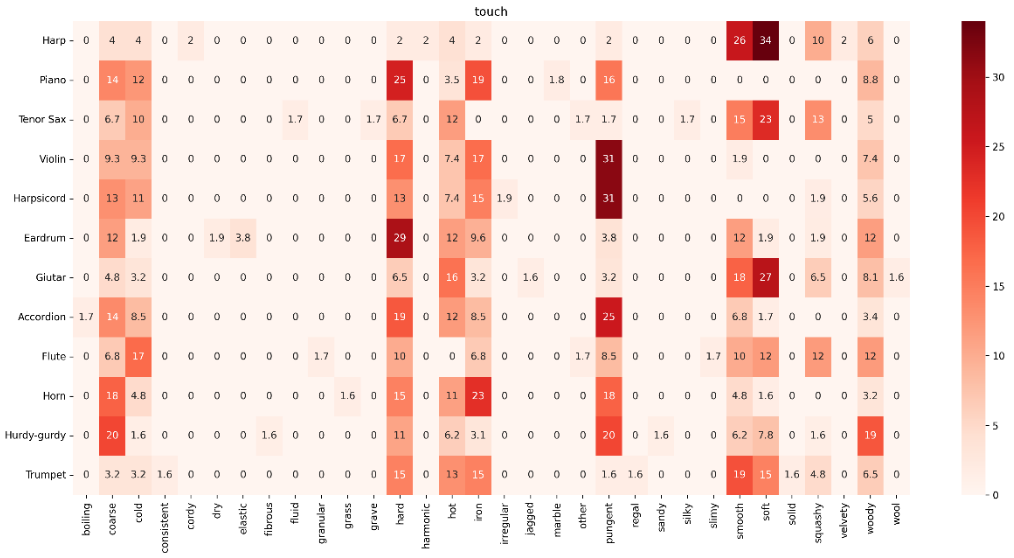

Image 49. Confusion matrix. Touch property.

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