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UNIVERSIDADE D
COIMBRA

Afonso Castiço de Campos Coelho e Silva

User Experience in Haptic Feedback

Dissertação no âmbito do Mestrado Integrado em Engenharia Electrotécnica e de Computadores, na especialização de Automação, orientada pelo pelo Professor Doutor Paulo Francisco Silva Cardoso e pelo Professor Doutor Paulo José Monteiro Peixoto e apresentada ao Departamento de Engenharia Electrotécnica e de Computadores da Faculdade de Ciências e Tecnologias da Universidade de Coimbra.

Outubro de 2021

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Obrigado!

Stay curious.

Abstract

Haptic displays have been gaining more relevance over the recent years, in part because of the multiple advantages they present compared with standard displays, especially when it comes to improved user experience and many different fields of application. Depending on where they are being used, some other advantages can be considered too.

Other than that, the brand new release of TanvasTouch® haptic device, which is settled on a subtype of haptic technology called electroadhesion-based haptics, allowed the creation of haptic solutions based on software, which makes the development of these applications much more accessible than in the past, back when the creation of this haptic solutions required a greater amount of research and investment, resulting on *ad hoc* solutions that were not commercially available on the market.

The current thesis actively presents multiple contributions to this haptic technology research field, especially when it comes to electroadhesion-based haptics. As so, this dissertation starts with a considerable haptic technologies state of art revision, analyzing main haptic actuators that are used in this industry, presenting main haptic displays, and then dives a little bit deeper on a significant review of literature related to user experience in electroadhesion-based haptics, which is one of the main focus of this academic work.

Having this said, this dissertation presents two use cases that were implemented, namely a haptic eBook application that can have a particular interest as an initial sketch solution used by visually impaired individuals. In addition, based on the consulted articles, five different experimental tests were designed to study the user experience related to the electroadhesion-based TanvasTouch haptic device so that it would be possible to understand how perceptible are the textures designed with this haptic equipment. Finally, it is relevant to say that the creation process of these use cases, user experience tests, and obtained conclusions are also reported in this academic work.

Keywords: haptic; electroadhesion; TanvasTouch; haptic touchscreens; user experience; literature review

Resumo

Os dispositivos hápticos de ecrã tátil (do inglês, *haptic displays*) têm vindo a ganhar cada vez mais relevância num passado recente devido às diversas vantagens que estes dispositivos apresentam em relação aos ecrãs táteis convencionais, nomeadamente no que diz respeito à experiência de utilização e às múltiplas áreas onde estes dispositivos podem ser utilizados. Algumas outras vantagens podem igualmente ser consideradas dependendo da área de aplicação onde estes dispositivos são empregues.

Além disso, o lançamento do equipamento háptico TanvasTouch®, que é baseado num subgénero de tecnologia háptica de nome háptica baseada em eletroadesão, permitiu a criação de soluções hápticas baseadas em software, o que torna o desenvolvimento destas aplicações muito mais acessível que no passado, onde a criação deste tipo de soluções requeria um volume de pesquisa e investimento muito mais avultado, resultado em soluções *ad hoc* que não se encontravam disponíveis comercialmente no mercado.

A presente tese, realiza múltiplas contribuições para este ramo de investigação em tecnologia háptica, especialmente no que toca à háptica baseada em electroadesão. Desta forma, esta dissertação é iniciada com uma considerável revisão das tecnologias hápticas, analisando os principais atuadores hápticos usados na indústria, apresentando igualmente os mais relevantes dispositivos hápticos de ecrã tátil existentes e ainda realizando uma análise em profundidade da literatura relacionada com a experiência de utilização em háptica baseada em eletroadesão, que é um dos focos principais deste trabalho académico.

Tendo em atenção o referido anteriormente, esta dissertação apresenta dois casos de uso que foram implementados, nomeadamente uma aplicação sob a forma de livro háptico eletrónico (do inglês, *haptic eBook*) que poderá ter particular relevância enquanto solução embrionária utilizada por pessoas com deficiência visual. Acrescentado ao que foi dito anteriormente e com base nos artigos consultados, foram desenhados cinco testes experimentais distintos com o objetivo de estudar a experiência de utilização associada ao equipamento háptico TanvasTouch baseado em electroadesão, de forma a compreender quão percetíveis são as texturas hápticas desenhadas com este equipamento. Por fim, é importante referir que tanto o processo de criação dos casos de uso, como os testes de experiência de utilização e as conclusões obtidas estão igualmente incluídas neste trabalho académico.

Palavras-Chave: háptico; electroadesão; TanvasTouch; ecrã tátil háptico; experiência de utilizador; revisão da literatura

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List of Acronyms

API Application Programming Interface.

AR Augmented Reality.

ERM Eccentric Rotating Mass Actuator.

GUI Graphical User Interface.

HDMI High-Definition Multimedia Interface.

LRA Linear Resonant Actuator.

PNG Portable Network Graphics.

TT TanvasTouch.

UC Use Case.

UI User Interface.

USB Universal Serial Bus.

UX User Experience.

VR Virtual Reality.

WPF Windows Presentation Foundation.

XAML Extensible Application Markup Language.

1 Introduction

What is haptic technology? This is one of the central and most important concepts to understand in this thesis. ”Haptics” concerns everything related to the sense of touch[1], which means that haptic technology is a specific branch of technology that recreates artificial tactile stimuli that can be perceived by average users. Haptic solutions are commonly found in consumer electronics, among other possible examples of application.

Having this clear, some other relevant questions may arise: why are haptic displays useful? And why are they preferable to traditional touchscreens? With these questions in mind, let's now focus on understanding the main benefits of haptic devices versus non-haptic devices, especially what concerns touchscreens.

To start with, besides having visual and audible traditional channels of interaction, haptic displays also have tactile stimulation that extends the capabilities known on standard touchscreens. Using haptic displays positively contributes to deeper and more immersive User Experience (UX) interactions, considerably extending the number of application areas where this type of technology can be used [1]: from consumer electronics to the automotive industry, from retail to gaming or even digital signature based on touch, there are many fields where haptic technology can be useful. Moreover, new innovative solutions can be designed to mitigate visual impairment and other possible disabilities, like deafness, creating much more inclusive technology.

Depending on the type of application, let's say for example the automotive industry, the integration of haptic displays on a vehicle's dashboard allows to reduce the interaction time and cognitive workload when driving, which contributes to higher security on the road [2], [3].

1.1 Motivation

To understand the motivation of this work, it is important to notice that from the five existing senses of human beings, touch has been one of the less explored by technology. This field has evolved very slowly over the years, probably because it is difficult to artificially reproduce touch, due to the subjective and complex nature of this sense. It is easy to understand why visual and hearing-based technology applications were the first ones to be developed, once they require less sensitive interaction from the user, and consequently, they are easier to implement.

This thesis is motivated by the opportunity to develop emergent and innovative technological solutions that contribute with applied knowledge to the field of human-machine haptic interfaces. Among many different possible applications, this work has a huge potential to be applied to

[1] https://dictionary.cambridge.org/dictionary/english/haptic

social inclusion fields, like visual impairment disabilities. There are still not many publications and examples of application in electroadhesion-based haptics, which works as another source of motivation too.

1.2 Goals

Several goals motivate this thesis, namely, the acquisition of a general overview of different haptic technologies available, with a special focus on the state of the art related to electroadhesion-based haptics. Another goal of this academic work was to contribute with examples of application, mainly with a haptic eBook application (see 3.2.2), in a field where there are not many application examples of this type of technology. Studying the UX related to electroadhesion-based haptic TanvasTouch® (TT) device and understanding how perceptible are the textures designed with this equipment is another main objective of this dissertation.

1.3 Strategy

Having the goals for this thesis in mind, it was adopted a considerable straightforward strategy. A significant literature review was conduced and many different articles were analyzed and selected the ones which were able to give a broader perspective of the haptic technology field. This allowed to contribute for a clear vision of different existing haptic technologies, haptic displays and UX results related to electroadhesion-based haptics.

Based on these consulted articles, a set of usability tests and Use Cases (UC) were created, allowing to understand how promising was this type of electroadhesion-based haptic technology and empirically validate the developed UX tests.

The desired goals were achieved and the electroadhesion-based technology was successfully validated, showing that this technology is extremely promising even though it turned clear with the UX tests that this technology still needs to be improved. A more detailed analysis of the reached conclusions is available in the last chapter of this thesis.

1.4 Structure

This thesis follows a five-chapter structure:

- **Chapter 1**, which is the current chapter, presents a short introduction to the dissertation, where it is given a wider context of haptic technology, motivation, goals, between some other initial information related to this academic work;

- **Chapter 2**, starts giving a general overview of the most popular haptic actuators (see 2.1) that are especially used for vibrotactile applications (see 2.2.3). Then there is a section dedicated to the most common haptic displays (see 2.2) and finally, there is a detailed analysis of current state of art publications related to electroadhesion-based haptics, which is the main focus of the current thesis, and respective examples of application;

- **Chapter 3** dives a little bit more on the details of TT technology. It presents the available APIs environments and identifies main areas of interest where this type of technology can be applied to;

- **Chapter 4** is dedicated to detail the process of designing the UX tests along with the different stages of development according to received feedback from participants. After this, there is a section that analyses individually the results obtained for each designed test (see 4.4) and finally the obtained conclusions with the UX experiment (see 4.5);

- **Chapter 5**, this last chapter does a final overview of the whole academic work, presenting the most relevant conclusions, along with the suggestion of possible future work related to the current thesis;

2 State of the Art

This chapter intends to give a broad vision of haptic technology, with a special focus on electroadhesion-based haptic one, which is the one that TT technology relies on. This TT haptic touchscreen equipment was used to develop some UCs and experiments that will be approached in more detail in chapters 3 and 4, respectively. The current chapter is divided into three different sections: haptic actuators, haptic displays, and a review of literature related to electroadhesion-based haptics.

The first section is dedicated to haptic actuators since these are the basic components of the majority of current haptic applications: Eccentric Rotating Mass Actuator (ERM), Linear Resonant Actuator (LRA), and piezoelectric actuators. Even though they are not the main focus of this academic work, these haptic actuators are relevant and important to understand this technology. They are still a very popular haptic resource nowadays, especially when it comes to vibrotactile displays and related applications.

The second section of this chapter, are presented some relevant haptic displays, including electroadhesion-based displays, which are a sub-type of electrostatic touchscreens, that are also presented in this dissertation. Vibrotactile displays and ultrasonic displays are presented too. As mentioned in the beginning and through this thesis, there is a special focus given to electroadhesion displays, which is a type of haptic device still not as popular as the other ones mentioned above, since it is relatively new. A good example of this type of electroadhesion technology is the TT device that was mentioned before.

Finally, the last part of this chapter is dedicated to a compact literature review of main articles related to UX and to the most important existing applications that are based on TT technology.

All the literature review from this chapter is intended to deliver a wide perspective of haptic technology and contribute to a self meaningful understanding of this field to better design haptic UCs and experiments mentioned previously.

2.1 Haptic Actuators

An actuator is a device that conventionally converts electric energy into mechanical motion. A haptic actuator is a type of actuator that converts this referred electric energy into a mechanical force that tries to recreate the sense of touch of human beings (tactile stimuli).

This section presents and reviews the most popular haptic actuators, which are: ERM, LRA, and piezo haptic actuators. For each haptic actuator presented a special focus is given to its working principle, main advantages, and disadvantages, and some examples of application, to give a more adequate general overview about the current most popular haptic actuators.

One should notice that not all haptic displays take advantage of these haptic actuators. Only vibrotactile ones take these actuators into account in their hardware design since both electrostatic, electroadhesion and ultrasonic displays are based on unique physical principles that are not based on these types of haptic actuators. Nevertheless and due to their considerable contribution to the development of the haptic field, it was crucial mentioning these haptic actuators (ERM, LRA, and Piezo).

2.1.1 Eccentric Rotating Mass Actuator

The ERM actuator is a type of rotary electromagnetic DC motor according to Basdogan and Giraud *et al* [4] and Choi and Kuchenbecker [5] that produces vibrotactile sensations, being a very popular haptic actuator.

Its general structure according to Choi and Kuchenbecker [5], consists of an off-centered mass on the output motor shaft, that by rotating, offers large radial forces on the motor's body, creating a vibrating sensation when it is touched by the user. This is why they are also called "vibrating motors". The intensity of the vibration is proportional to the voltage applied to the motor, requiring a constant input voltage or current to work properly. The analogy with a laundry machine is very useful to understand the behavior of this actuator, where the off-centered mass of the haptic actuator corresponds to the spinning clothes when the laundry machine is being used.

Many ERM haptic actuators like the one presented in Figure 2.1, are still frequently used on mobile phones to recreate vibrotactile notifications that alert users for incoming notifications and calls:

According to [5], the advantages of this type of haptic actuator are their rudimentary mechanical and electrical design and their very simple and reliable usage, which comes as a consequence of the first benefit. In another hand, these haptic actuators have low expressiveness due to their simplicity, which means that the number of different haptic stimuli available is considerably limited. Besides these rendering constraints, these haptic actuators have a considerable delay between the moment they are activated and the start of the haptic stimuli. Nevertheless, they are very popular when complex haptic stimuli are not required.

[2] https://www.precisionmicrodrives.com/vibration-motors/eccentric-rotating-mass-vibration-motors-erms/

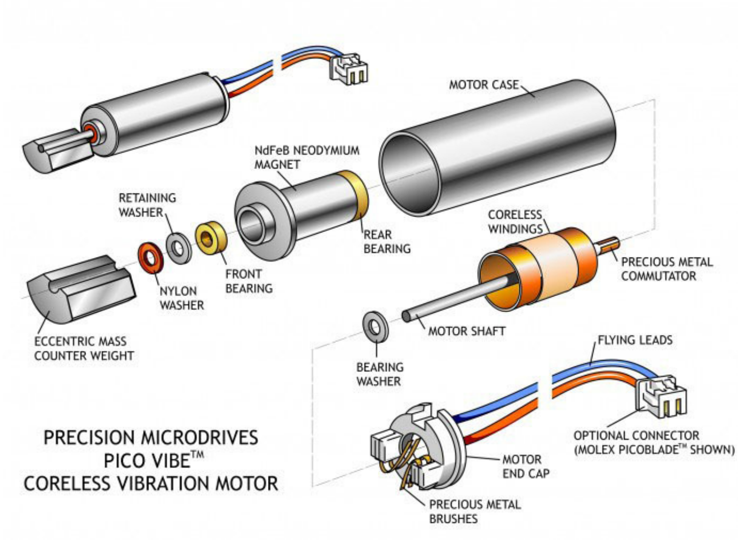

Figure 2.1: Standard representation of an ERM actuator. Image partially adapted from Precision Microdrives[2].

2.1.2 Linear Resonant Actuator

The LRA actuator, also known as LRA, is another type of electromagnetic-based haptic actuator designed to recreate vibrotactile sensibilities on haptic surfaces.

The working principle of this actuator according to Microdrives [6], is based on a vertical movement of an internal magnetic mass attached to a spring that is excited by an electrical AC signal through a coil (instead of an unbalanced movement as in ERM).This coil forces an up-and-down motion that is perceived as haptic vibration by users. This type of haptic actuator requires a variation of voltage or current to allow the movement of the coil, being an AC-based motor instead of a DC-based one like in ERM.

Figure 2.2 presents an example of a LRA actuator, including the mentioned coil responsible for the actuator's motion:

LRA coil-based haptic actuator presents faster response time with lower voltage requirements compared to ERM according to [4], [5] being these some of its main advantages. Nevertheless, LRA has a limited frequency of bandwidth, which means that its customization is not easy compared to ERM.

When it comes to the examples of applications where this haptic actuator is used, LRAs along with ERMs are commonly applied for the same purposes, according to Texas Instruments [7]. Besides the traditional usage of smartphones for improved UX, these haptic actuators have been integrated on tablets and e-readers, along with other technological accessories like computer touch haptic mice, television remotes, or even laptops.

[3]https://www.precisionmicrodrives.com/vibration-motors/linear-resonant-actuators-lras/

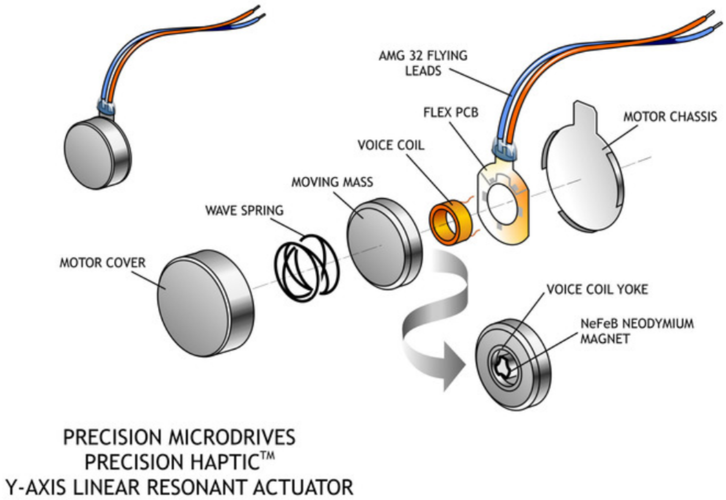

Figure 2.2: Standard representation of an LRA actuator.Image partially adapted from Precision Microdrives [3].

2.1.3 Piezoelectric Actuator

Piezoelectric actuators or just piezo actuators, according to [4], consist of a direct application of the piezoelectric effect property of certain materials, like quartz or some other specific crystals. The materials that integrate piezo actuators change their physical properties under a certain amount of input voltage (around 100V), which makes the piezo actuator stretch or shrink depending on the amount of voltage these materials are being fed with. When touched by a human finger, the user experiences a tactile stimulus based on this piezoelectric mechanical stress principle. Figure 2.3 gives a clear perception of how piezo actuators behave under the application of voltage:

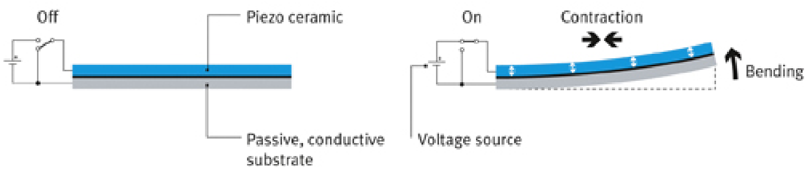

Figure 2.3: Piezoelectric actuator under the application of input voltage. Original image from `https://www.linearmotiontips.com/what-are-piezo-actuators/`

One of the main benefits of using this type of haptic actuator is its ability to perform under high-frequency applications and its high level of expressiveness, allowing the creation of a considerable amount of different haptic sensibilities [4], [5]. Besides that, this type of haptic actuator can accomplish relatively high forces with low physical displacement in incredibly thin capsules. The main downsides of this technology are the high amount of input voltage that is sometimes required and some physical fragility under the action of an external force.

This type of piezo haptic actuator was very recently incorporated by Microsoft on the brand new Windows 11 trackpads to improve UX and allow users to control the haptic feedback of the touchpad with an intensity slider, according to Boréas Technologies [8].

2.2 Haptic Displays

This section is dedicated to the most popular haptic displays that are used to produce haptic stimuli. It starts with electrostatic technology, where haptic textures are based on static friction of the haptic touchscreen. Then it mentions electroadhesion technology, which is included in electrostatics but exclusively focused on friction modulation, instead of a stationary friction approach as the one taken by electrostatic haptics. After this, there is a section dedicated to vibrotactile technology, focused on the mechanical stress of the haptic actuators reviewed on 2.1. Finally, there is an ultrasonic technology section, where the tactile stimuli leave the two-dimensions plan of the touchscreen to a three-dimensional space depth, allowing to feel haptic objects as a whole and in a much more interactive way.

2.2.1 Electrostatic Displays

This type of display owes its name to the electrostatic physical principle with the same name. This thesis reveals a particular interest in an electroadhesion effect, which is a subtype of electrostatics that will be better explained later in this document, once TT equipment relies on this specific effect.

When it comes to the physical phenomenon that sustains electrostatic displays, this type of technology is based on friction modulation between the human finger and the touchscreen, according to Nakamura and Yamamoto [9]. By changing the voltage difference between them, it is possible to vary the friction force on the surface, which is perceived by the user when touching the haptic touchscreen.

For this to happen, it is required a thin metal layer above the display, which reveals a characteristic sensation under the application of AC voltage to that layer. When a human finger gets close to this surface, the electrostatic force between the finger and the layer takes action due to the voltage difference between the two. When the finger slides over the surface, the electrostatic force is converted into friction, which is experienced by users as haptic texture.

Figure 2.4 presents a side view perspective during an interaction between the user's finger and the electrostatic touchscreen, just like described above:

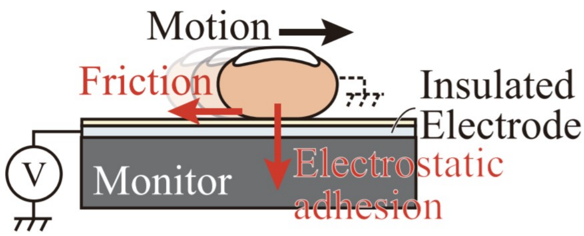

Figure 2.4: Electrostatic friction modulation between a human finger and an electrostatic display. Original image from [9].

Electrostatic haptic displays take benefit from the resulting electrical properties between human skin and a charged surface, a touchscreen display in this case [9].

According to [4], electrostatic actuation is highly effective in increasing the friction in a touchscreen, once the application of voltage to a conductive layer increases the electrostatic attractive force in a perpendicular direction to the surface, which means that haptic textures displayed on these touchscreens are better perceived by users. This tactile effect felt by a user can be changed and modulated by varying amplitude, frequency, or waveform of the voltage that is being applied to the touchscreen.

2.2.2 Electroadhesion Displays

Even though electroadhesion is electrostatic-based haptics, it was decided to highlight this effect in a new section to give a more detailed explanation about this specific physical principle and how it occurs, due to its relevance for this thesis.

The electroadhesion principle is also known as the electric-based adhesion effect. It consists of a local variation of electric fields where fingers interact with the touchscreen [10]. Another way to describe this effect, is as modulation of friction between the human fingertip and an active surface, according to Soft Matter journal [11]. The glass plate's insulating layer and the human fingertip are inductively polarized, which in practice means that charges with the opposite sign are progressively accumulated in each contact surface: the positive charges from human skin and the negative charges on the insulating layer. As it is known, opposite charges tend to attract each other and when the human fingers slip over the haptic touchscreen, this opposite charges crash between each other originating friction, that is perceived by users as a texture on the haptic touchscreen, just like is shown in Figure 2.5:

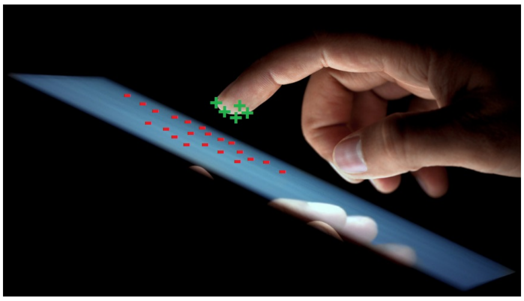

Figure 2.5: Interaction between a positively charged human fingertip and a electroadhesion haptic touchscreen. Partially adapted from from `https://interestingengineering.com/ever-wondered-how-your-touchscreen-works`.

2.2.3 Vibrotactile Displays

Putting it simply, vibrotactile displays consist of the mechanical vibration of haptic actuators, mainly the ones mentioned on 2.1 section. When it comes to this type of haptic display, it is important to notice that many different approaches can be made according to the desired result. Compared to electrostatic haptic displays, vibrotactile ones require the selection of actuators to match the haptic feedback that is needed.

The main haptic actuators for this type of vibrotactile displays and applications are: ERM actuator (section 2.1.1), LRA actuator (section 2.1.2) and piezoelectric actuators (section 2.1.3), which have already been discussed in this thesis.

There are two possible approaches to the design of haptic textures with this type of technology [5]: monolithic vibrotactile displays, which correspond to vibrating an entire rigid display or a localized vibrotactile display approach, where several haptic actuators are integrated on the displays to promote vibrating stimuli on localized areas of the touchscreen or object.

Some of the main advantages of this type of haptic technology are its high customization and goal-orientated personalization according to the desired purpose and haptic effect. Moreover, they can deliver a better UX once the design of these displays is much more flexible to adapt to specific user needs. The drawbacks of this technology are mainly the lack of robustness since the final products might not be as compact as the haptic displays assembled on a single component. Adding to this previous point, there is an increased design complexity, since the engineering of the whole device from scratch can be particularly challenging.

Finally, due to their ability to be customized and personalized, vibrotactile technology has been extended beyond touchscreens. Many different applications can be made based on vibrotactile haptics, mainly wearables, internet of things applications, gaming, remote controllers, haptic gloves, or armbands [5].

2.2.4 Ultrasonic Displays

Another type of haptic device is ultrasonic displays. According to Wilson and Carter *et al* [12], ultrasonic-based haptic solutions consist of the modulation of air pressure waves from a display of physical ultrasound transducers, instead of the previous haptic solutions that were mentioned before. Ultrasonic haptics can reproduce haptic stimuli without the need to call on modulation of physical friction or electronic enginery seen previously with electrostatic and vibrotactile displays.

According to Sun and Nai *et al* [13], the ultrasound transducers from the display generate a pulse that reaches a coincident focus point in the middle of air at the same time since all the pulses have the same phase at the targeted point. This process is known as ultrasound focusing. When a hand is positioned above the focus point, a tactile sensation can be experienced in 3D real-world space. Having this set and applying the same logic for multiple points in three-dimensional space, it is possible to produce 3D tactile objects that are perceivable by human skin.

Figure 2.6 illustrates the ultrasonic focusing process explained before:

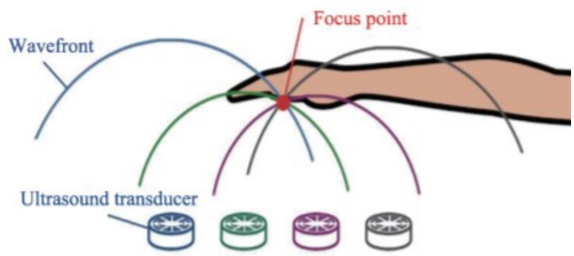

Figure 2.6: Illustrative example of the ultrasonic focusing process. Original image from [13]

Some of the advantages related to ultrasonic haptics are its larger haptic-based friction modulation without the need to use physical interfaces and the ability to represent haptic textures on three dimensions, which is a major advantage compared to electrostatic and vibrotactile displays [4]. The main disadvantages of ultrasonic haptic technology are the resonant nature of ultrasonic waves that introduce undesired noise and require an extra effort for canceling this unwanted resonance effect. Furthermore, it is important to keep a balance between energy efficiency and the amount of bandwidth required for the desired purposes, resulting in an extra concern that may limit the usage and applications of this type of haptic technology.

The biggest potential of this technology has not yet been reached and there is an enormous amount of different applications of ultrasonic technology that can be explored even further in the future, according to Rakkolainen and Sand *et al* [14], namely Virtual Reality (VR), Augmented Reality (AR) applied to gaming scenarios and simulated environments, buttonless interfaces for the automotive industry, telemedicine and remote surgeries, *etc*.

The main obstacles that ultrasonic haptics technology is facing are the reduced magnitude and limited reachability of ultrasonic-related haptic applications, weight, and size of the device, and high pricing. Nevertheless, the upcoming opportunities are huge and more work is progressively being done in this field.

2.3 Review of Literature

This section takes a careful look at some of the most significant articles related to TT, which is the most relevant electroadhesion-based haptic display nowadays. Most of them are related to UX, allowing to acquire meaningful knowledge that was useful for the design of the UCs and experimental tests done in this thesis.

In the last part of this section are mentioned two relevant solutions that result in direct applications on computer-assisted learning and haptic interfaces for visually impaired students, that explores the same field of interest of this thesis: an applied UX analysis on electroadhesion-based haptic feedback.

2.3.1 User Experience

This section is particularly focused on the UX of TT electroadhesion-based haptic feedback, which means, the way users experience the haptic touchscreen along the different experiments presented in this section.

Some of the most relevant papers in this field are mentioned. It starts with the presentation of generic best practices for friction modulation design of User Interface (UI). Next, it is presented an interesting article about how haptic interfaces can act upon the UX of the participants and their tactile-driven choices, once in this paper the same visual stimuli are presented to the user in combination with different tactile textures. After this, it is presented an article concerning texture renderization, that is, the creation of haptic patterns or regular homogeneous patterns to be more precise. Lastly, there is a final article dedicated mutually to haptic patterns detection and (visual image, haptic texture) duos matching.

All these four articles along with the examples of application deeply influenced and inspired the design of the implemented uses cases and the blind tests, without whom this academic thesis would not be possible.

2.3.1.1 General guidelines for haptic interface design

Breitschaft and Carbon [15], presented some of the most relevant recommendations that were followed in the implementations of this thesis. They inspired and oriented the developed work in both the UCs and the designed Blind Tests that are presented in more detail, respectively, in Chapters 3 and 4 of the current thesis.

The authors of this article, in partnership with BMW Group, designed two UI with TT equipment and studied the reaction of participants to electrostatic friction modulation in a UI-research environment. Two different studies were executed in this article. The first study was based on a single search task using low and high-frequency textures. The second study consisted of a target-selection task performed in a driving scenario in a simulated environment.

The conclusions reached with this experiment allowed to establish general guidelines for the design of different haptic UI.

The suggested guidelines for haptic UI design are the following:

1) **Use Analogies**. By creating different analogies and associations with reality is possible to create clear and tangible feedback with the user.

2) **Keep it simple**. Design a simple and basic set of differentiated haptic sensibilities.

3) **Make it strong**. A set of solid haptic sensibilities transmits better feedback and avoids misunderstandings and false interpretations by the user.

4) **Consider Habituation**. Allowing participants to get comfortable with haptic technology is halfway to a better UX.

This short article also mentions some other UX results achieved with their experiment.

Participants reported a very dynamic and aesthetic experience even though there was some negative feedback, including comparisons to electroshock's, which can evidence possible acceptance issues by the public to this type of haptic technology.

Volunteers experienced some difficulties distinguishing between the presented haptic stimuli. Based on received feedback, it is relevant to mention that soft feedback was seen as a cause of some insecurity to the user, who struggled to understand if this type of smoother haptic feedback was intentionally generated or not.

Nevertheless, the general feedback of users was positive and users considered this to be an unexpected and innovative experience.

2.3.1.2 TanvasTouch applied to tactile textures exploration

Park *et al* [16], focused its attention in understanding how tactile feedback can influence a user's preference under evaluation of 2D images. Their study evaluated the users' disposition to like 2D images based on the visual properties and the haptic feedback associated with these images while using a TT touchscreen. Other parameters were also evaluated, namely reach time, interaction time, and response time, measured from the performance of volunteers when executing the suggested tasks.

The procedure of this experience was considerably simple. Each person was presented with different visual stimuli (conventional 2D images) on a TT device. There were three visual stimuli in total. For each visual stimuli presented, a single tactile texture was added. There were four different haptic textures in total (no tactile texture, blurred texture, sharp texture, and mismatched texture). This means that each visual image was combined individually with each of the four haptic textures, resulting in four different experiences for the user. Each possible combination was presented randomly and repeated three times for better accuracy of results. Figure 2.7 presents the visual stimuli and the tactile textures used in this experiment:

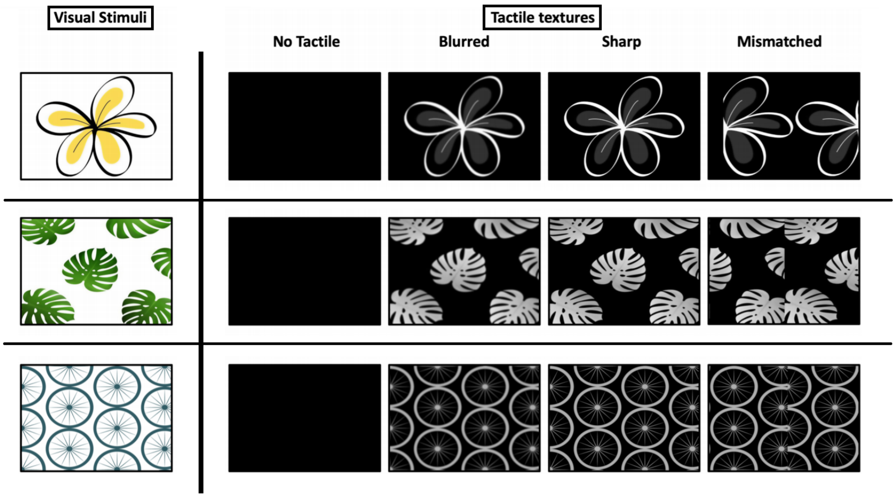

Figure 2.7: The three visual stimuli and the correspondent four tactile textures (for each visual stimuli) used in this experiment. Partially adapted from [16].

For a better understanding of the current experiment, Figure 2.8 presents a possible combination of visual stimuli and haptic texture:

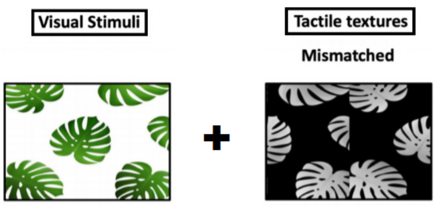

Figure 2.8: Possible combination of visual stimuli+tactile texture. Partially adapted from [16].

It is important to keep in mind that each of the tactile textures can only be perceived by touching the screen surface (they cannot be identified visually by direct screen observation). After each trial (combination of individual visual stimuli+haptic texture), the volunteers of this study evaluated their experience on a scale from ’0’ to ’100’, where ’0’ is translated as strongly dislike current experimental and ’100’ strongly liked current experimental.

When it comes to the result analysis, it was clear that volunteers preferred images that they could feel (images with a haptic texture added to the visual stimuli were preferred to the ones without haptic textures, Visual Stimuli+'No Tactile'). The sharp tactile texture was the most popular preference due to the high definition of its haptics compared to the blurred or mismatched ones. Having this said, the authors of this paper concluded that the quality of the haptic texture was essential to the user's experience and their preference in haptic feedback experiments.

As a future work, the paper mentions the relevance of real objects usage on similar experiences, mentioning its possible influence on the results accomplished by their investigation. This statement of the authors of the paper motivate the inclusion of a blind test section on this thesis (see 4.3).

2.3.1.3 Renderization of Regular Homogeneous Textures

A particular important paper, considered especially relevant in the context of the current thesis, was conducted in the field of haptic textures renderization [17]. The current study uses a TT Development Kit 1.0 touchpad (Android application for the TT device) and a Google Nexus 9 tablet.

Different textures were designed with the use of regular polygons tessellation (the name given to repeated homogeneous patterns composed by edge-to-edge polygonal tiles) and varying its properties (density, edge width, the intensity of the pixels, and manipulating image properties, namely, image reversal). With the combinations of the previous properties, 32 different textures images were generated as seen in Figure 2.9:

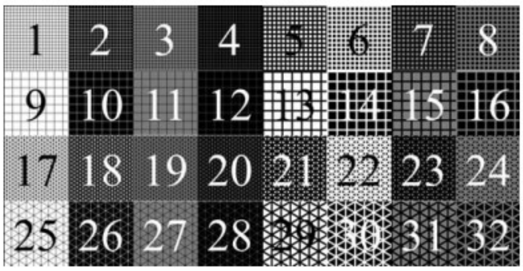

Figure 2.9: The 32 texture images designed with regular tessellation techniques. Original image from [17].

Different tests were led with several participants, which allowed to apply cluster sorting and multi-dimensional scaling techniques to the collected data and build a perceptual space associated with this same data. The study focused its attention on understanding the importance of the 5 design variables initially mentioned (density, edge width, pixels intensity, and image reversal) and their relevance to designing haptic textures. Results show that edge width and pixel intensity are the most relevant variables for identifying haptic textures.

The participants of this study were also inquired to rate the different textures using the following eight adjectives pairs from Figure 2.10:

#	Adjective 1	Adjective 2
1	Sharp	Blunt
2	Dense	Sparse
3	Vague	Distinct
4	Jagged	Aligned
5	Sticky	Slippery
6	Heavy	Light
7	Bumpy	Even
8	Rough	Smooth

Figure 2.10: The eight adjective pairs used for classification of the textures during the experiment. Original image from [17].

Another important conclusion of this study was that, from the previous pairs of adjectives, the ones that are more adequate to translate the texture sensations experienced by participants are: rough-smooth, dense-sparse, and bumpy-even pairs of adjectives.

They also concluded that when textures' intensity is strong enough, participants can distinguish different polygonal shapes, which has a particular interest if designing realistic textures is desired.

Overall, this article helps to design more distinctive and clear textures based on a comprehension of the most significant characteristics that define relevant haptic textures.

2.3.1.4 Detection and Identification of Haptic Patterns

Klatzky and Nayak *et al* [18] focused their attention on understanding how users detect and identify tactile information when dealing with haptic technology. The authors of this study fall back on the TT device to create two different exercises: the first one concerning the detection of friction change on haptic textures, and the second one related to matching haptic textures to visual images from where these haptic textures were created from.

This same article mentions that textures settled on electroadhesion friction can translate two different types of information to the user, namely patterns and textures. To prove this, the tests conducted within this study manipulated the size, scale, and form of different patterns. There were three available haptic patterns: a coarse fingerprint, a fine fingerprint, and a star pattern. The main criteria for selecting these haptic textures was the high intensity and variability of these patterns.

Figure 2.11 gives a good visual perception to the used tactile patterns on this experiment:

Let's now take a closer look at each of the two detection and identification tasks that were executed on this experiment to better understand the conducted study. On the detection task,

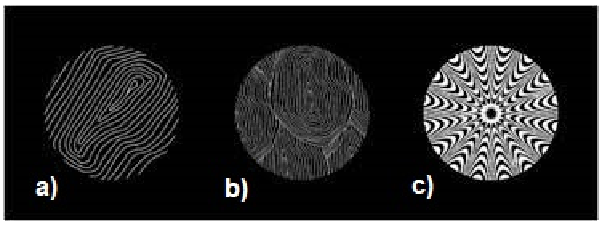

Figure 2.11: Used haptic patterns on this experiment: a) coarse fingerprint, b) fine fingerprint, c) star pattern. Original image from [18]

participants were presented with a visual interface containing 12 boxes numbered from 1 to 12, respectively. Each time this detection exercise was initiated, the haptic stimuli from Figure 2.11 were randomly assigned to some of the 12 existing boxes. The number of haptic stimuli in each detection task could vary from 0 (none haptic stimuli assigned) to a total of all 3 haptic stimuli, the ones represented in Figure 2.11. Every time a user would find out one of the available haptic stimuli on the haptic touchscreen, the user mentioned the number of the box where the stimulus was found. This exercise would end when the volunteer pressed a terminate button.

On the identification Task, the volunteer was encouraged to explore solely box number 5 from the previous detection task. All the other remaining boxes were removed from the interface. Moreover, all the 3 visual patterns visible in Figure 2.11 were printed on a piece of paper. On box number 5, one of the three haptic patterns from Figure 2.11 was presented. Next, the user was asked about which of the visual patterns on the piece of paper was being reproduced on box number 5 of the haptic touchscreen.

The identification task was executed three times in a random order, one for each available pattern. The participant would end the exercise by pressing a terminate button displayed on the haptic electroadhesion-based touchscreen.

This study concluded that there was a great difference between the ability of users to detect haptic patterns and their ability to match these same haptic patterns to visual images from where they were generated from. The study also reported some difficulty of users concerning pattern identification. This problem can be partly explained by the lack of users' ability to map edges from available patterns on the haptic display. It is highlighted some frictional-related problems during the interactions with the haptic display along with some rapid finger movement that might affect the obtained results.

This same study mentions that the available tactile information in the patterns used seems short for what is required for haptic textures identification and matching with the visual images available on the printed piece of paper. It is also referred to the need for increasing friction on the displayed interactive buttons used in these exercises, to allow better location and interaction. Furthermore, some effectiveness-related problems concerning the haptic touchscreen rendering are mentioned.

Finally, the article finishes with an appeal to identify image parameters that would improve the number of correct matches between haptic patterns and visual images. It is suggested that large-sized textures might improve this matching too. Further work is required to more clearly define distinct frontiers for better friction patterns identification.

2.3.2 Applications

This last section of the literature review presents two different papers that give a clear insight into which applications have been designed in the past based on electroadhesion haptic technology. These articles contributed to the design of the UCs of this thesis, especially the haptic eBook from UC 2, which was conceptually inspired and guided in the papers mention in this subsection.

The first article concerns a haptic e-learning straightforward application, where TT display is used to support the learning process of new concepts, like electric circuits basics. The haptic eBook implemented on 3.2.2 can also be easily adapted to this type of educational purpose, which is an opportunity for future work too.

The second article shows how this type of haptic technology can have a huge contribution for visually impaired students that can benefit from tactile-based technology like this one when applied to learning and education. Along with this article, the implemented eBook on UC 2, shares the same interest in supporting visually impaired students and calling attention to new applications in this area.

2.3.2.1 Computer-assisted Learning based on Haptic Feedback

Beheshti *et al* [19] explore haptic feedback as an education tool to better explain complex and abstract concepts which are normally difficult to understand by young children. An example of this is the functioning principle of electric current flowing on a circuit. To do so, this case study targets parent-child duos that are invited to execute different tasks related to the selected topic.

Furthermore, the haptic feedback solution described within this paper presents useful information concerning the UX and its translation into the haptic design, which is considerably useful for both UCs and blind tests implemented in this thesis.

As so, to achieve the purpose of this research, different parent-child duos were invited to execute the same group of tasks. Figure 2.12 displays the interface presented to the user during the experiments:

Each parent-child duo is invited to glide their fingers across the circuit in different available tasks, like the one presented in Figure 2.12, and then they were asked to give some feedback

Figure 2.12: Visual interface with a simple circuit that was used in this experiment. Original image from [19].

about their UX while performing each task.

By asking for feedback, the authors of this study intended to answer the following research questions:

1) Which is the best haptic texture to represent an electric current flowing along a circuit;

2) How can the intensity of the haptic texture traduce the intensity of an electrical current.

To understand the answer to the first question, the authors pre-selected a group of textures with regular patterns and homogeneous intensity. The textures were chosen from a Tanvas texture library of 620 different textures in total. Irregular and asymmetrical textures were automatically excluded due to their lack of texture balance and minimum suitability to represent the texture of an electrical current. Figure 2.13 presents the textures that were selected to represent electrical current in this study:

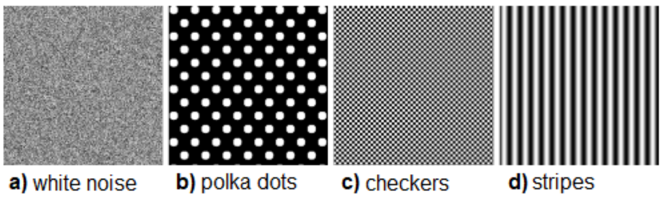

Figure 2.13: Best pattern candidates for electrical current representation. Partially adapted from [19].

Each of the patterns in Figure 2.13 was recreated in three different variations of intensity: high texture intensity, medium texture intensity, and low texture intensity. The purpose of these texture variations is to realize if participant duos expect to feel higher texture intensity with the increment of current on the circuit (direct mapping) or the opposite, which means, lower texture intensity with a higher amount of current on the circuit (inverse mapping). The second stage of the experiment was designed to answer the second research question mentioned previously.

The white noise patterns from Figure 2.13 were used on Figure 2.14 in three different variations of intensity:

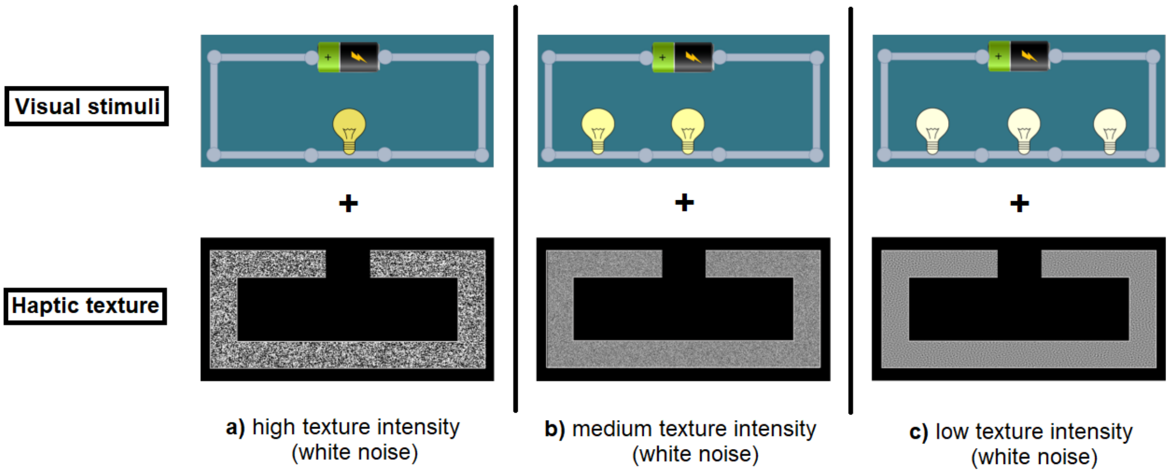

Figure 2.14: Visual stimuli and underlying haptic texture in three different intensities (high, medium, low) for white noise texture. Partially adapted from [19].

After the execution of the different tasks, volunteers shared their opinion about the experiment. According to the obtained results, 50% of individuals (10 out of 20) answered that the stripes pattern from previous Figure 2.13 was the haptic pattern that better represented electrical current, answering the first initially proposed question.

Let's now focus on how volunteers establish a relationship between an electric current increase and the expected intensity of the haptic pattern. About this second question, 90% of individuals (18 out of 20) opted for the direct mapping option, which means that the majority of the users considered it more adequate to have a higher texture intensity with a higher amount of current in the circuit, which is coherent with natural cause-effect logic.

The electrical current representation-based case study appreciably helps to understand the replication of subjective textures in a haptic touchscreen environment. Moreover, this article was very useful for the exploration of different alternatives for representing the same entity (recall candidates to best texture from Figure 2.13), the electric current in this case. Also, it turned clear how these variations of intensity can influence participants' perception about a certain matter, namely, how an increment of texture can communicate to the user an increment of electric current in the circuit.

This academic research showed how broader and subjective is the creation and design of haptic textures and their effect on UX, traducing better general understanding of the haptic and interactive design of applications, very useful for this thesis.

2.3.2.2 Haptic Feedback supporting Visual Impaired Students

One of the many different applications of haptic feedback to touchscreens is supporting visually impaired students, due to their understandable difficulty to follow usual lessons at school, when compared with students without visual impaired difficulties.

Bateman *et al* conducted a usability study [20] concerning this important subject, presenting a deeper understanding of the importance of designing haptic solutions oriented to the UX (user-centered design) of visually impaired people.

They proposed three main goals: to design an easy-to-use platform able to allow sighted teachers to create proper material to support their visually impaired students, to study UI features that allow a spatial orientation to visually impaired students, and to code a short software for quick prototyping and testing, and then a general result analysis of the implemented solution.

The solution designed with the TT touchscreen presented different graphical information with embedded haptics, allowing visually impaired people to have an easier perception of the visual information that was being shown on screen. This study required the participants to locate different haptic points and figures on screen, testing the efficiency of the system, as well as identifying user patterns when interacting with the designed haptic solution.

The implemented solution had two different working principles: 1) a time-based haptic effect, consisting of increasing gradually the haptic intensity with time; 2) a spatial-based haptic effect, by having constant and time-invariant haptic sensations occurring in specific areas of the touchscreen. It is important to notice that each haptic sensation was covering at least 14 pixels of diameter, to guarantee that the desired haptic effect was noticed by the user.

Results show that the majority of visually impaired people can execute simple tasks using an electrostatic touchscreen (TT, in this case) and that they can progressively develop more agility the more they interact with this type of touchscreen. Besides that, it was possible to identify four main strategies adopted by visually impaired people when exploring the haptic touchscreen, like is shown in Figure 2.15:

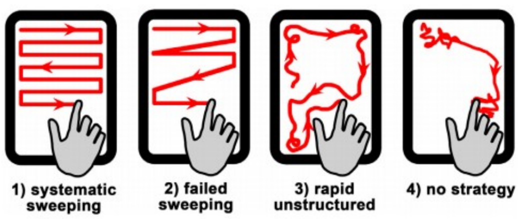

Figure 2.15: Main strategies adopted by visual impaired people to explore the haptic touchscreen. Original image from [20]

Given those four main strategies, it is important to mention that the systematic sweeping strategy and the rapid unstructured exploration of the screen turned to be the most popular among the users.

Figure 2.16, is presented an accuracy heatmap that allows a deeper understanding of the navigation usability performed by the users of this study:

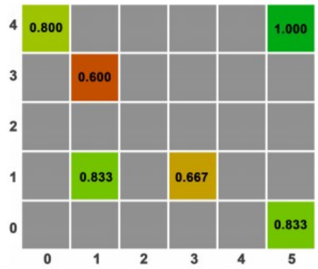

Figure 2.16: Accuracy heatmap associated to the screen exploration by the visual impaired users. Original image from [20]

Visual impaired people tend to identify more easily haptic patterns that are located in the corners of the touchscreen surface rather than central areas of the screen, which can be an extra aspect to take into account when designing haptic solutions for visually impaired users.

Finally, one of the most relevant conclusions of this article is held by the significant participants' accuracy in location haptic dots on the touchscreen, which confirms the usability of the TT technology in general. Besides that, the different strategies adopted by the visually impaired users to locate the dots in the touchscreen demonstrate that the TT device is intuitive and very well accepted by visually impaired users in general.

3 Technology Overview and Use Cases

According to the State of the Art, TT haptic displays are currently a unique surface haptics technology without moving parts, unlike standard vibrotactile technologies where the entire device vibrates at the same time. As so, TT technology combines uniquely multi-touch sensing and haptics, which results in a considerably innovative product in the market [10].

Having this said, this chapter includes two main parts: a general summary of this technology and a description of the implemented UCs in this thesis.

The first part starts with a general introduction to the technology that includes the architecture basics of TT , the available APIs that TT supports, and finally are presented main areas of application where this haptic technology has the most potential to be applied.

The second part of this chapter presents the two implemented UCs on this thesis: UC 1 describes the implementation of a simple haptic application based on a bookshelf image and UC 2 that describes the implementation of a haptic eBook library. About this last UC, it is relevant to say that some of the articles presented in the previous State of the Art section contributed to the creation of this second UC, namely the article related to computer-assisted learning and the article concerning the haptic application for visual impairment students. Both of them helped to better introduce this UC and contributed to more clearly thinking about the design of the UX.

3.1 TanvasTouch General Overview

TT is a haptic touchscreen that can generate software-based haptic textures. Unlike other haptic devices and technologies seen on State of the Art, TT is the first commercial ready-to-buy technology that allows the creation of haptic effects on an API-based environment.

This device relies on electroadhesion principles. As explained on 2.2.2, this electroadhesion effect is in fact friction variation along with the touchscreen. When the user drags his fingers across the haptic touchscreen, this electroadhesion layer offers a natural resistance that is recognized by the user as being a haptic texture, which when combined with visual stimuli gives a tactile relief impression. The TT touchscreen is presented in Figure 3.1:

Figure 3.1: The TT touchscreen. Original image from [21].

When compared with standard haptic actuators (ERM, LRA, and piezoelectric actuators), TT technology allows performing screen interactions without the need for surface vibration, which is the basic functioning principle of other haptic technology mentioned before. Moreover, with a continuous movement of fingers along with the TT touchscreen, it is possible to execute almost every required task on the display, allowing a smoother UX.

When it comes to the creation of haptic applications, all possible designed solutions require the creation of a Graphical User Interface (GUI) and the design of an underlying haptic layer that is responsible for adding haptic effects to the elements of the GUI. It is important to say that only the GUI is presented to the user, the haptic layer is never visible. Figure 3.2 shows an example of these two elements of any haptic application designed with TT technology:

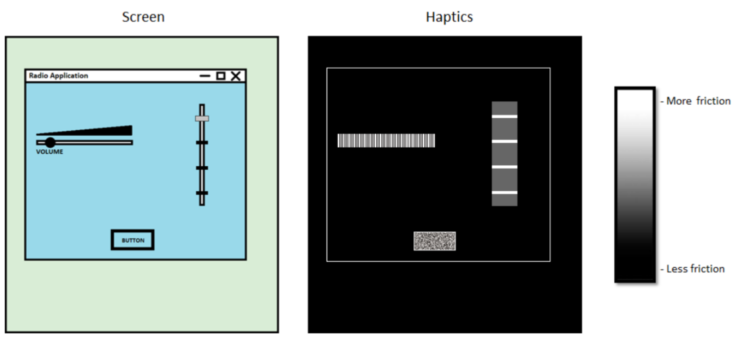

Figure 3.2: GUI and respective underlying haptic layer. Original image from [22].

Notice the vertical sidebar on the right of Figure 3.2, where it is presented an intensity map. This sidebar maps the intensity of a texture according to the given color of the map: darker colors mean less friction while brighter colors mean higher friction.

After this short introduction to visual and haptic interfaces, lets now focus the attention on understanding the general architecture of TT technology, which can be seen in Figure 3.3:

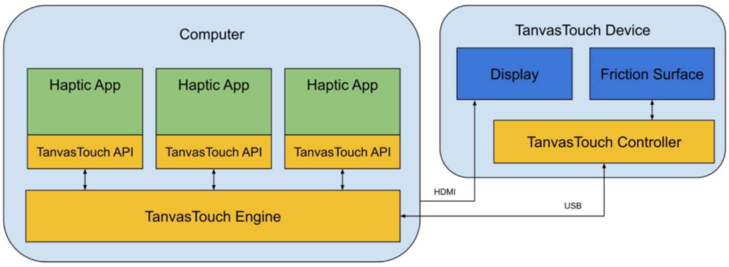

Figure 3.3: General architecture of the TT technology. Original image from [23].

As seen above, there are two main components of this architecture [23]: the personal computer of the user and the TT device itself. Any haptic application (haptic app) created with this device requires adopting a specific TT API that directly communicates with the TT Engine. This Engine uses a USB cable to exchange friction-related data between the computer and the TT Controller, which is responsible for changing the friction of the haptic display. In more detail, the TT Engine is a software driver that translates the functions of the APIs into practical commands that can be interpreted by the TT Controller to vary the friction of the screen (Friction Surface), according to the code developed in each haptic app.

While the friction of the touchscreen is changing, it is necessary to do real-time updates of the image displayed on the TT screen, which is done with an HDMI cable that directly connects the computer to the Tanvas device.

In the next section, the TT APIs are introduced and more details are given related to their main components.

3.1.1 TanvasTouch API

TT supports three different APIs [24]:

- **.NET API**, which is the most high-level API available for surface haptic interactions. This API uses a .NET framework based on C#.

- **C API**, which is the most low-level API available for TT Engine interactions.

- **C++ API**, which is a little bit more high-level than the previous one but is not yet currently stable.

3.1.1.1 .NET API

This API has four different namespaces:

`Tanvas.TanvasTouch` is useful for TT library initialization.

`Tanvas.TanvasTouch.Error` deals with code errors related with .NET API.

`Tanvas.TanvasTouch.Resources` contains useful classes for haptics design, mainly Materials, Sprites, Textures, Views, between other available classes.

`Tanvas.TanvasTouch.WpfUtilities` presents useful tools for integrating TT into Windows Presentation Foundation (WPF) applications. As an example, it includes important helper functions useful for converting PNG images to friction maps so that the engineering team can be released from this type of responsibility, since this type of procedure is done automatically.

3.1.1.2 C API

The C API includes three main header files where core TT functions are defined:

`tanvastouch.h` is the main TT C API header. It includes many functions that can manage different haptic resources (Textures, Materials, Sprites, Views), haptic resources reposition, define haptic resources size, between other functions.

`tanvastouch_diagnostics.h` is a header file mainly designed for dealing with diagnostic tests run on TT. It includes diagnostic functions that return the current path of the diagnostics server or even start or stop the diagnostics server.

`tanvastouch_errors.h` includes status codes that are used in the TT Engine API.

3.1.1.3 C++ API

The C++ API is still not completely stable, since Tanvas is still currently working on it, which means that it is likely to happen different backwards-incompatible changes over time.

Having this said, current C++ headers available in this API are:

`api.hpp` contains API initialization functions.

`call_conv.hpp` contains call conventions.

`material.hpp` contains representations of the material resource.

`sprite.hpp` contains representations of the sprite resource.

`texture.hpp` contains representations of the texture resource.

`view.hpp` contains representations of the view resource.

3.1.2 Applications

One of the main areas of applications of TT technology is mainly the automotive industry [25]. Many road accidents are caused by driver's distractions while performing non-essential tasks on the vehicle's touchscreen panel, which quite often challenges the driver to divert his attention from the road. Many articles have already proved that adding haptic feedback to the vehicle control dashboard, significantly improves security while driving, according to Pitts *et al*

[26] and Polities *et al* [27]. The reason for this to happen is because haptic feedback response can give a clear and perceptible tactile confirmation about the status of a certain request (e.g. turn on the air conditioner), avoiding the driver to take a look at the cockpit panel to get the same confirmation that he could have had haptically. Figure 3.4 presents an application related to the air conditioning example mentioned before:

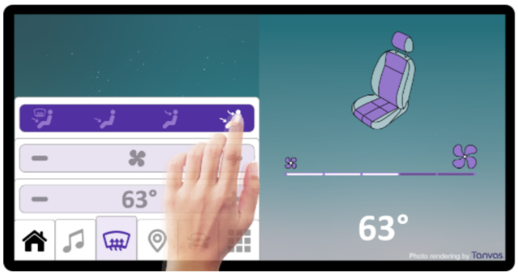

Figure 3.4: Example of user interaction with a TT display to set air conditioning configurations. Original image from [28].

Besides that, this type of technology can be particularly interesting when applied to e-commerce and online shopping, allowing customers to precept the textures and having a tactile experience of clothes before paying for it first [29], like Figure 3.5 exemplifies:

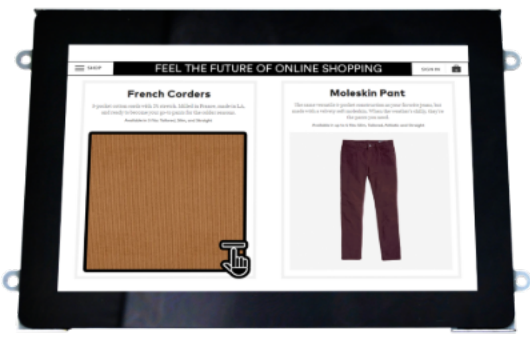

Figure 3.5: E-commerce example of application based on TT technology. Original image from [29].

Finally, there are many other examples of application in this field, namely assisted learning (see 2.3.2.1), consumer electronics, gaming, and custom displays, between many different possible applications of this technology, once this haptic feedback technology is extremely customizable to different products and applications.

3.1.3 Related Products

The haptic technology field is considerably vast and includes many different areas of application, just like seen in the previous section. When it comes specifically to alternative products to the TT haptic touchscreen, there are still no direct competitors presenting a commercial product with an open-source API software-based environment that allows the development of haptic applications to the general public.

Nevertheless, there is a growing trend in the market to incorporate more haptic technology in electronic devices. Different companies are approaching the same automotive, gaming, and consumer electronics markets where Tanvas is focused on. Immersion Corporation is a good example of that, the company owner of TouchSense, a technology that allows the integration of haptic feedback on other existing devices, empowering them with haptic feedback based on built-in actuators, that allow the creation of high-definition haptics and the implementation of tailored UCs [30].

Many other companies that have been incorporating haptic touchscreen technologies in their devices could be mentioned, especially in the automotive industry. However, none of them has presented a final product that could be acquired by final consumers just like TT did.

Senseg FeelScreen haptic touchscreen was another relevant reference in this field, demonstrating similar capabilities to TT equipment since the technology on which Senseg FeelScreen is based is also electrostatic haptics [31]. Unfortunately, around the beginning of 2016, the company discontinued the development of this haptic device, and the company was acquired by O-Film later that year.

Considering the existing alternatives to TT, this haptic equipment continues to be the most adequate for the design of haptic applications, allowing the design of customized and personalized applications based on software-defined haptics.

3.2 Use Cases

In this section, the two different UCs considered in this thesis are presented. UC 1, a simple haptic application based on a picture of a bookshelf where the book spines have embedded haptics, and UC 2 which is a haptic eBook library where it is possible to select a specific book, open it and navigate through the different pages available.

Both these UCs were implemented in C# and XAML to design the app's logic and GUI interface design, respectively.

3.2.1 Use Case 1

The goal of this UC 1 was to design a generic first example of a haptic TT application where different tactile textures could be experienced. This UC presents a simple bookshelf image with books with different shapes, sizes, and textures to allow users to experience distinct haptic textures in a single application. This UC went through two different implementation stages: bookshelf 1.0 and bookshelf 2.0, which will be presented next in more detail. Bookshelf 2.0 is an improved version of bookshelf 1.0 after getting some feedback from users' experience when interacting with this haptic application.

3.2.1.1 Bookshelf 1.0

Since this is a highly experimental and subjective implementation, the first approach was considerably based on personal taste. As so, the first version of UC 1 includes many different haptic textures which are not necessarily the most adequate ones for representing tactile textures of the spine of a book, as Figure 3.6 evidences:

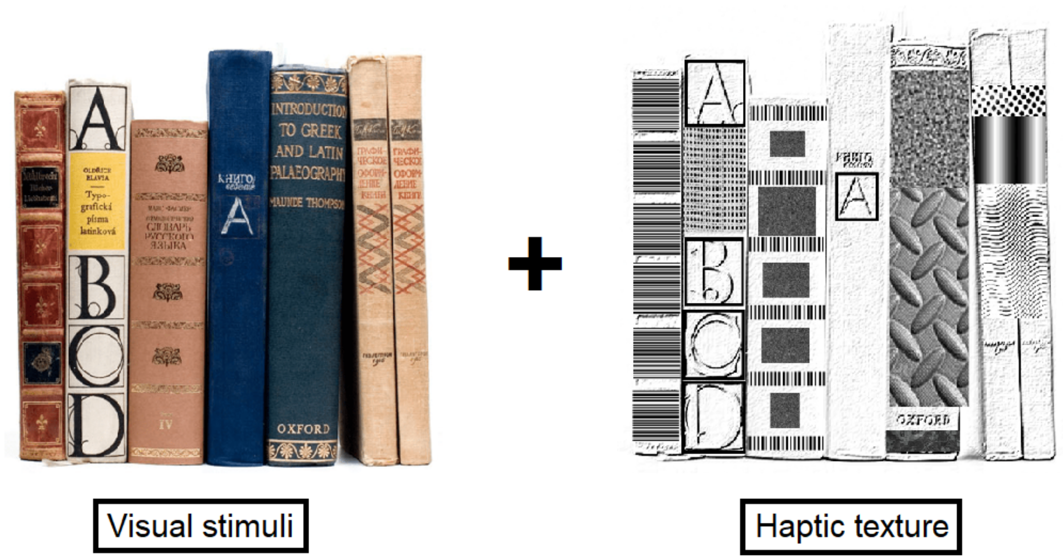

Figure 3.6: Bookshelf visual stimuli+haptic texture from first version of UC 1. Partially adapted from `https://www.artlebedev.com/mandership/122/`

After receiving some feedback concerning bookshelf 1.0 initial implementation, many changes occurred in the haptic texture presented in Figure 3.6, as the new bookshelf 2.0 implementation enunciates next.

3.2.1.2 Bookshelf 2.0

As it is possible to observe in Figure 3.6, it is easy to understand that many textures were not compliant with the user's tactile expectations, according to the received feedback. Having this in mind a new approach was taken.

This time, instead of focusing the attention on introducing as many different textures as possible, which were most of the time inappropriate for this type of visual stimuli, the priority turned to highlight the books' spines' reliefs. Having this in mind, a manual image editing of the books' spines was made to bring out its reliefs, just like is shown in Figure 3.7:

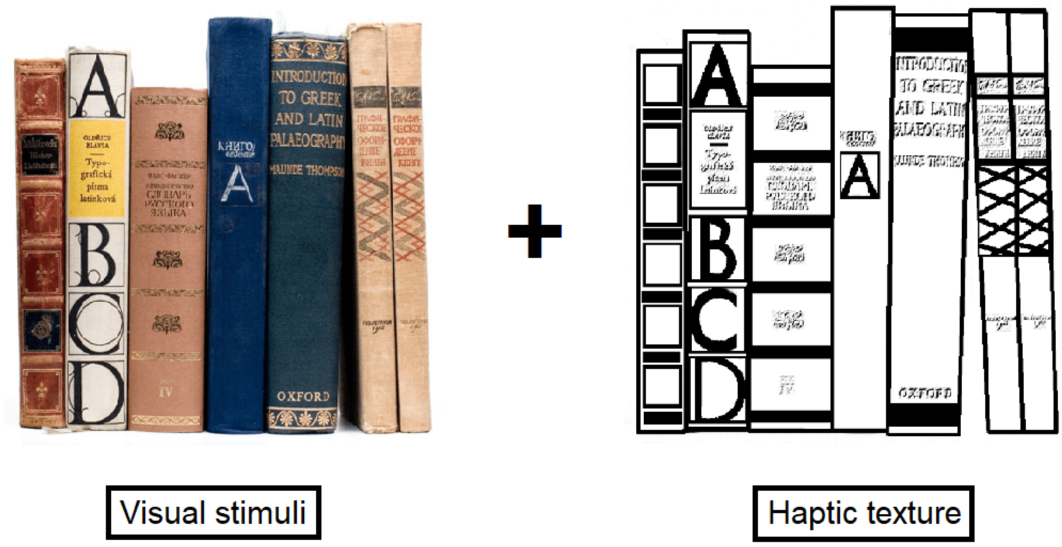

Figure 3.7: Bookshelf visual stimuli+haptic texture from second version of UC 1. Partially adapted from `https://www.artlebedev.com/mandership/122/`

In Figure 3.7 it is noticeable a clear change on the haptic texture presented to the user comparing with previous haptic texture from Figure 3.6. On this new haptic texture, the original relief of the letters on the book's spine was taken into account, along with a better definition of books' contours, contributing to an overall better UX that matches the user's natural tactile expectations.

3.2.2 Use Case 2

This second UC goal is to implement a haptic eBook where besides the normal content of standard eBooks it has some haptics attached to it, allowing to have a richer and deeper UX when reading a certain book.

Unlike UC 1, UC 2 only went through a single stage of implementation, nevertheless there are certainly improvements that can be done to this haptic eBook implementation that will be better discussed on next chapter 5, where a general overview is made of the entire academic work, including some suggestions for future work.

Figure 3.8 presents the haptic eBook library that was considered, with the different books available[4]:

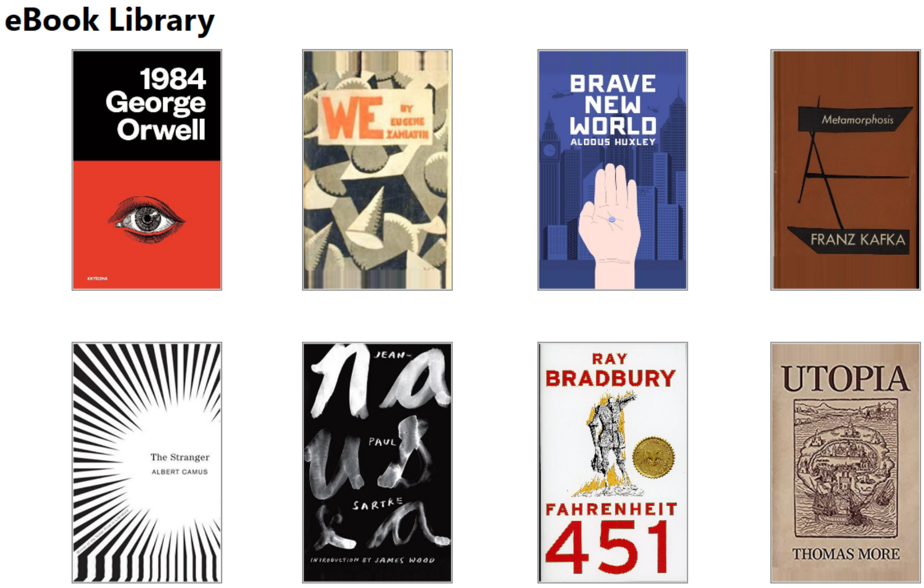

Figure 3.8: eBook library.

As seen in the first UC, this second UC besides the GUI visual interface that is presented to the user also requires a haptic layer to provide texture to the presented eBooks. Once this haptic layer is just a grayscale version of the visual image presented on the GUI, it was decided not to present it on this document, since displaying it would add nothing relevant to a better comprehension of this UC implementation.

As so, when one of the virtual books displayed on the haptic eBook library is selected, a second GUI pops up presenting the book's content. On this second GUI, there are different features implemented, namely: a slide bar for changing a book's page faster and two navigation

[4] *1984* book cover: `https://static.fnac-static.com/multimedia/Images/PT/NR/f8/9e/0d/892664/1507-1.jpg`
We book cover: `https://vonnegutbookclub.wordpress.com/2018/05/30/meeting-may-24-2018/`
Brave New World book cover: `https://www.themarysue.com/wp-content/uploads/2016/08/cover-new.jpg`
Metamorphosis book cover: `https://d3525k1ryd2155.cloudfront.net/h/029/070/1015070029.0.x.jpg`
The Stranger book cover: `https://1.bp.blogspot.com/-JUvFTkJHTis/UiD_7e8bLFI/AAAAAAAAATk/hUL1-R2UR6o/s1600/The+Stranger.jpg`
Nausea book cover: `https://prodimage.images-bn.com/pimages/9780811220309_p0_v6_s1200x630.jpg`
Fahrenheit 451 book cover: `https://weltbild.scene7.com/asset/vgwwb/vgw/fahrenheit-451-english-edition-268131314.jpg?\protect\TU\textdollarmax-size\protect\TU\textdollar&wc57`
Utopia book cover: `https://images-na.ssl-images-amazon.com/images/I/51TW%2BMqijuL._SY445_QL70_.jpg`

arrows that allow to sequentially read the content of the book. Besides that, the text itself has embedded haptics for a more immersive reading experience, like it is shown in Figure 3.9:

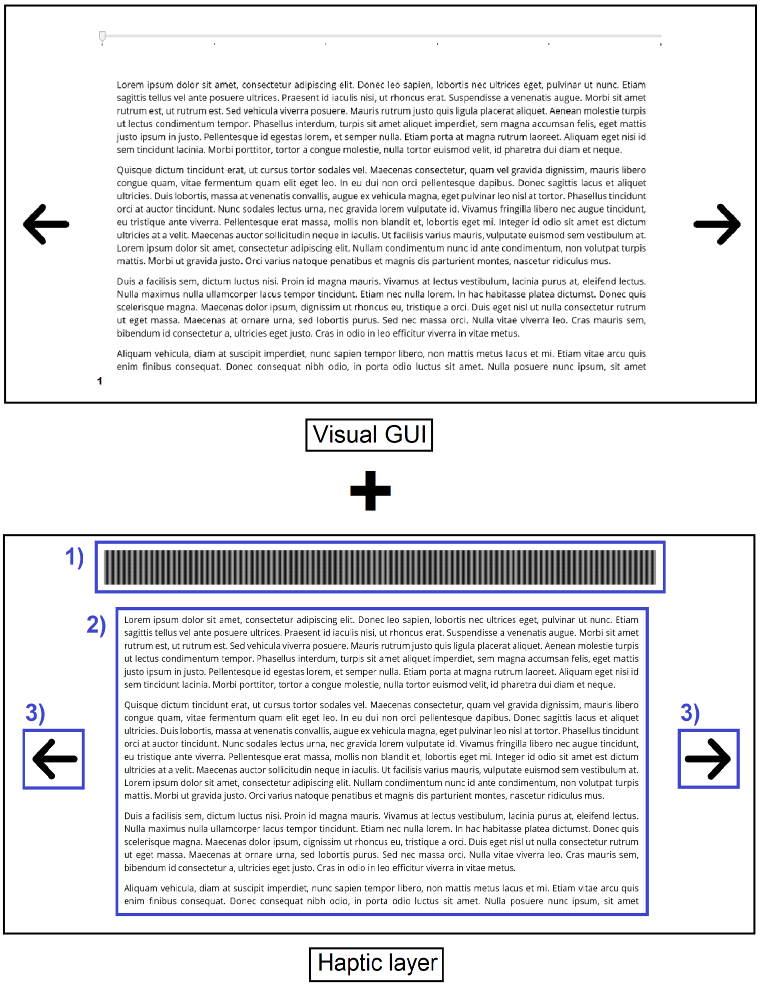

Figure 3.9: GUI and haptic layer of the same page of one of the available eBooks in the library. On the haptic layer: 1) corresponds to the slide bar haptics; 2) corresponds to haptics of this eBook page; 3) corresponds to the navigation arrows haptics

It is important to say that each of the eight eBooks of Figure 3.8 has the same type of navigating features that were presented in Figure 3.9.

4 Tests and Result Analysis

In the context of the current thesis, a set of different experiments was designed to evaluate the similarity between the textures designed with electroadhesion-based haptic technology and textures of real-world objects.

The set of tests will be frequently named ”blind tests” once the visual stimuli interface of the touchscreen will be the same for all five tests. As so, the visual stimuli displayed on the haptic interface are visually ”blind”, which means it is insensitive to the test that is being executed, since the same visual stimuli are shown to the user independently of the executed test. Nevertheless, the haptic sensibility of the touchscreen (haptic texture) will be changing from test to test, which means that the volunteer can only identify the textures when touching the screen.

All the 20 volunteers participating in this set of tests were first-time users that never had previous experience with any haptic technology, which allows obtaining more trustworthy and reliable results.

4.1 Purpose

The main goal of the experiments was to understand how average users perceive electroadhesion-based haptic technology when interacting with the designed textures. It is crucial to highlight that this academic document is focused exclusively on the analysis of the UX of the electroadhesion-based haptic equipment and nothing else.

The results obtained with the blind tests should be interpreted qualitatively and not in a quantitative one, as traditionally happens in the majority of published articles in this field. Nevertheless, the obtained results are considered relevant, due to their contribution to a better understanding of the viability of this type of haptic technology in many different fields. As so, the presented tests can be seen as a State of the Art of texture design on haptic electroadhesion-based Tanvas technology, allowing to understand how promising this technology can be and if it is reasonable to further invest and develop work in this area in the future.

The developed tests were based and partially adapted from Park and Jamil *et al* [16], which has been already reviewed in the State of the Art section of this thesis. The article from Klatzky and Nayak *et al* [18], which was reviewed too in the same previously mentioned section of the current thesis, gave a significant contribution for understanding the identification and matching process between haptic textures and patterns and the correspondent visual images.

4.2 Setup

As mentioned before, the tests in this experiment were designed to study volunteers' correspondences between textures of real world objects and haptic artificial textures created with electroadhesion-based haptic technology.

In Figure 4.1 is presented the electroadhesion-based haptic device from TT:

Figure 4.1: The TT electroadhesion haptic technology developed by Tanvas and the four available objects used in the tests.

For each of the tests, for both versions blind tests 1.0 and blind tests 2.0, besides the electroadhesion-based haptic touchscreen, the volunteer had the same group of four different objects available: an embossed cardboard box, a cork stopper, a set of small tiles, and a phone case. The selected objects are presented in Figure 4.2:

Figure 4.2: The objects used in this experiment: a) embossed cardboard box, b) cork stopper, c) set of tiles, d) phone case.

4.2.0.1 Selection of real-world textures

There are countless textures of so many different objects in everyday life that turned to be a little bit difficult to select which objects would have the most adequate textures to use in this experiment.

Some guidance for texture selection was taken from the pair of adjectives 'rough smooth', 'dense-sparse' and 'bumpy-even' which were the most used words used by volunteers of the textures design and renderization article from Mun, Lee and Choi [17] that was better analyzed on the State of the Art section of current thesis. Thus, to maximize the experience brought by the limited sample of possible chosen objects, the selection was done according to the overall texture contrast they had between them.

Having this in mind and after evaluating many different possibilities, the set of selected objects for this experiment were: an embossed cardboard box, a cork stopper, a set of small tiles, and a phone case.

These four objects have a significant contrast between their correspondent textures which allows having a more distinctive and differentiated overall experience for the final user. The disparity between the cardboard and phone case textures is considerable, along with the significant differences between the tiles and the cork textures, between other possible comparisons.

4.2.0.2 Design and selection of haptic textures

The design process of the haptic textures is deeply connected and based on the different articles and documentation analyzed during the consolidation of the State of the Art section of this thesis.

The design of these textures was partially *ad hoc*, which means that even though the previously mentioned article was the major influence in the design of virtual haptic textures, the personal opinion of the author was considered for the selection of the most adequate haptic textures for this experiment.

It was required to have four haptic virtual textures, one for each object (cardboard, cork, tiles, and phone case). The tiles and phone case textures were manually designed by using an ordinary image editor, while the cardboard and cork haptic textures were based and partially adapted from available grayscale images[5], once these last two were more difficult to be manually designed, unlike the first two ones.

After this step, a small trial test was conducted with a reduced number of individuals to have first general feedback about the blind tests protocol and the designed haptic textures

[5] https://www.dreamstime.com/

themselves.

4.3 Tests and Protocol

In this section, more details will be given concerning the first implementation, blind tests 1.0, and the improved version of it, blind tests 2.0, considered after the constructive feedback given by some of the volunteers.

4.3.1 Blind test 1.0

Blind test 1.0 was the first draft of this experiment. In this initial trial, there were only four tests. For each test, the volunteer was given a single object and was invited to feel its texture and then return the object before the start of each test. Only then, the volunteer would interact with the virtual textures on the haptic touchscreen, one at a time. Each of the four tests was executed twice for better results. A total of five volunteers gave feedback about this first version of the blind tests.

The visual stimuli given to the user in Figure 4.3 was the same for all tests:

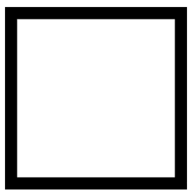

Figure 4.3: Visual stimuli given to the user in blind test 1.0.

Along with the previous visual stimuli, a different tactile texture was used in each test, as Figure 4.4 shows:

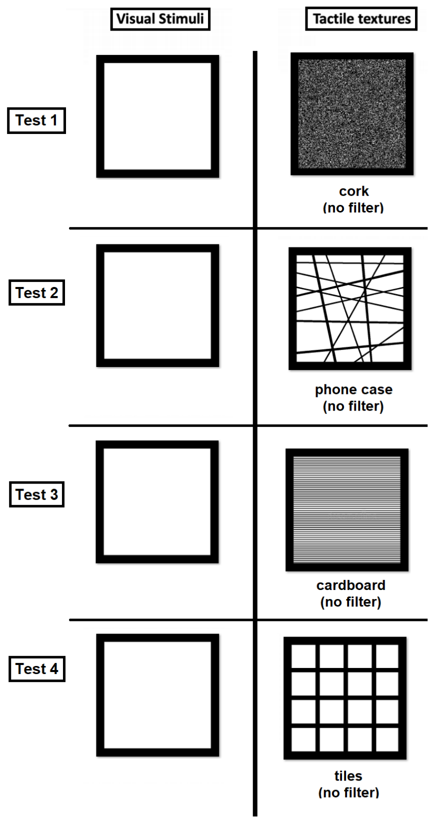

Figure 4.4: Visual stimuli and tactile textures for each test. Partially adapted from [16].

A possible combination of visual stimuli with a haptic texture would be similar to what is presented in Figure 4.5:

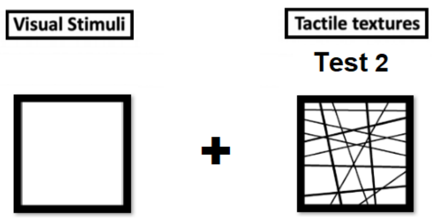

Figure 4.5: Example of a visual stimuli and haptic texture for test 2. Partially adapted from [16].

With the feedback of the small group of volunteers, it was possible to do several improvements to this original blind tests set.

To start with, one of the suggestions concerned the amount of time spent for the completion of the all tests that was almost one hour, which was considerably long. To improve this, the new visual stimuli (blind test 2.0) would have four independent smaller windows or canvasses to display the four virtual textures at the same time on the haptic touchscreen. During this improvement process, an article from Park, Jamil *et al* [16] turned to be one of the major references for this improved version and considerably influenced the creation of tests 2, 3, 4, and 5 of the blind test 2.0. An extra test was added to the previous existing tests, now being five tests in total. This additional test, which in blind test 2.0 corresponds to test 1, allowed to have four different virtual textures displayed simultaneously on the haptic touchscreen (cardboard, cork, tiles, and phone case), one in each of the four canvasses designed for the electroadhesion-based haptic touchscreen, which gave a precious insight of volunteers feedback that was not possible until then.

Each of the remaining tests 2 to 5 had a single virtual texture displayed, but with the application of small changes in each of the four canvasses (application of a blurred filter, sharp filter, mismatch version, or no texture). Nevertheless, the represented texture (cardboard, cork, tiles, and phone case) was always the same in each canvas. More details will be given shortly on the next section blind test 2.0. This allowed a better perception of participants when it comes to subtle variations of intensity and shape, which is an adapted idea from article [16].

Participants of this experiment were allowed to touch and handle the textures from real-world objects freely during the whole experiment, which was not possible until now.

Furthermore, another improvement was to inform participants about the possibility of not choosing any correspondence between the real world and haptic textures in case they considered there was not a reasonable choice to be considered in the set of available haptic textures. This avoided forced correspondences between real and virtual textures when participants could not identify them. This would allow the identification of which haptic textures were not successfully identified and might need to be improved in the future.

Besides that, some other small changes were introduced with obtained feedback, namely concerning shape, size, and modification of all four haptic textures, to make them even more realistic.

Finally, based on all feedback obtained it was possible to create a more adequate feedback form that would be answered by participants while they executed blind test 2.0, which is presented next.

4.3.2 Blind test 2.0

For all previously mentioned tests (1 to 5), even though there is always at least one correspondence between physical and virtual textures, the volunteer is allowed to give 'no correspondence' as a valid answer during each of the five tests.

It is important to mention that this time, contrasting with what was happening in blind test 1.0, volunteers could now give the same answer in different tests, which means that if volunteers considered the same virtual texture was being reproduced in different tests, this was considered a valid answer, avoiding any possible manipulation or bias on the results during volunteers' experience, that was more prone to happen in blind test 1.0.

Adding to this, previous to the execution of these tests, the order of tactile textures was defined only one time in random order and kept unchanged during the execution of the blind tests for all volunteers.

Each test was executed only once. Each volunteer decided independently the amount of time required for the execution of each test.

During the experiment, volunteers answered a survey (see Appendix II) to track and better understand the quality of their subjective experience and performance.

The visual stimuli interface of the five tests is shown in Figure 4.6:

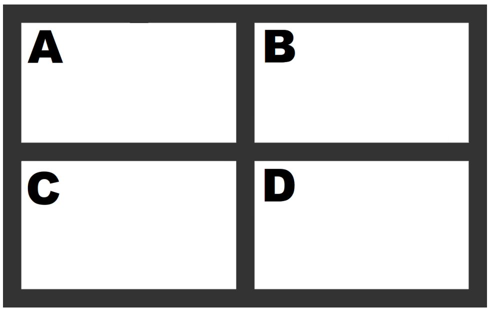

Figure 4.6: Visual stimuli interface of the blind tests.

In Figure 4.7 is presented an image that exemplifies the interaction of a standard user with the electroadhesion-based haptic equipment for blind test 2.0:

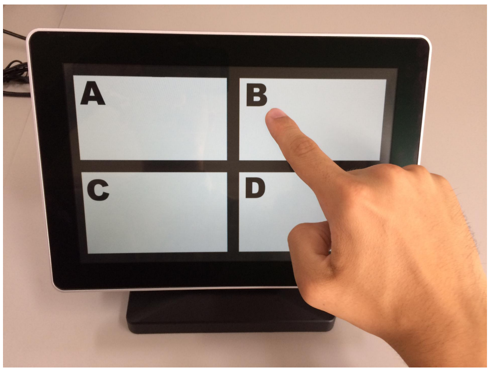

Figure 4.7: Example of a user interaction with TT equipment.

At the beginning of blind test 2.0, each volunteer had their first contact with haptic technology by interacting with Tanvas Intro App designed by Tanvas. This app allows a general perception of different textures and applications that can be developed with Tanvas haptic technology that is inspired by the physical principle of electroadhesion. This was a crucial preparation step for the experiment, extremely important for the users to get comfortable with TT touchscreen and have the first contact with textures reproduced on it, allowing a better preparation and sensitivity adaption to the blind tests, skipping the initial natural adaption moment of volunteers to this haptic equipment. When the user is comfortable with the technology, the execution of blind tests begins.

As mentioned before, the blind tests are a set of five different and independent tests. All the blind tests require correspondences between real textures and virtual textures (the ones reproduced on the touchscreen).

To better establish the relationship between objects' physical textures and their possible representation on the electroadhesion-based haptic touchscreen, Figure 4.8 establishes a direct correspondence between these two:

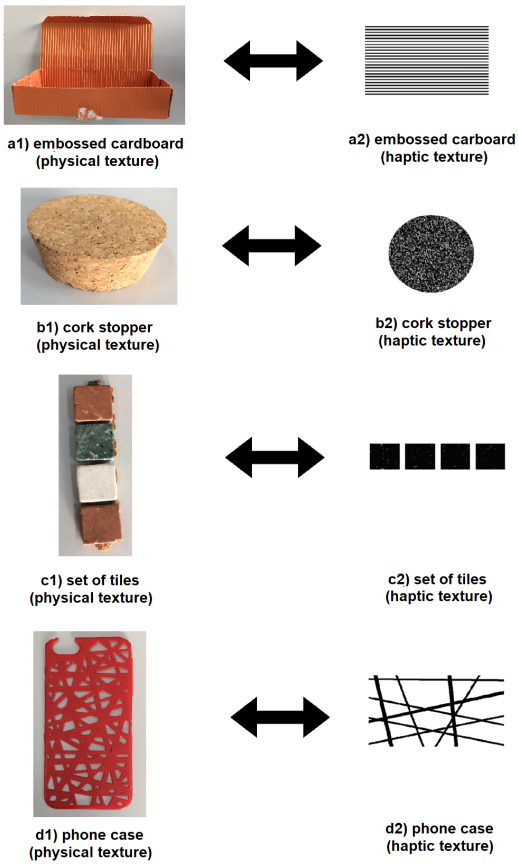

Figure 4.8: Correspondence between physical textures from real-world object and haptic textures.

4.3.2.1 Test 1

Test 1 uses the following combination of virtual stimuli and tactile texture for this specific test, as Figure 4.9 evidences:

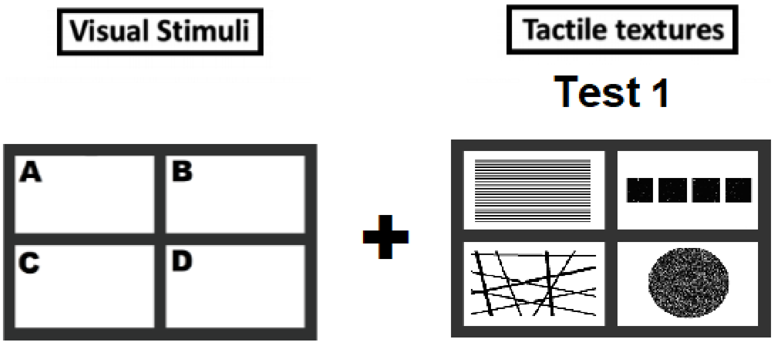

Figure 4.9: Visual stimuli and tactile texture for Test 1. Partially adapted from [16].

This first test consists of the univocal matching of all four physical textures to the corresponding four virtual ones, represented on the haptic touchscreen.

Please notice the Textures Overview for blind test 2.0 that is available on Appendix I, to better understand the displayed textures in each of the canvasses of this first test.

Besides presenting a better understanding of test 1, where each of the four canvasses A to D has a different texture displayed, this same Appendix I allows taking a look at tests 2 to 5, where each canvas has variations of the same texture (excluding ’no tactile’ that is common in all tests 2 to 5).

4.3.2.2 Tests 2, 3, 4, and 5

The remaining tests of blind test 2.0 consist of the identification of only one of the physical textures based on the virtual textures reproduced on the haptic touchscreen.

This time, all virtual textures on the touchscreen correspond to the same physical one, but with slight variations of intensity, by the use of blurred image filters, sharp image filters, or variation of textures’ shape, like mismatched textures or even the complete removal of texture. In none of the tests (2 to 5) was mentioned what was the physical texture from the object that was specifically being evaluated in that test.

Having this said, lets now list the different combinations of visual stimuli and tactile texture available for tests 2 to 5:

Test 2: The second test that corresponds to cork haptic texture, had the following combination of virtual stimuli and tactile texture, presented in Figure 4.10:

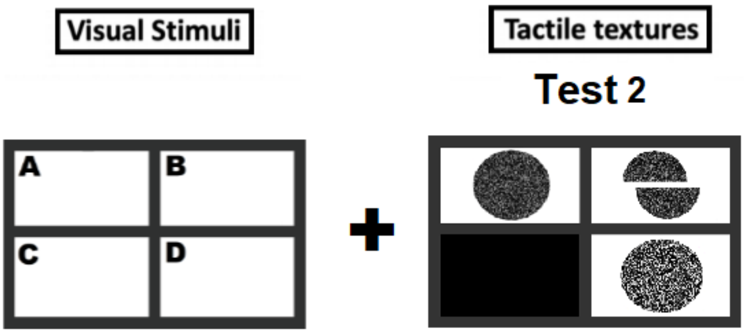

Figure 4.10: Visual stimuli and tactile texture for Test 2. Partially adapted from [16].

Test 3: When it comes to the visual stimuli and haptic texture for phone case haptic texture in test 3, the correspondent pair is shown in Figure 4.11:

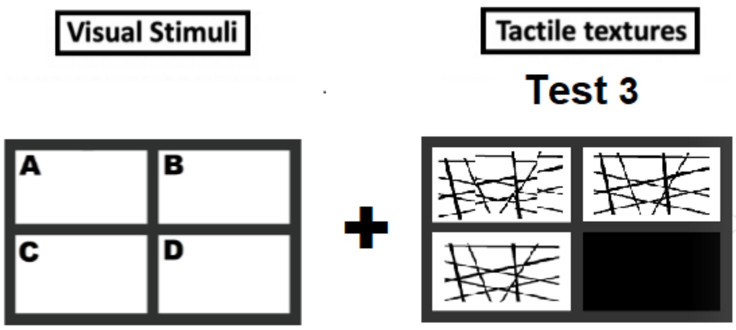

Figure 4.11: Visual stimuli and tactile texture for Test 3. Partially adapted from [16].

Test 4:, Figure 4.12 presents both the visual stimuli and tactile texture that this time correspond to cardboard's virtual texture:

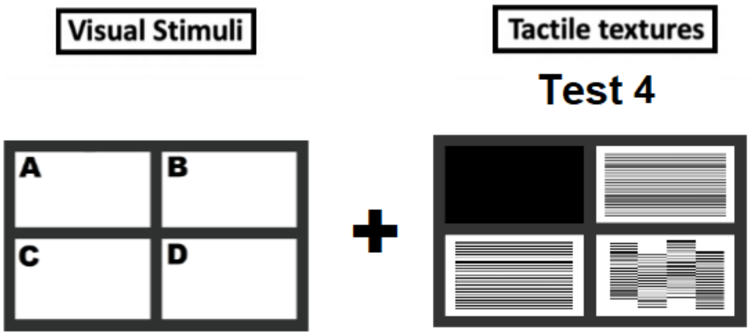

Figure 4.12: Visual stimuli and tactile texture for Test 4. Partially adapted from [16].

Test 5: The correspondent combination of visual stimuli and haptic tiles texture is presented in the following Figure 4.13:

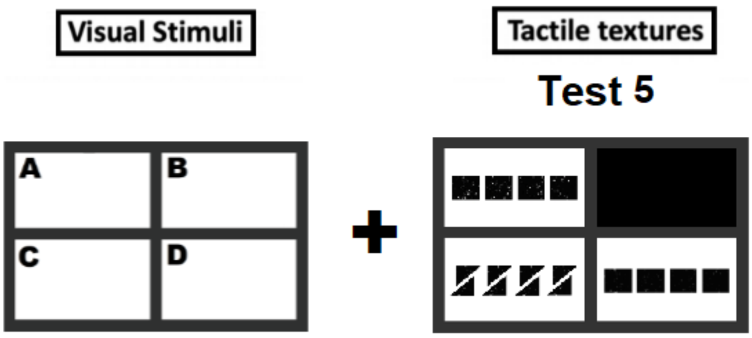

Figure 4.13: Visual stimuli and tactile texture for Test 5. Partially adapted from [16].

Appendix I gives a final general overview of all five experiments considered in this set of blind tests, including both visual stimuli and haptic texture for each test. This schema was partially adapted from [16].

It is now more clear which are the correspondences between physical textures from objects and tactile textures reproduced on the electroadhesion-based haptic device, along with which are the represented haptic textures on canvasses A to D for each test. Appendix I facilitates the introduction of section 4.4 concerning the analysis of results related to blind test 2.0 that will be presented shortly.

4.3.3 Feedback Survey

With the suggestions and improvements from blind test 1.0, it was possible to create a more adequate UX feedback survey answered by volunteers during their blind test 2.0 performance. The questions of this survey are presented at the end of this document on Appendix II and are core for the Results Analysis section that will be presented next.

Finally, after delineating all these procedures and introducing the feedback survey, it is now time to move to the analysis of results, where the described experiment is examined along with the obtained results.

4.4 Results Analysis

This section focuses on a detailed analysis concerning the volunteers' answers to the feedback survey (see Appendix II) during their performance on the five tests of blind tests final version - blind test 2.0.

Each test will be analyzed separately in the following sections for a more adequate understanding of the obtained results.

4.4.1 Test 1

Test 1 was designed to understand how a standard user would match the physical textures of the objects displayed on the table with the correspondent set of virtual textures reproduced on the touchscreen.

This test allows identifying which textures are the easiest and the hardest to identify when reproduced on haptic electroadhesion-based equipment.

For better analysis of the results, it is important to notice Table 1, where the correct correspondence between virtual and physical textures is displayed:

Table 1: Correct correspondences between virtual and physical textures for Test 1.

Virtual texture	→	Physical texture
Canvas A	→	cardboard
Canvas B	→	tiles
Canvas C	→	phone case
Canvas D	→	cork

After the introduction of Table 1, it is now adequate to introduce the answers given by users when asked to establish a correspondence between physical textures of the objects and the virtual textures experienced on the haptic device. The volunteers answered as follows in Figure 4.14:

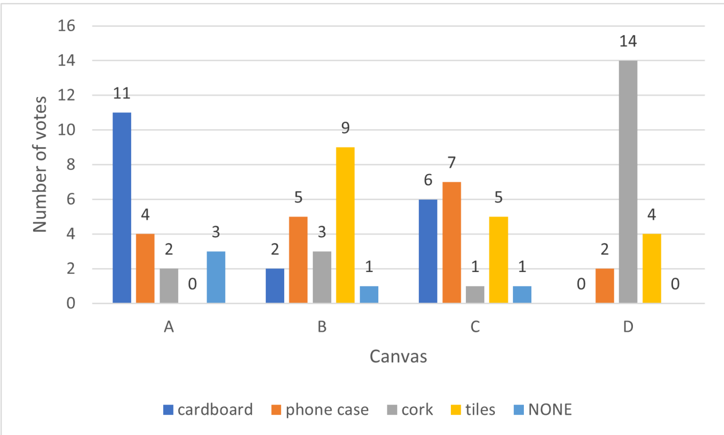

Figure 4.14: Correspondence between physical and virtual textures for Test 1.

Table 2 presents the same results from Figure 4.14 under percentage, for a better understanding of the distribution of participants votes:

Table 2: Percentage of correct correspondences between virtual and physical textures for Test 1.

	Cardboard	Phone case	Cork	Tiles	NONE
Canvas A	**55%**	20%	10%	0%	15%
Canvas B	10%	25%	15%	**45%**	5%
Canvas C	30%	**35%**	5%	25%	5%
Canvas D	0%	10%	**70%**	20%	0%

It is noticeable that most volunteers correctly established the correspondences between physical and virtual textures. The texture with more correct correspondences was the cork one, followed by the cardboard. The texture that users experienced more difficulties identifying was the phone case texture. Despite the majority of volunteers voting for the correct correspondence for the phone case texture, the second and third options are very close to the first one, which is translated in an unclear perception of this texture by most of the volunteers.

Even though the texture with more correct correspondences was the cork one, the texture that volunteers mention to be the easiest to identify was the cardboard one, as shown in Figure 4.15:

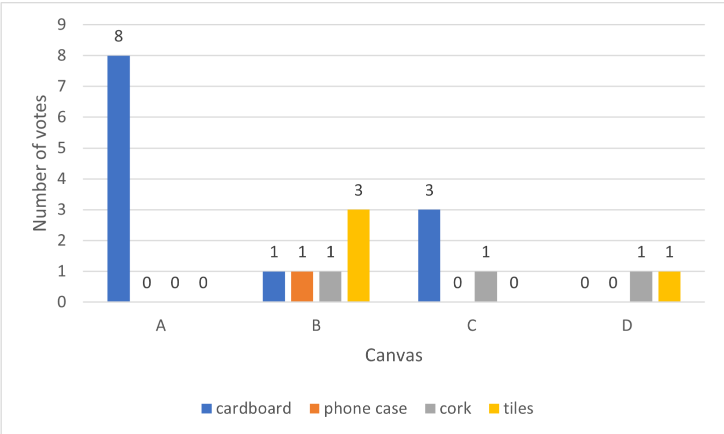

Figure 4.15: Easiest physical-virtual texture correspondence according to volunteers (Test 1).

Having all the previous results presented, it is clear that more uniform textures like cork, are the ones that users can identify with more precision. Textures that have a regular pattern like the cardboard texture, are the easiest to identify since their uniform structure is more recognizable than non-regular ones like the phone case texture, which is the one that most users struggled to identify. About the texture of the tiles, it was not possible to infer any type of conclusions in this test, since users were able to identify this texture relatively well, contributing to satisfactory average performance.

Finally, when asked if any of the physical textures had no correspondence on the haptic touchscreen two users identified the cardboard texture, the other two identified the tiles texture and one person identified the phone case texture, which may translate some design deficiencies on this textures reported by the volunteers.

4.4.2 Test 2

From Test 2 on, the main goal was to understand which virtual texture would volunteers select as the most adequate one to represent the physical texture of a certain object presented on the table and how they would describe the remaining virtual textures that they did not select.

After interacting with each canvas (A to D) of the previous combination of visual stimuli and tactile texture, volunteers elected the texture that they thought was being represented on the touchscreen as follows in Figure 4.16:

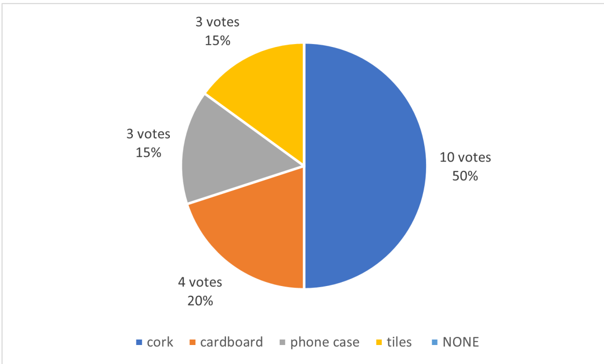

Figure 4.16: Volunteers' perception of the virtual texture displayed on the touchscreen for Test 2.

According to Figure 4.16, half of the volunteers (10 individuals) correctly identified the texture represented on screen, which was cork.

Next, as reported in Figure 4.17, volunteers were asked which virtual texture on the available canvasses (A, B, C, D, or NONE of them) better represented the physical texture of the object that was being reproduced in Figure 4.17:

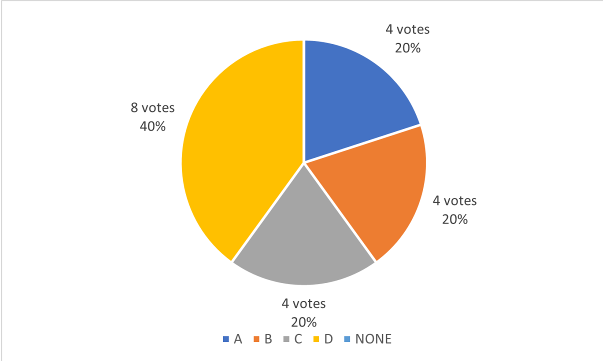

Figure 4.17: Volunteers' perception about the canvas that better represented the physical texture for Test 2.

The most voted answer was canvas D with 40% of the votes (8 individuals out of 20), which corresponds to the sharp filter version of the cork texture.

Finally, users were asked to order by magnitude the intensity of each canvas A to D. The obtained results are displayed in Figure 4.18:

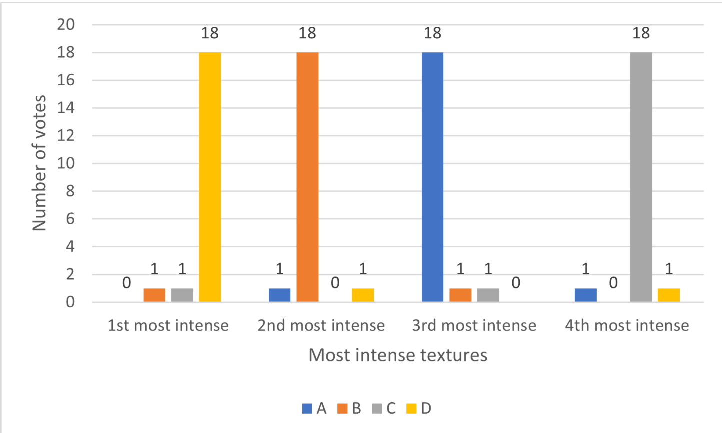

Figure 4.18: Canvasses sorted by textures' intensity according to volunteers in Test 2.

From Figure 4.18, it is clear that users were able to identify without problem the order of intensity of each texture, from the most intense to the less intense. This means that a variation of texture intensity in uniform textures is greatly perceived by users.

Analyzing all previous results, it is noticeable that the cork texture was easy to identify by the volunteers.

When it comes to the election of the most adequate haptic texture to virtually describe the physical cork texture, the most voted option was the sharp version of cork texture, which corresponds to canvas D.

Furthermore, in the open question about the virtual haptic textures, the majority of volunteers were able to notice a variation of intensity between textures and successfully established comparisons between them, according to their intensity.

The main adjectives to describe these textures were ’rough’ and ’harsh’.

About canvas B, 1 person was able to identify the discontinuity brought by the mismatched version of the texture on that canvas.

Canvas C was generically recognized by the volunteers to be smooth. Other individuals considered that this canvas’ texture was not noticeable or the texture did not even exist.

Finally, canvas D was frequently considered to be the most intense and partly the one where the texture was more exaggerated.

4.4.3 Test 3

Similar to Test 2, this third test had the same goals: to understand which virtual texture was the best to represent its correspondent physical texture. This time, the virtual texture that was being represented on the haptic touchscreen was the phone case.

For this third test, the volunteers of the experiment identified with 55% of the votes (11 people out of 20), the correct physical texture that was being displayed on the haptic touchscreen, as indicated in Figure 4.19:

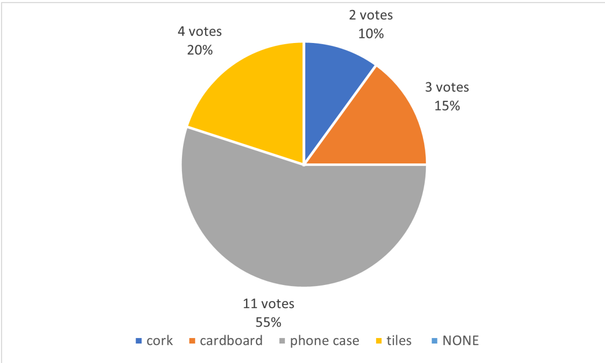

Figure 4.19: Volunteers’ perception of the virtual texture displayed on the touchscreen for Test 3.

When it comes to deciding which of the canvasses better represented the physical texture from the object, volunteers did not find a consensus, and canvas A (mismatched image), B (sharp filter), and D (no texture) are tied at first place with 30% (6 individuals out 20) of the votes each, as Figure 4.20 presents:

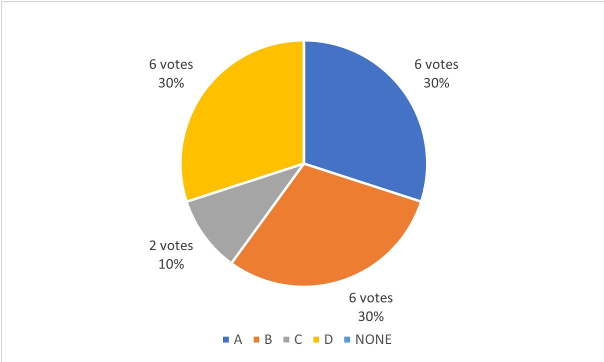

Figure 4.20: Volunteers' perception about the canvas that better represented the physical texture for Test 3.

The previous result can be partially understood as this virtual texture is particularly irregular and unusual, making the selection of one of the four canvasses especially difficult and doubtful.

Regarding the virtual textures' intensities sorting, the volunteers suggested the distribution presented in Figure 4.21:

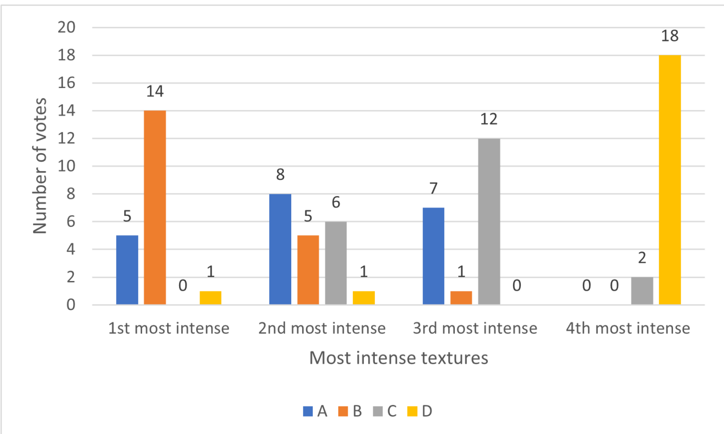

Figure 4.21: Canvasses sorted by textures' intensity according to volunteers in Test 3.

Users were particularly in doubt when it comes to the second most intense texture, as Figure 4.21 points out.

Lastly, when it comes to the open question about the representation of textures on the haptic Tanvas device, the audience successfully established different comparisons between the virtual textures.

Canvas A, B, and C are extremely similar in terms of texture.

Adding to that, one person mentions a more accentuated vertical texture on canvas A, another person refers that canvas B has too much texture and canvas C too little.

Another person reports that the spacing between the wholes of the texture is smaller in canvas A, which is coherent with the fact that this canvas corresponds to the mismatched version of the original image.

Once again canvas D was considered as a no-texture canvas.

4.4.4 Test 4

Just like the previous two tests, test 4 had the same purposes. About the perception of volunteers about the virtual texture represented on this test, the results of the survey are shown in Figure 4.22:

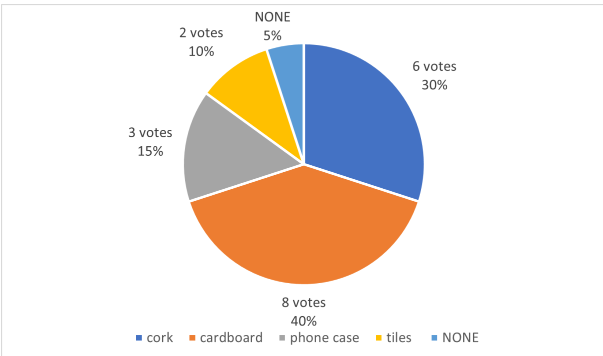

Figure 4.22: Volunteers' perception of the virtual texture displayed on the touchscreen for Test 4.

According to previous Figure 4.22, it is noticeable that 40% (8 individuals out of 20) of users identified correctly the cardboard texture, which is the correct answer. Nevertheless, a remaining 30% of users (6 individuals out of 20) considered that the represented texture was cork.

After this, volunteers were asked which of the canvasses A, B, C, D (or NONE of them), better represented the physical texture during this test. Figure 4.23 presents the obtained results:

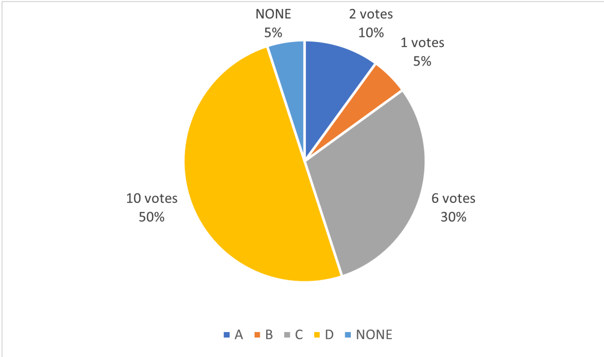

Figure 4.23: Volunteers' perception about the canvas that better represented the physical texture for Test 4.

It is visible in Figure 4.23 that 50% of the audience (10 people out of 20) mentioned that the most adequate texture was being reproduced on canvas D, which corresponds to the mismatched version of the original cardboard texture.

Finally, in what concerns to textures' intensity on this test, volunteers answered as depicted in Figure 4.24:

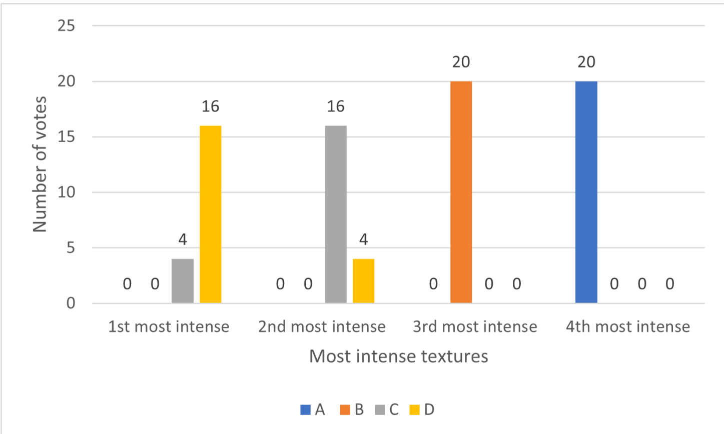

Figure 4.24: Canvasses sorted by textures' intensity according to volunteers in Test 4.

The majority of volunteers (16 out of 20 volunteers, 80% of volunteers), considered that texture from canvas D (mismatched version of original texture) was more intense than texture from canvas C (sharp filtered texture).

The truth is that, contrary to volunteers' opinion, the sharp filtered texture from canvas C is, in fact, more intense than the one from canvas D, since it reinforces the edges from the original cardboard texture. Meanwhile, the mismatched version only consists of a distortion of the image with vertical cuts, maintaining the texture's intensity.

This phenomenon might be explained by the vertical cleavage of the mismatched texture of canvas D, which persuades the user to feel more discontinuities on it, and so, to have the illusion of a more intense texture when compared with the one from canvas C.

When it comes to the third and fourth most intense textures, volunteers were certain, with 100% of the votes (20 individuals in total), that the blurred version of the texture on canvas B was more intense than the one from canvas A, which did not have any texture at all.

When it comes to the open question about the virtual textures, volunteers generically mentioned that canvas D was more intense than canvas C, even though their similitude is big.

Many people used the word 'curvy' to describe the textures from this test.

Besides this, two people refer that texture from canvas B does not have horizontal texture, only a vertical one. One person mentions that all textures are very similar between themselves. Finally, one person says texture from canvas D is overdone and texture from canvas B is softer but perceptible.

Once again, canvas A was identified as a flat or non-existent texture with one person referring that in canvas A the texture seems to be turned off.

Finally, canvas B is frequently mentioned as a softer texture than canvasses C and D.

4.4.5 Test 5

Like the previous tests 2 to 4, test 5 has the same purposes, with the difference that this time, the physical texture that is being represented is the texture of the tiles.

The distribution of the answers when it comes to answering which virtual texture was being displayed on the touchscreen goes, is presented to Figure 4.25, like:

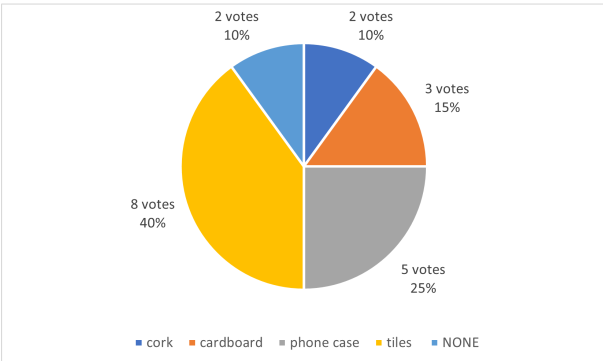

Figure 4.25: Volunteers' perception of the virtual texture displayed on the touchscreen for Test 5.

Figure 4.25 reflects that 8 out of 20 volunteers (40% of votes) considered that the represented texture on the electroadhesion-based haptic equipment was the tiles, followed by the phone case texture that was voted by 5 out of 20 individuals (25% of votes).

The volunteers' impression about the most adequate virtual texture to represent the correspondent physical texture is represented in Figure 4.26:

In Figure 4.26 it is noticeable that 40% of the volunteers (8 out 20 participants in total)

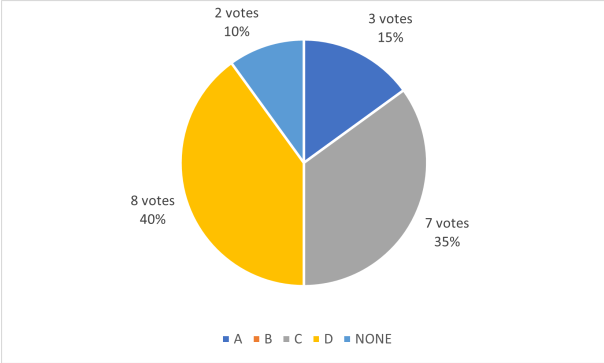

Figure 4.26: Volunteers' perception about the canvas that better represented the physical texture for Test 5.

considered canvas A, which corresponds to the smoothed filtered version of the original texture, as the most adequate one to represent the chosen physical texture.

The second most voted option was canvas C, with 7 out of 20 votes (35%) and only one of difference from canvas A, where it is represented the mismatched version of the original texture of the tiles.

Having this in mind, one can observe a very short difference of votes (only one vote of difference) between both these textures from canvasses C and D, where canvas C corresponds to the mismatched version of tiles' virtual texture.

About the textures' intensity sorting, volunteers considered the following order as visible in Figure 4.27:

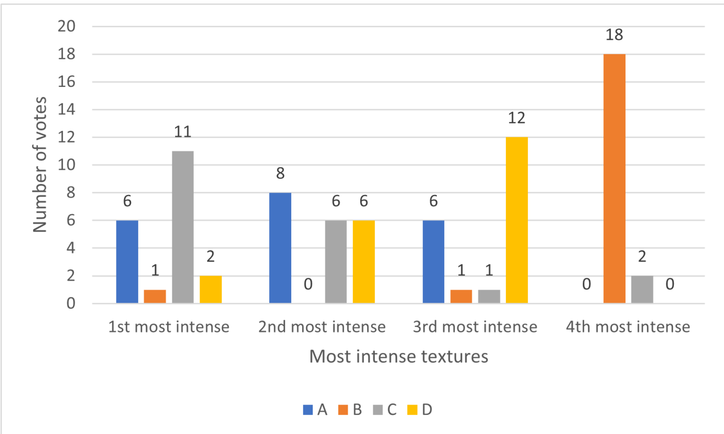

Figure 4.27: Canvasses sorted by textures' intensity according to volunteers in Test 5.

Along with test 4, the results obtained with test 5 are very similar, since the texture that was considered to be the most intense was the mismatched version of the original image (canvas C), followed by the sharp filtered version of that image (canvas A), then the blurred filtered version of it (canvas D) and finally the no-texture, which corresponds this time to canvas B.

The repetition of this event along with the one already observed in test 4, reinforces the idea that the discontinuities brought by the mismatched version of the original textures work as an intensity incremented effect of textures on the user's perception, even though the sharp filtered version has more intensity than the mismatched version of that same texture.

Finally, When it comes to the open question about volunteers' experience related to virtual textures, the participants of this experiment established multiple comparisons between virtual textures, especially between the ones from canvasses A, C, and D, that was considered very similar to each other.

About canvas A, 2 individuals considered the texture in this canvas to be very rough, having a high screen' resistance offered to finger sliding.

Canvas B was considered a flat surface without texture.

In canvas C, one person considered this texture to be too granular when compared with the remaining textures.

Overall, the participants were able to identify with precision which virtual textures corresponded to sharp and blurred versions of the original virtual texture.

Besides that, one person stated to detect the tiles of the virtual texture throughout the exploration of textures' form, and to finish with, 1 person stated that was not able to do a good evaluation of the textures of the present test, which influences the results and reinforces the need of design improvement of textures.

4.5 Conclusions

Just before the end of the survey (see Appendix II) that volunteers answered during the experiment, participants of the blind tests were inquired which of the tests (excluding test 1), was easier to identify the physical texture that was being reproduced on the haptic touchscreen. Figure 4.28 presents the obtained responses:

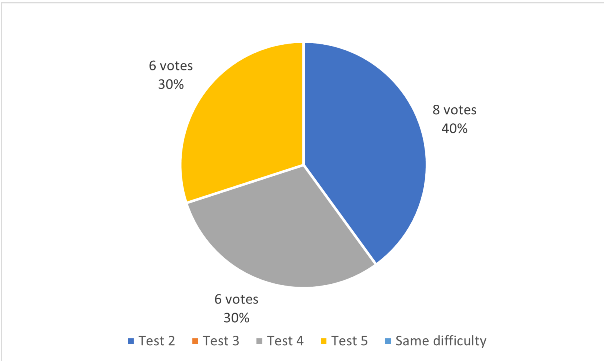

Figure 4.28: Responses of the volunteers when questioned about which test was easier to identify the virtual texture on the touchscreen.

The most popular answer was test 2, which corresponds to cork virtual texture, with a total of 8 of the 20 votes (40%). With 6 of the 20 votes (30%) each, both tests 4 (cardboard texture) and 5 (tiles texture) occupy the second position.

Based on the previous distribution of volunteers' votes, one of the conclusions reached with this experiment is that users tend to find it easier to recognize virtual textures that have a uniform pattern (like cork) or a regular texture, like cardboard or tiles textures, that occupy the second positions with more votes. The phone case texture that has an irregular and aleatory pattern was not even considered by a single volunteer on the answer to this question.

The second final question was designed to understand if any of the virtual textures from tests 2 to 5, was especially easy to recognize from the remaining tests. Figure 4.29 shows that the results were the following:

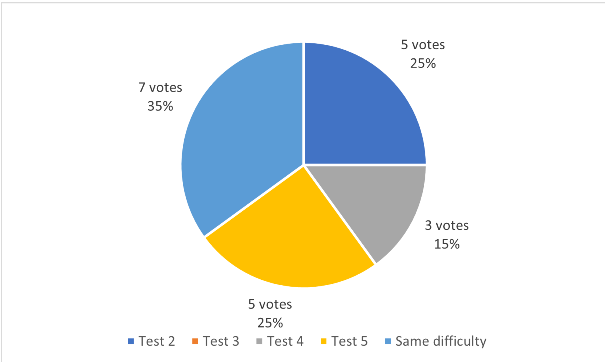

Figure 4.29: Responses of the volunteers when inquired about which of the tests was more difficult to describe the textures.

The majority of the volunteers, 7 out of 20 (35%), answered that they experienced the same difficulty performing this task in all tests from tests 2 to 5. As so, no conclusions were reached based on the answers to this specific question.

Besides that, one of the most recurrent opinions on the survey refers that the reproduction of textures on a haptic touchscreen works better when these textures are more elementary. Moreover, some of the best characteristics that help to recognize textures are their patterns regularity and texture' roughness. The more roughness the texture has, the more ability the user has to recognize it. As so, if the texture is more complex and detailed, it is harder to recognize and the lack of ability to reproduce fine details makes it difficult to distinguish textures that are very similar to each other. Nevertheless, it is possible to distinguish different textures and give the idea of a specific one with this haptic equipment, but its reproduction on the screen is not very realistic yet.

Adding to the previous conclusions, another conclusion of this survey is certainly that uniform and regular textures, respectively, cork and cardboard textures, are the ones able to have a better virtual representation on haptic electroadhesion-based TT equipment, just like TT. Test 1 demonstrated this very well.

Another relevant conclusion is that users can identify virtual textures better throughout relative comparison between each other, since the amount of votes for correct correspondences is, in most cases, much higher in test 1 than the isolated votes on correct correspondences from any of the remaining tests, as Table 3 demonstrates:

Table 3: Comparison of volunteers' votes between test 1 and the remaining tests.

Virtual texture	**Test 1** (votes)		**Other tests** (votes)	**Votes variation (%)**
Cork	14 (Test 1)	vs.	10 (Test 2)	↓20%
Phone case	7 (Test 1)	vs.	11 (Test 3)	↑20%
Cardboard	11 (Test 1)	vs.	8 (Test 4)	↓15%
Tiles	9 (Test 1)	vs.	8 (Test 5)	↓5%

It is visible in the previous Table 3 that most of the virtual textures have a negative variation in the number of votes from test 1 to the remaining tests.

All textures obtained a higher amount of votes during the first test (with exception of phone case texture), where all virtual textures were reproduced at the same time, then the votes were obtained individually during the remaining tests, where there was a single texture displayed at each time.

Besides the technology itself, other subjective factors significantly influence the user's experience and its perception of virtual textures. In the survey, three people referred that fingers humidity and temperature, along with its natural sweating, can affect user's perception of reproduced textures on haptic devices; two individuals mentioned that adding images (the visual component) to haptic textures plays a decisive role when it comes to corresponding virtual textures to the respectively physical textures of a certain object; one person refers that user's ability to recognize virtual textures on electroadhesion-based haptic technology is improved with practice from test to test.

When it comes to participants' feedback about textures design, it turned clear that there is a lot still to improve by perfecting specific textures, or even the technology itself. Volunteers mentioned that the cork texture requires improved details to be recognized more easily. Besides that, in the opinion of a participant, the cardboard texture was a little difficult to recognize once the interior of the cardboard box only had a vertical texture and during the blind tests it was perceptible to have both vertical and horizontal textures. About the phone case texture, the main reason for participants' difficulty was related to its irregular pattern. Finally, what concerns the texture of the tiles, the texture's relief needs to be improved to be better perceived by regular users.

Adding to the previous conclusions, it is clear that volunteers were able to notice with ease different textures' intensity. Nevertheless, volunteers considered twice during the tests that the mismatched version of the image had more texture intensity than the sharp version of that same image, which points out that the recognition of textures' intensity can still be a little bit tricky at times.

Furthermore, it was not possible to notice any type of volunteer preference by one of the texture variations during tests 2 to 5 (blurred, sharp, mismatched, and no-texture version of the original texture), since the most voted answer in each of these tests was always different.

To conclude, even though it is a consensus that this technology has enormous potential, it is frequently mentioned by users that is still a bit limited, since the sensibility of the human finger has not been enough explored yet. Nevertheless, participants showed to be extremely curious and interested in this type of haptic technology and mentioned its vast potential in many different areas of application.

Overall, it is possible to recognize simple, regular, and homogeneous textures using TT haptic equipment, but there are still several open challenges regarding the exploration of this technology and its relationship with human touch and sensibility.

5 Conclusions and Future Work

Haptic technologies have been growing considerably in recent years compared to the past, being progressively adopted in many different areas, with a special focus on consumer electronics. This type of technology focused on human sensitivity to haptic stimuli substantially extends the known capabilities of standard touchscreens, presenting novel opportunities for the implementation of new features and functionalities, and a more immersive UX. As seen, there are many different areas where this technology can be applied to and the opportunity for designing new innovative solutions based on haptic technology is vast. Taking this into account, let's now take a look at the goals initially purposed in the first chapter of this thesis.

Regarding the objectives defined in the beginning of this academic work, it is adequate to say they were successfully satisfied. A deep analysis of the state of the art on haptic technology displays was done, with a special focus on electroadhesion-based haptic touchscreens, contributing to a general overview of this haptic technology field. Based on this revision of literature it was possible to design different UX tests and UCs, contributing to an increment of available TT applications for this field, where there are still not many.

The UX results obtained in the blind tests showed that this technology is very promising and arouses great interest in the users. The conducted tests demonstrated that TT can reproduce well simple and regular textures. Nevertheless, this electroadhesion-based haptic device still has a considerable opportunity for technological improvement, since more complex textures are not that much perceptible by the users. The device is possibly missing a little bit more texture resolution to allow the creation of more demanding textures in terms of detail. For the future, it would be interesting to explore a hybrid technology that would combine both vibrotactile stimuli with electroadhesion haptics, since user's interaction on TT displays are friction-based only, which means that it is not possible to reproduce any haptic stimuli based on vibration and other interesting features, like vibrotactile push buttons, for example.

Besides that, different challenges were faced during the creation process of the haptic applications in this thesis: the technology is relatively new, which means there are still not many available examples to use as guidelines and there is no online support community for the development of haptic solutions based on TT technology. More documentation and code examples would be an advantage too.

What concerns the developed UCs, several conclusions can be mentioned. Starting with UC 2, which is the haptic eBook application, this UC presents a new relevant electroadhesion-based haptic example that adds haptics to traditional eBooks displays, which has not been explored until now. Even though this is still an embryonic haptic solution, this application casts the fundamental pillars for possible future work related to haptic eBooks. What is more, it drives the interest of this technology to the design of more complex applications, that can benefit from the work developed in this UC. Also, it can take advantage of the conclusions of the blind tests reached with this thesis, which can be particularly helpful for the design of a better UX that can be easily applied to this kind of application. Overall, this application points out new innovative solutions that have a huge potential to support vision-impaired individuals but also other possible impairments, like deafness-related disabilities, to have a more immersive reading experience based on touch, and calling attention to social awareness issues related to this type of disabilities, opening new possibilities for future work.

Regarding UC 1, the bookshelf haptic application was conceived as an introductory demo to this technology, presenting different possible textures that can be reproduced with a TT device, which means that its contribution to the haptic-related field is not very relevant, since its content is purely demonstrative of haptic feedback patterns and textures that can be experienced on this device. Nevertheless, it is useful as an initial introduction to haptic technology for first-time users.

What concerns to possible future work, this thesis showed that there is still a considerable opportunity to improve the design of textures along with the possibility to improve the technology itself, allowing users to experience more complex and realistic textures. The haptic eBook can also be further developed and incorporate solutions for improved experience to better support visually impaired users, between other possible disabilities. The developed blind tests can be complemented with extra layers of complexity to further extend the amount of other possible conclusions that can be obtained from this kind of research in haptic UX. This haptic technology has a vast potential on a growing market in the next upcoming years, not only concerning the field of tactile displays, but also the future of the technology itself.

Finally, taking into account the bigger picture of this academic work, it is important to highlight that this thesis was able to give a wide perspective of the state of the art haptic technology, with a special focus on electroadhesion-based haptics, along with the development of different UCs and tests, with associated detailed analysis, that will allow creating better UX in the future work on this field.

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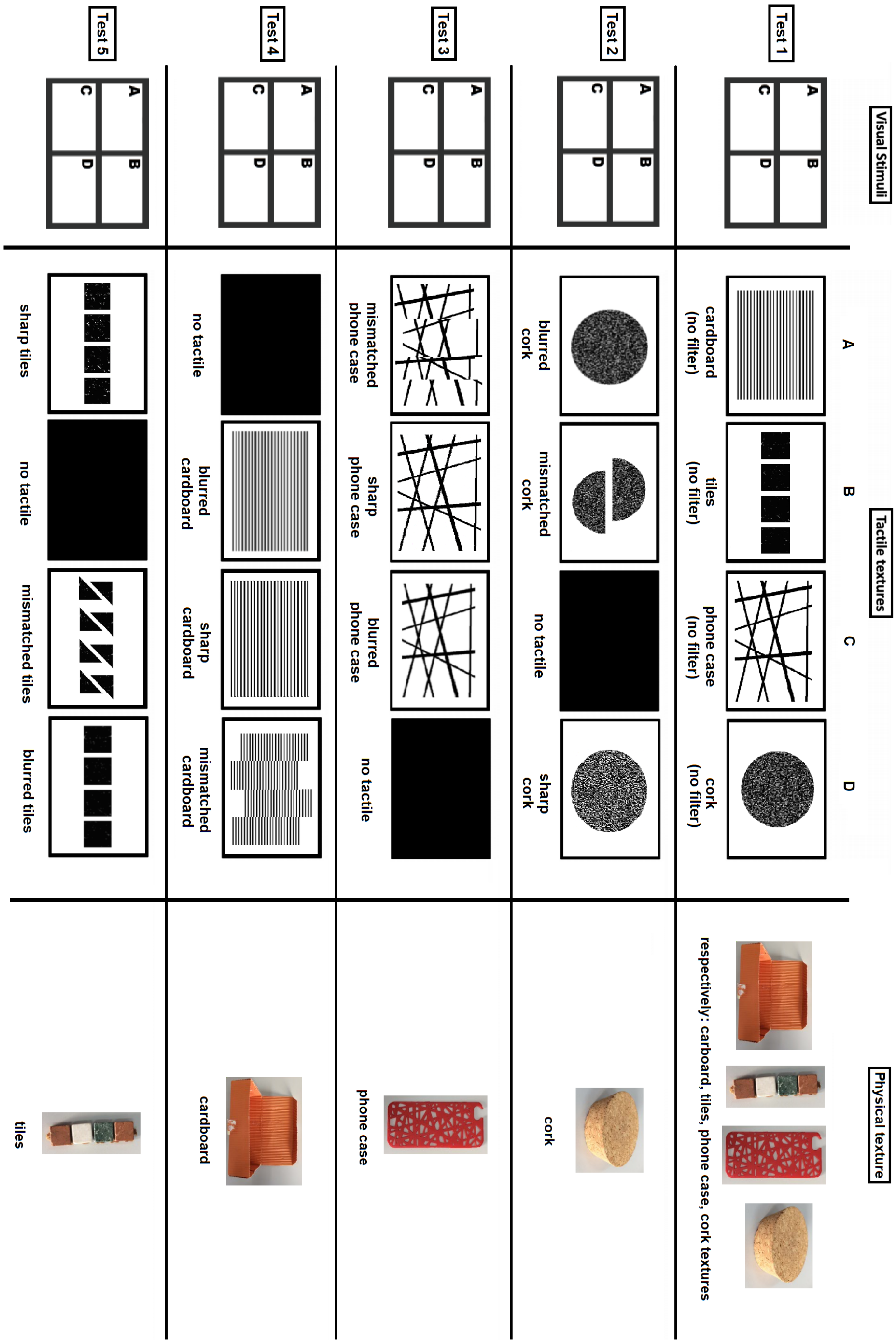
Appendices

I Textures Overview for blind test 2.0



II Feedback Survey

TEST 1

T1Q1 Establish the correspondence between each canvas and the textures from the objects:

	Cardboard	Phone case	Cork	Tiles	NONE
Canvas A					
Canvas B					
Canvas C					
Canvas D					

T1Q2 Which of the correspondences was the easiest to identify? Select only one.

	Cardboard	Phone case	Cork	Tiles
Canvas A				
Canvas B				
Canvas C				
Canvas D				

T1Q3.1 Were there any objects without correspondence? (Yes/No).
T1Q3.2 (OPTIONAL) If yes, please identify the object.

TEST 2

T2Q1 Which of the textures from the presented objects is being represented on the haptic touchscreen? ('NONE' is a valid answer)
T2Q2.1 Which of the canvasses (A, B, C or D) better represents the texture from that object? ('NONE' is a valid answer)
T2Q2.2 How would you describe the texture of the remaining canvasses? This is an open question.
T2Q3 Please order the canvasses according to their texture intensity:

	Canvas A	Canvas B	Canvas C	Canvas D
1st most intense				
2nd most intense				
3rd most intense				
4th most intense				

TEST 3

T3Q1 Which of the textures from the presented objects is being represented on the haptic touchscreen? ('NONE' is a valid answer)
T3Q2.1 Which of the canvasses (A, B, C or D) better represents the texture from that object? ('NONE' is a valid answer)
T3Q2.2 How would you describe the texture of the remaining canvasses? This is an open question.
T3Q3 Please order the canvasses according to their texture intensity:

	Canvas A	Canvas B	Canvas C	Canvas D
1st most intense				
2nd most intense				
3rd most intense				
4th most intense				

TEST 4

T4Q1 Which of the textures from the presented objects is being represented on the haptic touchscreen? ('NONE' is a valid answer).
T4Q2.1 Which of the canvasses (A, B, C or D) better represents the texture from that object? ('NONE' is a valid answer).

T4Q2.2 How would you describe the texture of the remaining canvasses? This is an open question.
T4Q3 Please order the canvasses according to their texture intensity:

	Canvas A	Canvas B	Canvas C	Canvas D
1st most intense				
2nd most intense				
3rd most intense				
4th most intense				

TEST 5
T5Q1 Which of the textures from the presented objects is being represented on the haptic touchscreen? ('NONE' is a valid answer)
T5Q2.1 Which of the canvasses (A, B, C or D) better represents the texture from that object? ('NONE' is a valid answer)
T5Q2.2 How would you describe the texture of the remaining canvasses? This is an open question.
T5Q3 Please order the canvasses according to their texture intensity:

	Canvas A	Canvas B	Canvas C	Canvas D
1st most intense				
2nd most intense				
3rd most intense				
4th most intense				

FINAL QUESTIONS
FQ1 Which of the canvasses (A, B, C or D) was easier to identify the object's texture? ('Same difficulty' is a valid answer).
FQ2 Which of the canvasses (A, B, C or D) was easier to describe the object's texture? ('Same difficulty' is a valid answer).
FQ3 (OPTIONAL) Feel free to add any other comments to this experiment.