Haptikós

A Design Toolkit for Dynamic Vibrotactile Interfaces

Elio Raineri

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" When something exceeds your ability to understand
how it works, it sort of becomes magical. "

— Jonathan Ive, 2010

Abstract

ENG

Before the advent of digital technologies, multisensory perception enriched the way we interacted with objects. Nowadays, with the adoption of screen-based devices, people can access information and perform the majority of their actions through finely crafted graphical user interfaces which mainly rely on visual and auditory prompts, leaving behind precious tactile data we used to perceive in the past. As of now, just a few are the devices that integrate haptics as a primary communication channel, and the experience of using these is considered by users as different and somehow magical. If so, why then haptic applications are limited?, and given the visual and auditory overload of current interfaces, how can haptic technology be used to improve Human Computer Interaction?

This thesis explores the field of haptics in his entirety in order to understand the limitations and gaps that prevent companies and designers from leveraging such communication channel in their digital products and interfaces. Starting from these insights, it develops a design solution aimed at bringing designers closer to haptics.

The following study starts with a general investigation on human haptic perception from a physiological and psychological perspective. Then it traces back the history of haptic human-machine interaction, and, through a systematic literature review and an analysis of case studies, it explores the benefits of this sensory channel within HCI. The second part of the research focuses on dynamic vibrotactile interactions for sensory augmentation, by exploring vibration's properties and the current state-of-the-art in the design discipline through desk and field research.

What has been discovered throughout the research will be then exploited to create a design toolkit aimed at providing designers with the basic knowledge about haptics and supporting them during their entire design process to include haptic interactions in their products and interfaces. The effectiveness of the toolkit has then been evaluated through user testings.

The knowledge produced in this work can be considered as a foundation for designers looking into designing novel and unique tactile rich interactions.

ITA

Prima dell'avvento delle tecnologie digitali, la percezione multisensoriale arricchiva il nostro modo di interagire con gli oggetti. Oggi, con l'adozione dei dispositivi basati su schermi, le persone possono accedere alle informazioni e svolgere la maggior parte delle loro azioni attraverso interfacce GUI attentamente progettate basate principalmente su segnali visivi e uditivi, lasciando indietro preziose informazioni tattili. Al momento, sono pochi i dispositivi che integrano l'aspetto tattile come canale primario di comunicazione, e l'esperienza di utilizzo di questi dispositivi è considerata dagli utenti come diversa e in qualche modo “magica”. Se è così, perché le applicazioni di dispositivi tattili sono limitate? E, dato il sovraccarico visivo e uditivo delle attuali interfacce, come possono tali tecnologie essere utilizzate per migliorare l'interazione uomo-computer?

Questa tesi esplora l'intero campo della comunicazione aptica al fine di comprendere le limitazioni e le lacune che impediscono alle aziende e ai designer di sfruttare tale canale di comunicazione nei loro prodotti digitali e nelle interfacce. Partendo da queste considerazioni, si sviluppa una soluzione di progettazione mirata a avvicinare i progettisti alle tecnologie aptiche.

Lo studio inizia con un'indagine generale sulla percezione tattile umana da una prospettiva fisiologica e psicologica. Successivamente, ripercorre la storia dell'interazione tattile uomo-macchina e, attraverso una revisione sistematica della letteratura e un'analisi di casi studio, esplora i vantaggi di questo senso nell e interazioni uomo-computer. La seconda parte della ricerca si concentra sulle interazioni vibrotattili dinamiche per un arricchimento sensoriale, esplorando le proprietà delle vibrazioni e lo stato dell'arte attuale nella disciplina del design attraverso una ricerca teorica e sul campo.

Ciò che è emerso dalla ricerca sarà poi sfruttato per creare un toolkit volto a fornire ai progettisti le conoscenze di base sull'haptic design e a sostenerli durante l'intero processo di progettazione al fine di includere interazioni aptiche nei loro prodotti e interfacce. L'efficacia del toolkit è stata quindi valutata attraverso test condotti sugli utenti.

Le conoscenze prodotte in questo lavoro possono essere considerate come una base per i designer coinvolti nella creazione di nuovi tipi di interazioni tattili.

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Intro

The importance of haptics

Since when I was a kid, my passion for digital devices and technology have filled my free time and shaped my life and the person I am, influencing the choices I've made in the academic and professional paths. With time, I've realised that what really intrigued me wasn't just how these innovative objects worked from an engineering perspective. It was how, as every technological advancement, they empowered people, including those around me, to do things they couldn't do otherwise. I was fascinated by how simple interactions between humans and technology could unlock a whole new level of human potential.

This passion drove me to constantly seek new knowledge, to experiment, and to be at the forefront of using the latest innovative solutions and technological advancements, so that I reached a point where merely being an observer was no longer satisfying — I felt a strong desire to become an active participant and contribute as one of the protagonists of human-computer-interaction. By immersing myself in the field of design, I've had the chance to unlock this need. It has provided me with the know-how and sensitivity to create experiences that truly matter, capable of influencing, changing, simplifying, and empowering the lives of users.
Throughout my journey as an Interior Designer during my bachelor's degree, an Interaction Designer in my Master's program, and now as a professional, I have constantly pushed the boundaries and experimented with innovative ways of interacting with spaces, devices, and content, incorporating the use of digital technologies. From creating immersive museum experiences to designing inclusive and accessible products for the elderly, or VR applications for educational purposes, I have had the privilege to work with and explore various sensory modalities. Embarking on this thesis has provided me with a unique opportunity to take a step back and reflect on what truly captivates me about Human-Computer Interaction.

Being born in the late 90s, I grew up in the middle of the information technology revolution and I quickly saw the world moving from analog devices (VHS, Walkman, Polaroid, CRT TV), to more and more digitalised solutions (Game Boy, Smartphones, Wearables, IoT).

With this transition, a multitude of physical actions needed to interact with the old systems, like choosing a VHS from the shelf, removing it from its case and inserting it into the video recorder, and then clicking play with the physical remote; have been replaced with digital - and sometimes automated - interaction. What used to be a fully immersive sensory experience has now transformed into effortless interactions mediated through touchscreens, like opening the Netflix app, searching the right movie in a search bar, and tapping on the play button. I'm not saying that we should bring back "the old good technologies", or simulate the complex interactions they required (new technologies solve great challenges and fulfill people's needs); but I've always loved the way devices felt in my hands and how they responded to my actions.
From swiping on the simple and well designed click wheel of the original iPod, to the satisfying feeling of inserting the cartridge of the brand new Pokémon game on my old Game Boy Color, these habitual and sometimes repetitive actions, along with their tangible feedback, added a remarkable sense of physicality to the overall experience.

To be honest, it's not that physical experiences have been completely lost, but when we consider the majority of products and interfaces available on the market right now, their utilisation of such dimension is minimal. Products that integrate any kind of innovative multisensory interaction modalities feel like magic, creating a deeper connection between users and the device. **(Brownlee, 2020)**

At the beginning of this thesis, I reflected on why applications with haptic feedback, which offer numerous benefits, are so limited. Additionally, I wondered why, as a designer, I had never been introduced to these concepts during my academic and professional journey. These arguments revealed to be more complex and broad than expected, and that is why I decided to embark on a journey through the world of haptics and haptic design, led by a specific research question: "**How can haptic technology be used to improve Human Computer Interaction?**"

The thesis is divided in three parts and chronologically presents the work of 9 months of research and design efforts.

In the **first part** of the research, I started by defining the term and delving into how humans perceive physical cues when interacting with objects and their environment, considering both physiological and psychological perspectives. I then delved into the history of haptic research and development, from its origins to its role in human-computer interaction (HCI), including the current state of the art. This phase aimed to provide me with a comprehensive understanding of haptic interfaces and haptic communication, laying the groundwork to address the main research question.

By the end of this first part, I was introduced to a wide range of topics within the field of haptics, each presenting its own set of challenges and opportunities. This sparked additional questions in my mind, such as "**Which use cases could benefit the most from haptic communication?**", "**Why is haptics often overlooked in digital design?**", and "**How can designers effectively incorporate haptic communication in digital interfaces, products, and virtual experiences?**"

Recognising the broad range of topics within the field of haptics, I felt the importance of narrowing my focus for the **second part** of the thesis. Thus, I directed my research efforts towards exploring the potential of dynamic vibrotactile feedback as a bidirectional means of human-computer interaction. Specifically, I aimed to investigate how designers could leverage this technology to incorporate a physical dimension into the interaction with their digital products and interfaces. This decision was driven by a careful evaluation of the opportunities and relevance that this specific area of haptics holds within the broader context of human-computer interaction (HCI). During this phase, I conducted a thorough analysis of vibration properties through desk research and also developed an application to test and explore these properties further. Additionally, I delved into haptic prototyping solutions and conducted research, surveys, and interviews to gain insights into the current state of haptics within the design discipline.

At the conclusion of the narrowed-down research on dynamic vibrotactile interfaces, it became evident that the reason the physical dimension is often overlooked in today's product interactions is due to designers' lack of awareness regarding the potential benefits of incorporating this sensory modality. Furthermore, there is a lack of guidance, best practices, and overall support for designing with haptics. To bridge this gap and empower designers, in the **third part**, I created a design toolkit that provides essential knowledge about vibrations and supports designers throughout the entire design process. This accessible toolkit includes a website, a booklet, templates and cards for activities, and a mobile application.

To assess the effectiveness of the toolkit, two user testing sessions were conducted. The first involved a facilitated workshop with a team of four participants, while the second consisted of a supervised individual session.

In closing, marking the end of the design phase and the entire thesis, a final reflection contemplates the results and the potential future directions.

Methodology

The Double Diamond

The design process of the thesis follows the model of the Double Diamond. This methodology was first introduced by the UK Design Council in 2004 and consists of a framework that clearly conveys a design process. The model is divided into four phases: discover, define, develop, and deliver. It involves a two-phased approach to problem-solving, first exploring an issue more widely or deeply through a divergent thinking approach, and then taking focused action through convergent thinking.

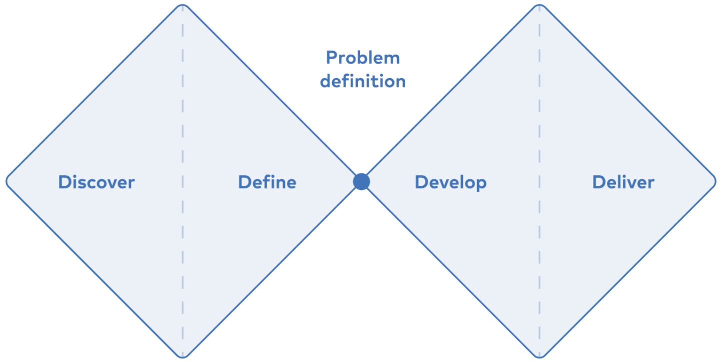


fig. 1 | Double Diamond - UK Design Council, 2004

The first phase of the Double Diamond is **Discovery**, which helps gather information, and insights from various sources such as papers and online articles to gain a deep understanding of the problem we are trying to solve. The objective of this phase is to identify the basics of haptic perception, the history of haptic R&D, and the role of touch in HCI. During the initial research, I had the opportunity to explore how humans sense tactile and kinaesthetic stimuli physiologically and how the brain translates these changes into meaningful information.

Next, I delved deeper into the history of haptic machines from the 17th century to the present day, including the birth of HCI. Finally, I explored how different experts in the field of human-computer interaction are using the tactile channel to improve HCI and enhance people's perception of digital things.

The **Define** stage aims to synthesise the collected information to identify a core problem and create a design brief that outlines the problem statements and goals to achieve. In this stage, I gathered the insights gained during the first phase and reflected on them to assimilate the most relevant problems and opportunities. The culmination of this phase was the formulation of an HMW (How Might We) question that guided the process of conceptualisation and design.

In the second diamond of the Double Diamond model, the focus is on gaining knowledge from secondary research that is more contextualised. Therefore, for the **Develop** stage, I decided to narrow the context to dynamic vibrotactile stimuli as a bi-directional Human Computer interface for sensory augmentation, and conducted secondary research accordingly. This research analysed the properties of vibrations (an app was developed to test them first hand) and how they can convey meaningful and immediate information through the use of metaphors.

To understand the designer's journey in prototyping dynamic vibrotactile stimuli, I conducted a benchmarking activity of haptic hardware (actuators and boards) and software solutions. Additionally, I carried out market analysis through surveys, expert interviews, and first-hand research to understand the designer's awareness of haptics and the state of the art in haptics and design. Lastly, I developed a concept aimed at bridging the knowledge gap between designers and the world of haptics.

The last phase of the Double Diamond model, **Deliver**, is where designers refine the best solution and produce a final product or service. This stage involves testing and iterating the solution to ensure it meets the needs of the users and achieves the goals established in the first stage. During this stage, I tested the toolkit artefacts twice, each time with different personas and scenarios, to validate the toolkit in various settings it was developed for. The testing activity provided valuable insights and critiques, which allowed me to refine and build the final version of the toolkit.

By using the design thinking methodology to guide the development of your thesis project, you were able to gain a deeper understanding of the problem you were trying to solve, generate a range of potential solutions, and create a solution that was more likely to meet the needs of the users.

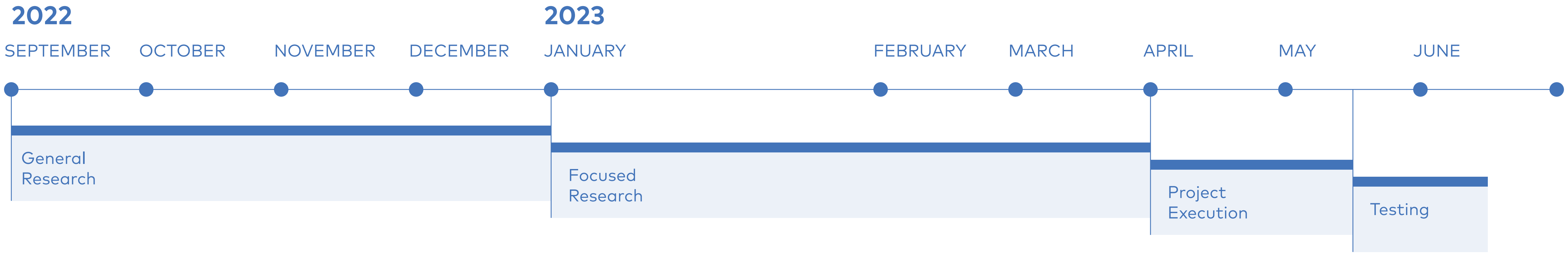


fig. 2 | Thesis Timeline

Part I

General Research

Human haptic perception

01

Before diving into the details of human perception of haptics, I believe it's important to have a clear definition of the general term haptics, a word rarely heard in the everyday language and most of the times over and misused in the technological field and in the one of consumer electronics, which often refer to haptic technologies.

If its etymology can be traced back to the old Greek word "*haptikós*", meaning "*able to grasp or perceive*" **(Jones, 2018)**, in modern English the term has enlarged his scope. Although a unique definition hasn't been agreed, we can identify in literature two main interpretations **(Srinivasan, 1995)**: the first is used in the medical field - Human haptics - namely "*the scientific study of the sense of touch*" **(Collins English Dictionary)**; while the latter can be found in technology - Machine haptics - "*the design, construction, and use of machines to replace or augment human touch*" **(Srinivasan, 1995)**.

The word haptics refers so in its generic form "*to the sense of touch, in particular relating to the perception and manipulation of objects*" **(Oxford English Dictionary)**.

Given the definition of the term and the main research question: "How can haptic technology be used to improve Human Computer Interaction?", is fundamental to understand and have a clear overview on how humans perceive touch (haptic perception) both from a physiological and psychological manner. Therefore the first chapter is divided in two parts: "*The human body*", with a dive into the systems in charge of sensing haptics and the biological elements involved; and "*Interpretation of stimuli*" in which all the features relevant to haptic perception and how they are interpreted by the human brain and its psychology will be presented.

Being the general focus of the thesis about haptics from a design and prototyping perspective, the role of this chapter is not to be a comprehensive medical and psychological guide, but rather a brief and concise summary aimed at acquiring a basic knowledge about human perception of haptics, needed to proceed with the scope of the research.

1.1

The human body

When we interact with things that surround us we make use of our senses, which allow us to perceive them and act consequently according to the result that we want to achieve. Think about the simple act of preparing a coffee with a moka. We first search for it in the cupboard, we grab it together with powdered coffee, afterwards we pour water in the boiler, and gently insert the correct quantity of coffee in the filter basket. We close it firmly and we put it on a heat source.

As soon as it is ready, we hear a boiling sound, and so we slowly pour it into a mug and start drinking, feeling its pleasant hot temperature, smell and taste.

During the five minutes that took to prepare and drink the coffee we use all our senses without too much effort: vision, to locate the objects and their relative position, hearing, to understand the coffee was ready to drink through the boiling sound, smell and taste gave us the pleasant reward that we were expecting, and haptics was the fifth sense that supported the entire routine. It not only allowed us to feel objects' properties through skin contact, like the material texture of the moka, the cold temperature of aluminum, the heat of the coffee in our mouth, and the rounded shape of the mug; but it also allowed us to understand when the moka was properly closed, sensing the end stop, and to feel the weight of the mug full of coffee, making us moving it with caution.

In this scenario, haptic sensing was only possible thanks to the proactive interaction with objects (the moka and the mug), in literature described as Active haptic perception.

1.1.1

Active and Passive haptic perception

As we can understand, haptic perception - oppositely to other human senses - is bidirectional, as it is linked to the movement made to perceive an object properties and information (haptic exploration) **(Jones, 2018)**, whether the movement is generated by the person who is interacting with the object - Active haptic perception - or by the object itself - Passive haptic perception.

In case of **active haptic perception**, the person who is interacting with the object, feels the properties through active exploration. Meaning that moving his body to interact with the object, he perceives its features: that is not only the informations coming from the surface in contact with the skin, but also the spatial dimension and the physical properties. For example, holding and shaking a bottle of water allows to perceive its weight and the presence of liquid, together with an estimation of its volume and viscosity.

On the contrary, with **passive haptic perception**, touch properties are transferred to the haptic sense through movements done by the object itself, without requiring an active exploration by the human body. An example are vibrations or perception of wind, for which no human movement is required.

Haptic perception involves so two fundamental and distinct, but correlated senses: **kinaesthesia**, related to body movement, and **tactile**, related to skin contact.

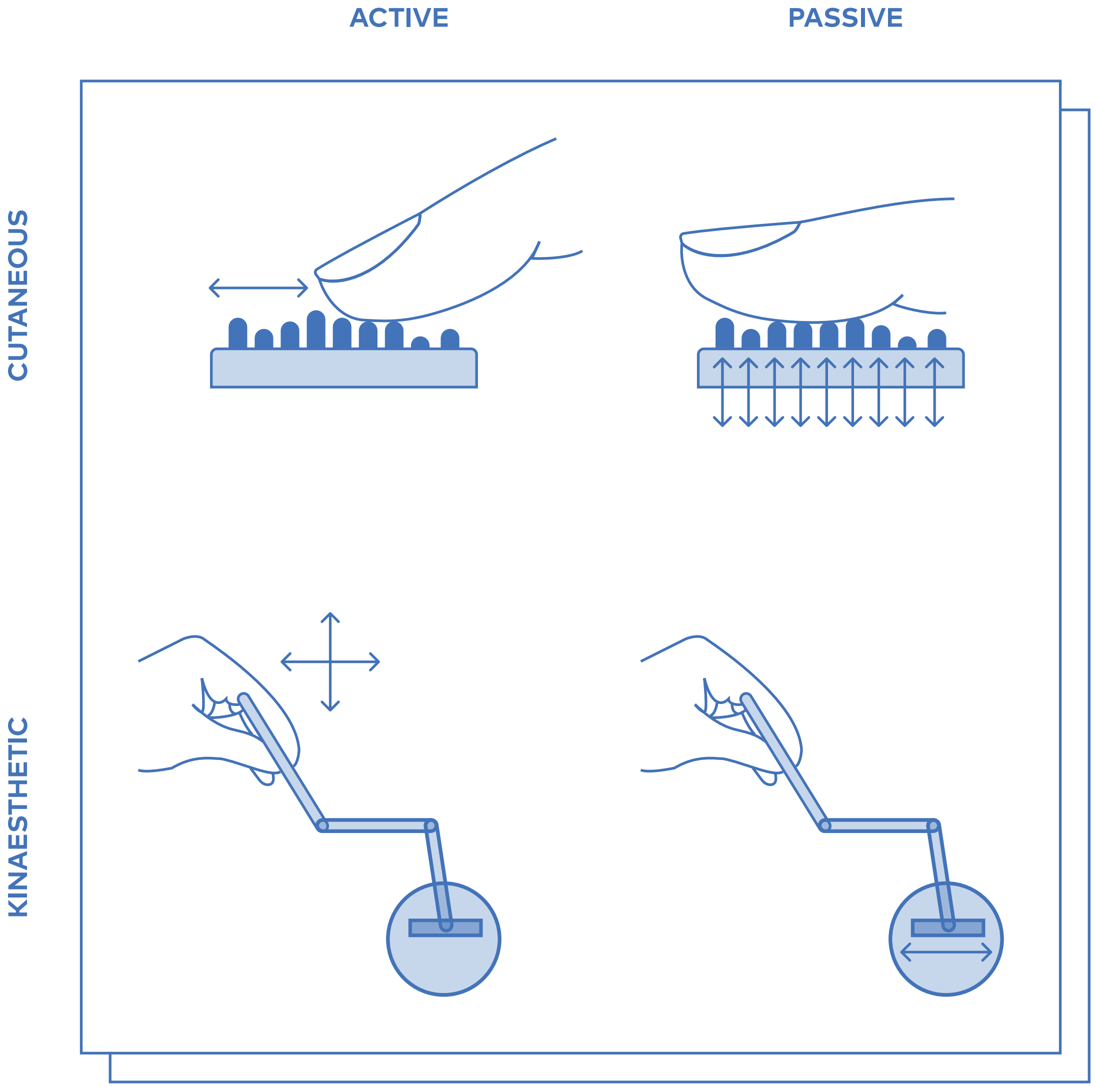


fig. 3
Active vs passive perception
Adapted from: Rodriguez, et. al. , 2019

1.1.2

Kinaesthesia

Kinaesthesia, often interchanged with the term proprioception, is the sensation of relative position, movement and tension of parts of the body **(Collins Dictionary)**.

Thanks to kinaesthetic information, we are able to perceive the force, direction, amplitude, and velocity of limb movements **(Jones, 2018)**, so that we can distinguish for instance the friction of a slider, the resistance of a button, the frequency of indents in a knob and the weight of a notebook by comparing the force generated and the subsequent movement.

Kinaesthetic informations are provided by sensory mechanoreceptors located in **muscles and joints**.

According to the literature receptors located in the **joints**, play a minor role in kinaesthesia, only by sending signals to the central nervous system when the joint position is reaching the extension and compression limits.

Real time information about force generated by **muscles** through voluntary movements, is sensed by **Golgi tendon organs (GTO)**, receptors found at the injunction between muscle fibers and tendons.

1.1.3

Tactile system

The tactile system, also called in literature somatosensory system, is the umbrella term used to refer to the four skin senses present in the human body, which are:

- **Touch;**
- **Temperature;**
- **Pain;**
- **Itch.**

These categories are based on the nature of stimuli each receptor class transduces and are all located in the largest and heaviest sense organ - the skin - which in an average adult covers an area of about 1.8 m2 and weights around 4 kg **(Jones, 2018)**. It is composed by the **epidermis** and the **dermis**, respectively the outer and protective layer, and the inner one of the skin.

The next pages of the chapter will focus on Touch.

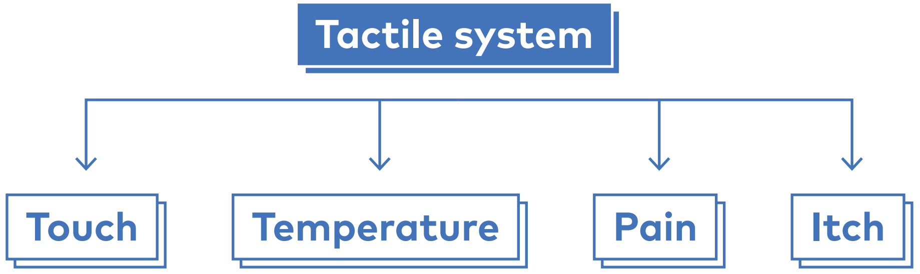


fig. 4
Tactile system composition

Touch

Touch is the primary and the first sense that we think about when we talk about haptics and object perception. Going back to the coffee example, touch is the system that allows us to detect when our hand comes into contact with the moka and, swiping the hand palm across the surface, also its unique shape. This is possible because as we interact with the object, plasma membranes of specific mechanoreceptors embedded in the skin deform when encounter edges and physical features. This deformation fires a feedback that is sent to our brain. For the aim of the thesis is interesting to describe the different mechanoreceptors and in particular how they are distributed across the human body, what type of stimuli activate each of them and what's their role in haptic perception. Only with this information we can make more conscious and punctual decisions when we want to achieve a desired outcome, by applying the right kind of haptic feedback, in the right skin area.

The first characteristic to be aware of, is that human skin is not entirely populated by the same kind of cutaneous mechanoreceptors. The presence of specific mechanoreceptors is in fact influenced by the two types of human skin: **Glabrous skin** and **Hairy skin**.
The **glabrous skin**, present on the palm of the hands, the sole of feet, face, mouth and ears, includes **four types of tactile receptors**:

- Meissner's corpuscles;
- Pacinian corpuscles;
- Merkel cells;
- Ruffini corpuscles.

The **hairy skin**, found in the rest of the body, has **five main types of mechanoreceptors**:

- Pacinian corpuscles;
- Merkel cells;
- Ruffini corpuscles;
- Hair-follicle receptors;
- C-tactile (CT).

Epidermis ■
Dermis ▨
Hypodermis □

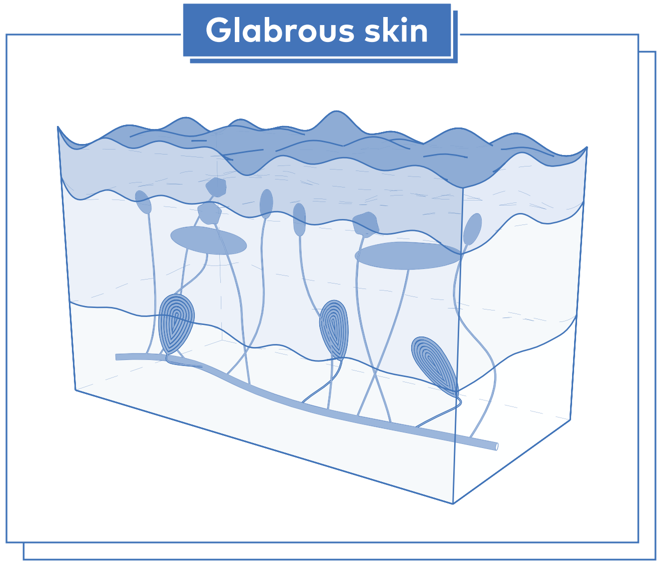


fig. 6 | Glabrous skin mechanoreceptors - Adapted from: Grunwald, 2008

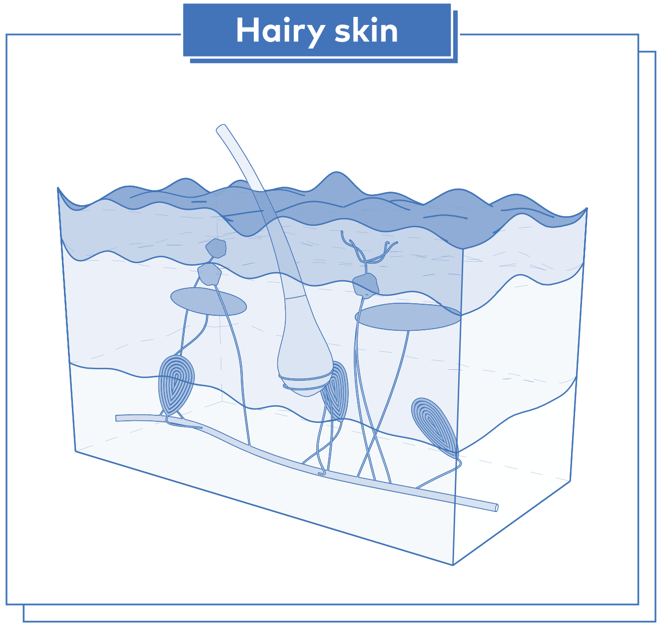


fig. 5 | Hairy skin mechanoreceptors - Adapted from: Grunwald, 2008

Before analyzing them into details, there are two properties that identify the role of each cutaneous mechanoreceptor within touch perception, that are useful to quickly distinguish how they get activated, and so their role in haptic perception: the **size** of the area of skin that when stimulated the single receptor sends the information to the central nervous system: the **Receptive field**; and its response to sustained indentation of the skin: the **Rate of adaption**.
For what concerns the **Receptive field**, mechanoreceptors can be:

- **Type I**, when the receptive field is small, so from 2 to 8 mm in diameter;
- **Type II**, when the receptive field is relatively big, from 10 to 100 mm of diameter.

Higher density of Type I receptors allows to better recognize small features and changes.
For example, the threshold for detecting the height of a small dot moving across the skin, or the distance between two points in contact with the skin (**Tactile discrimination**), is much smaller in areas with higher densities of receptors. **(Jones, 2018)**
The granularity in sensing haptic details in a specific skin area is known as Spatial resolution or **Tactile acuity**.

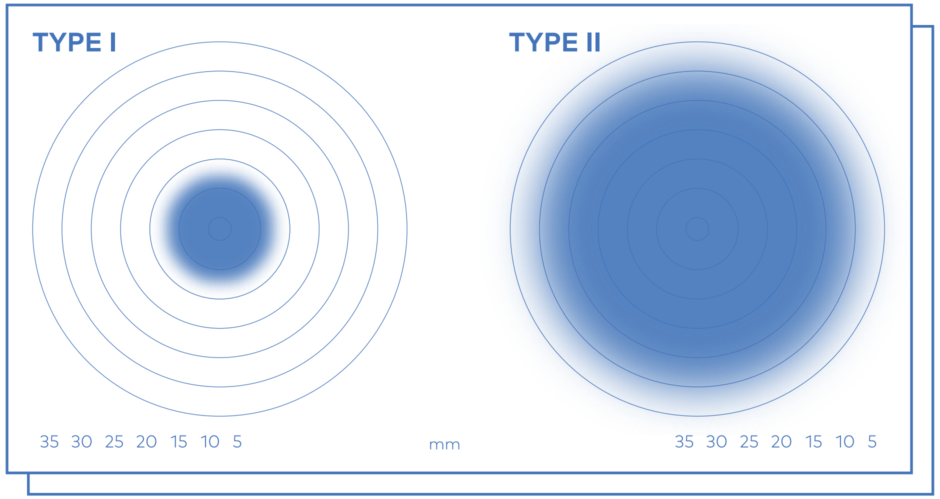


fig. 7 | Mechanoreceptors' Receptive field - elaborated from Jones, 2018

The second property, the **Rate of adaption**, also subdivides them in two categories:

- **Fast adapting (FA)**, are receptors that fires as soon as they perceive - also very small - skin movements and indentations, like the contact with an object, the presence of a surface bump during haptic exploration or a vibration, but that stop to send signals as soon as there is no movement or the indentation stabilizes (they cannot perceive sustained contact and pressure);
- **Slow adapting (SA)**, are indeed receptors that keep firing when are subjected to continuous stimuli, like sustained indentation and movement. However, they don't perceive small haptic changes.

All mechanoreceptors are usually distinguished by a code indicating the rate of adaption and the receptive field, eg. FAI (Fast Adapting, Type I) or SAII (Slow adapting, Type II).

With a good understanding of the main categorization properties of tactile mechanoreceptors, we can briefly describe each of them, starting from the ones present in the glabrous skin and later the ones in the hairy skin.

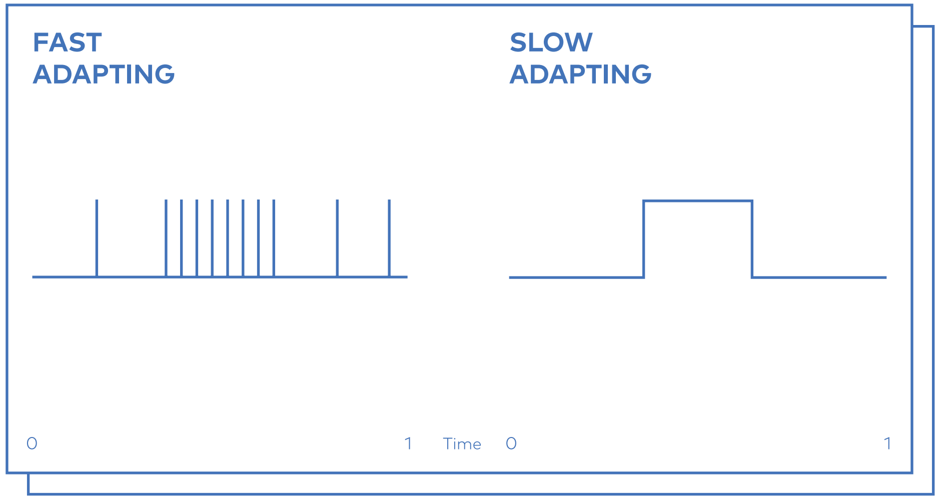


fig. 8 | Mechanoreceptors' Rate of Adaption - adapted from Jones, 2018

Meissner's Corpuscles

Rate of adaption: FA
Receptive field: Type I

Meissner's corpuscles are mechanoreceptors that can be found in glabrous skin, just under the epidermis, below the papillary ridges and are so superficially located. They are oval in shape and small (100-150 µm tall and 40-70 µm wide). One square mm in the hand, can contain up to 24 of this type of mechanoreceptor.

Sensitive to
Meissner's corpuscles respond to very **small changes**, **low frequency vibration** and perceive primarily **light touch**, **skin motion** and **slipping objects** (Delmas et al., 2011).

They are sensitive to frequencies ranging from 20 to 30 Hz.

Example
Gently tapping a touch display, sensing a rough - continuously changing - surface, or interacting with fabric.

Meissner's Corpuscles

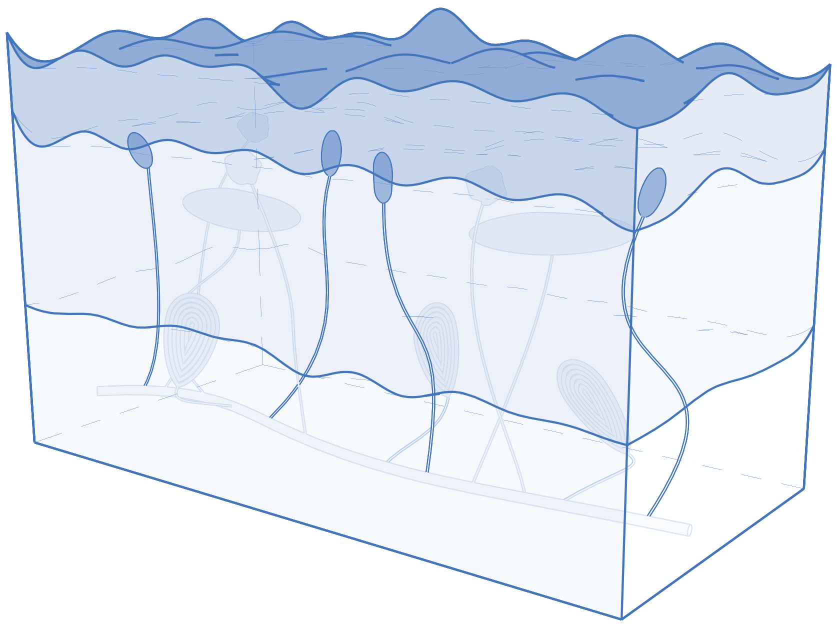


fig. 9
Meissner's Corpuscles
Adapted from: Grunwald, 2008

Pacinian Corpuscles

Rate of adaption: FA
Receptive field: Type II

Pacinian corpuscles are located in the deeper part of the dermis both in glabrous and hairy skin. They have the shape of a disc and are the biggest human mechanoreceptors, with a dimension of 1 to 2 mm.

Sensitive to
Given their generous dimension, Pacinian corpuscles have a large receptive field. They are in charge of sensing **high frequency vibrations** cues transmitted by body contact with objects.

They are sensitive to frequencies ranging from 40 to 500 Hz.

Example
Constantly changing stimuli, like a controller vibration, or strong temporary compressions.

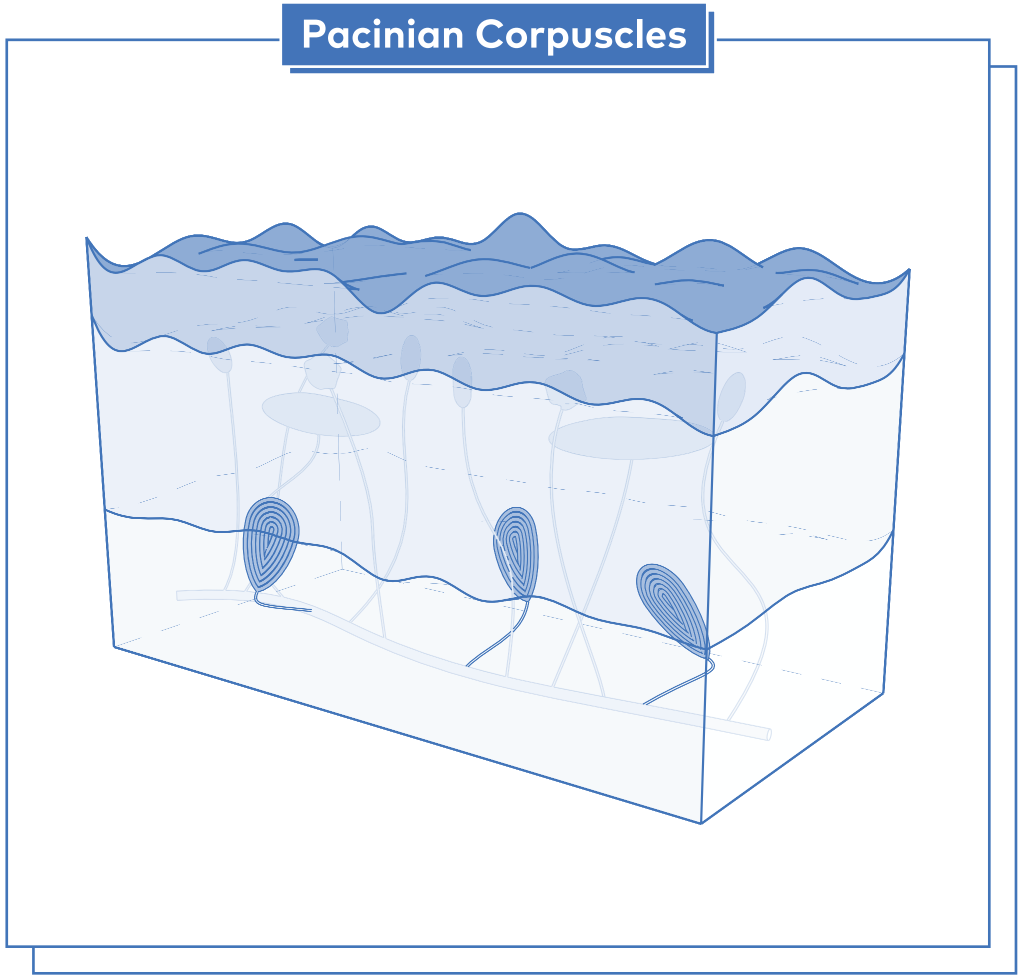


fig. 10
Pacinian Corpuscles
Adapted from: Grunwald, 2008

Merkel Cells

Rate of adaption: SA
Receptive field: Type I

Merkel cells are very small superficial mechanoreceptors located at the base of the epidermis, present both in glabrous and hairy skin, at the basal layer of the papillary ridges, in clusters of 50-70 cells.

Sensitive to
As SAI, their high density and small receptive field allow for an high Tactile acuity. They are able to perceive the **form and texture of objects**.

They are sensitive to very low frequencies of about 4 Hz.

Example
Sustained light touch, like the presence of a smartwatch on the wrist, or the continuous touch of a surface, as a button or fingerprint reader.

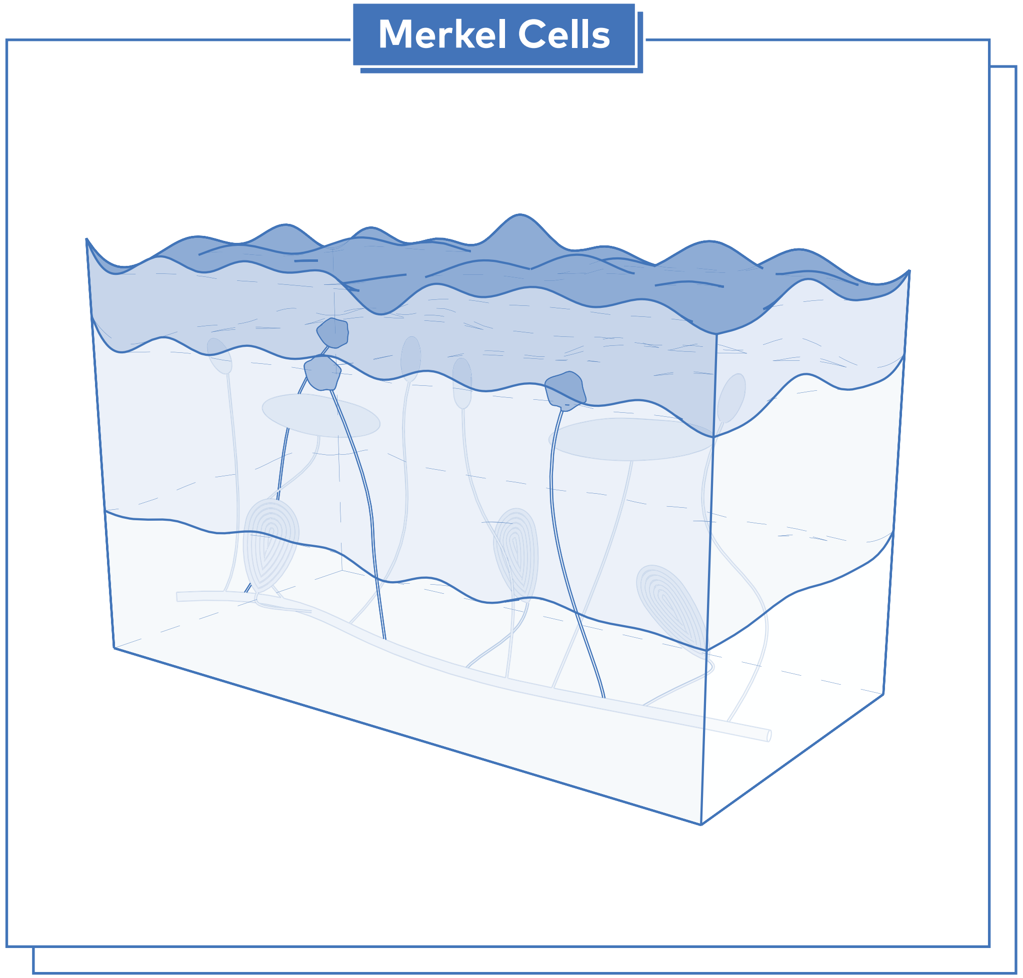


fig. 11
Merkel Cells
Adapted from: Grunwald, 2008

Ruffini Corpuscles

Rate of adaption: SA
Receptive field: Type II

Ruffini corpuscles, present in the dermis, are considered deep receptors. They can be found in both glabrous and hairy skin.

Sensitive to
Ruffini corpuscles are able to perceive **pressure** and **skin stretch**, thanks to which we can sense the direction of object motion and finger relative position.

Example
Interacting with a joystick's analog to move a game character, or sliding to change picture in the gallery app.

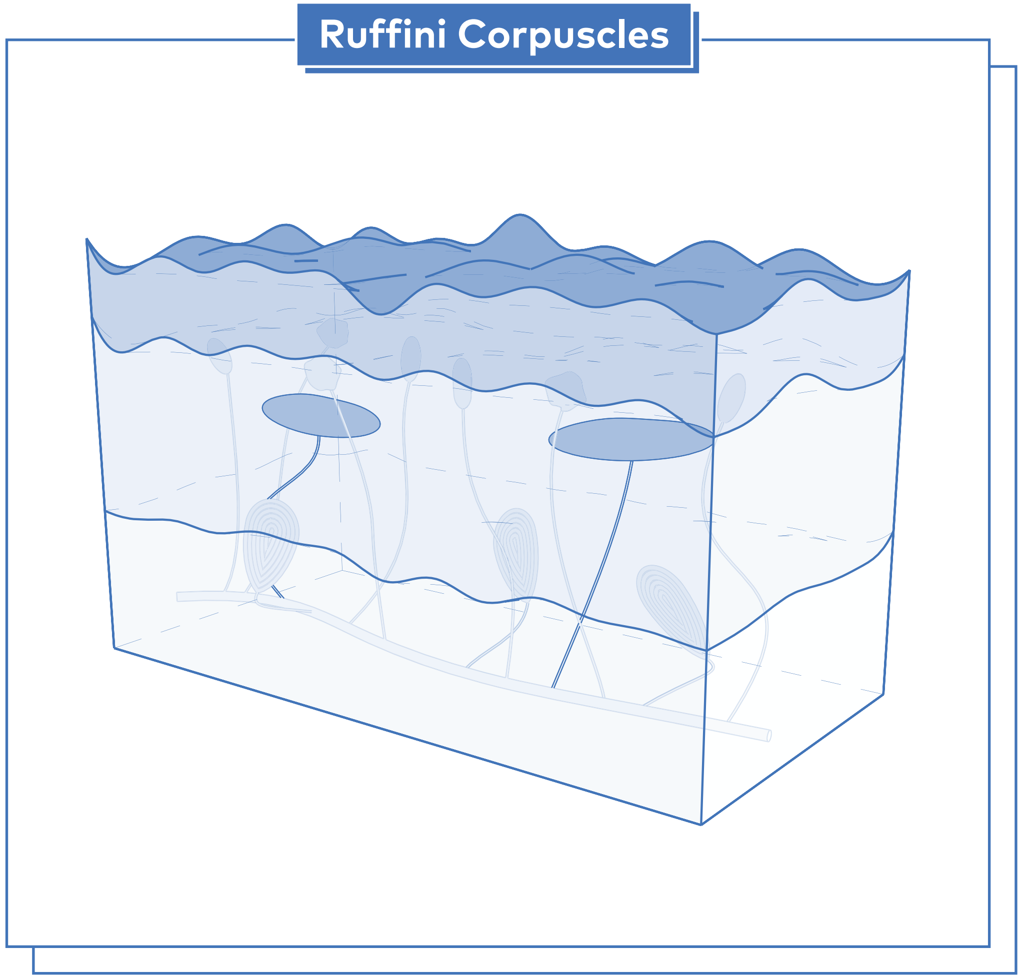


fig. 12
Ruffini Corpuscles
Adapted from: Grunwald, 2008

Hair-follicle Receptors

Rate of adaption: FA
Receptive field: Type I

Hair-follicle receptors are located around hair follicle and are so present only in hairy skin.

Sensitive to
Being around hair-follicle, this kind of mechanoreceptors can sense **hair and skin movement**, but also **light touch**. The tactile acuity of a hairy skin area is proportional to hairs' density in that area.

Example
Wind sensing, object gently sliding on a body part.

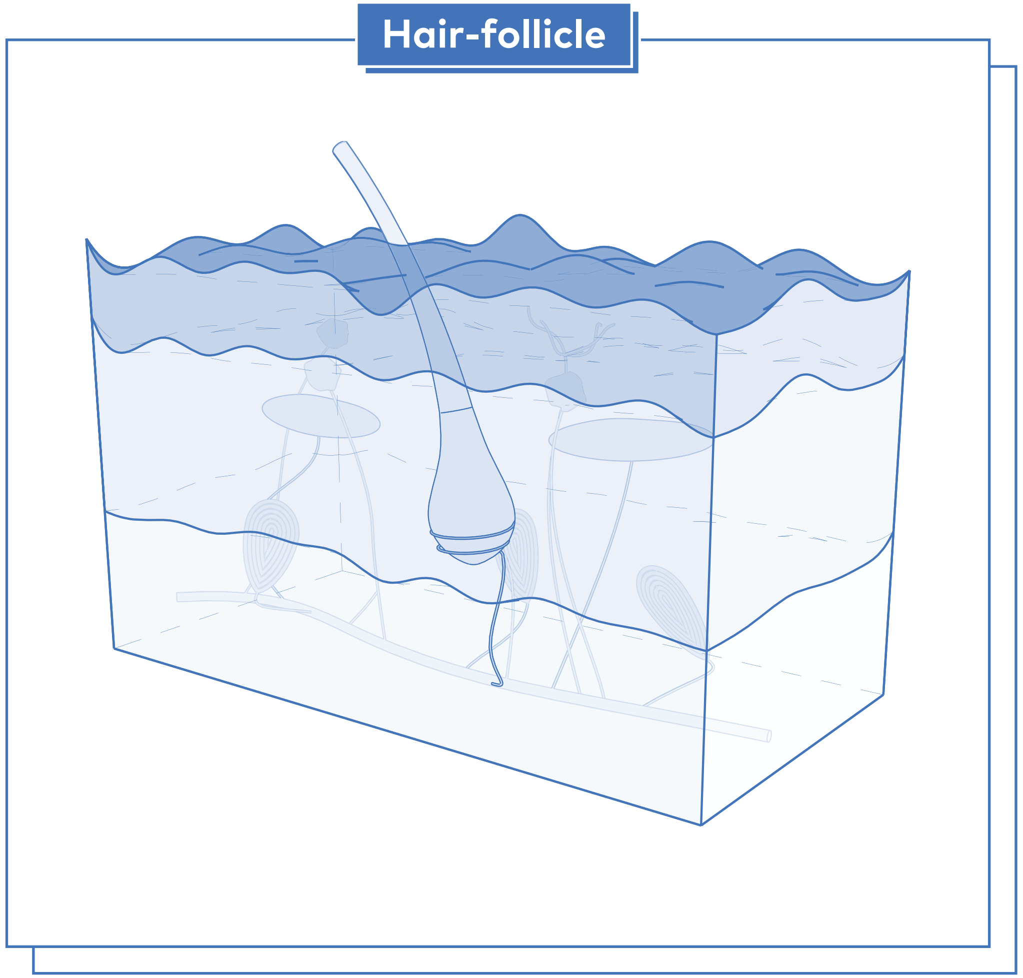


fig. 13
Hair-follicle Receptors
Adapted from: Grunwald, 2008

C-Tactile (CT)

Rate of adaption: FA
Receptive field: Type I

They are free nerve endings located in the epidermis.

Sensitive to
C-Tactile respond to slow, gentle movements across the skin and associate intimate movements to **tactile pleasantness**. According to the literature they modulate their firing according to movement speed and to the temperature of the skin and the object in contact.
They are generally most triggered when slow movement is applied and the temperature of the moving object is near to 32 degrees Celsius.

Example
Gentle touch from a close person, petting a cat.

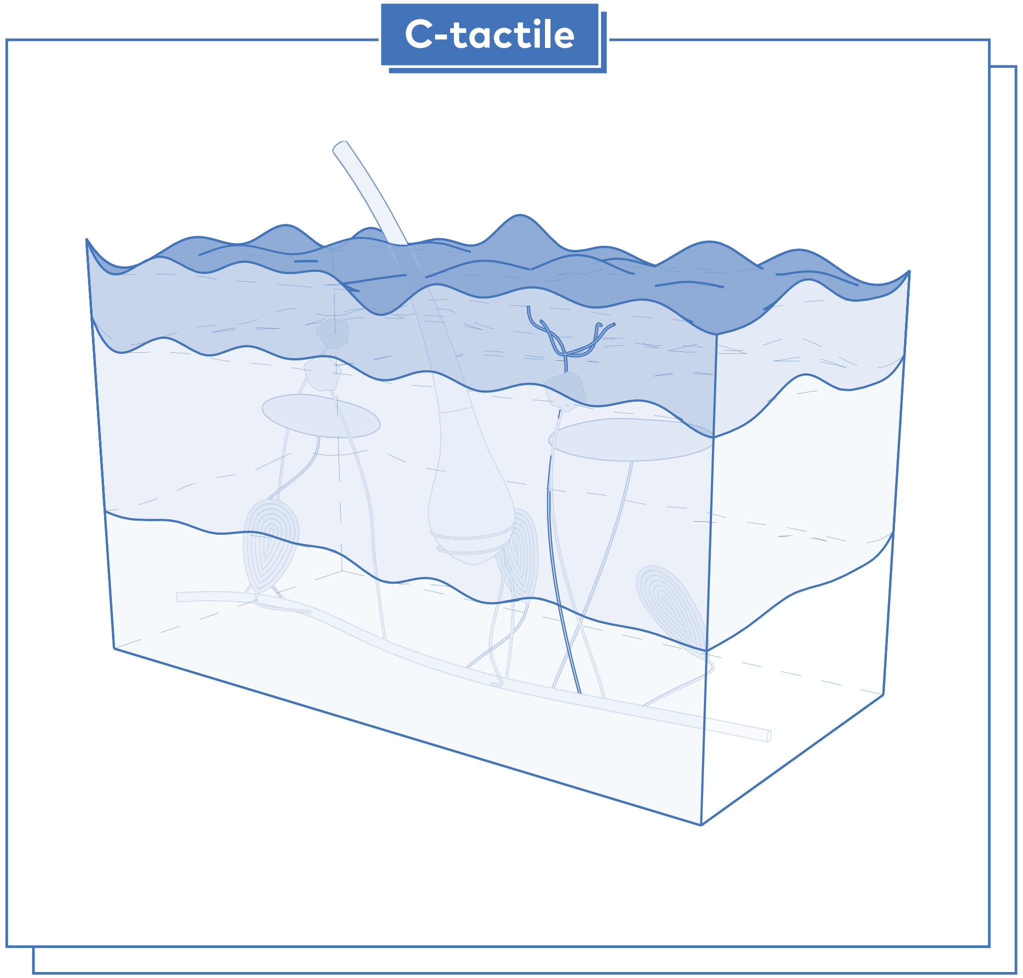


fig. 14
C-Tactile (CT)
Adapted from: Grunwald, 2008

With an overview on all kinds of mechanoreceptors, is clear that each has a different role and doesn't respond to the same stimuli. The mix of diverse types allows us to perceive more than one sensation in a single contact area. In addition to that, we can notice how the human body can detect a great range of vibrotactile stimuli from very low frequencies - as low as 0.5 Hz - to 700 Hz, however the most sensible vibrations are between 200 and 300 Hz **(Jones, 2018)**. The sum of all the tactile sensations results in precisely defined objects' features. However, not all the skin areas are populated by the same density and variety of mechanoreceptors.

Human body spatial acuity

Imagine a laptop keyboard. We interact with it daily, our fingers easily recognise each different key: the shape and the texture; through kinaesthesia we are able to remember their relative position and write words without even looking at them. Thinking about spatial acuity, we can immediately identify the fact that we are capable of doing so, because of an high density of mechanoreceptors embedded in our fingertips (high spatial acuity). If we try, indeed, to type, or even just to actively explore the keyboard layout with another part of our body with a lower spatial acuity, by swiping it over the keys - like the forearm - we can barely recognise an uneven surface.

Although a detailed map or guide of the distribution of each type of mechanoreceptor in the human body is not available yet, studies provide **estimated maps of the body spatial acuity**. More recent literature integrate these maps with the distinction between Fast Adapting mechanoreceptors and Slow Adapting mechanoreceptors present in specific body parts **(Corniani & Saal, n.d.)**.

The most famous investigation in this direction is the one carried on by Wilder Penfield and the book published in 1950. The research includes a map, in which he presents the human body stretched proportionally to the size of brain in charge of each body part's skin sensing: the **Homunculus**.

Even though Penfield's findings were somehow accurate, in more recent years researchers tried to estimate tactile innervation densities across the human body, which is proportional to spatial acuity.

In particular **the human body has around 230.000 tactile afferent fibers** - connections that transport signals from mechanoreceptors on one end, to the central nervous system - of which **60% of them are Slowly Adapting** (SA) and **40% Fast Adapting** (FA).

Studies point out the fact that glabrous skin, present in the palm, sole and the lips is generally more sensitive to tactile stimuli compared to hairy skin, due to the higher density of receptors and to the presence of the small and highly sensitive Meissner's corpuscles (FAI). The rest of the body, covered by hairy skin with a ratio of 65% of SA

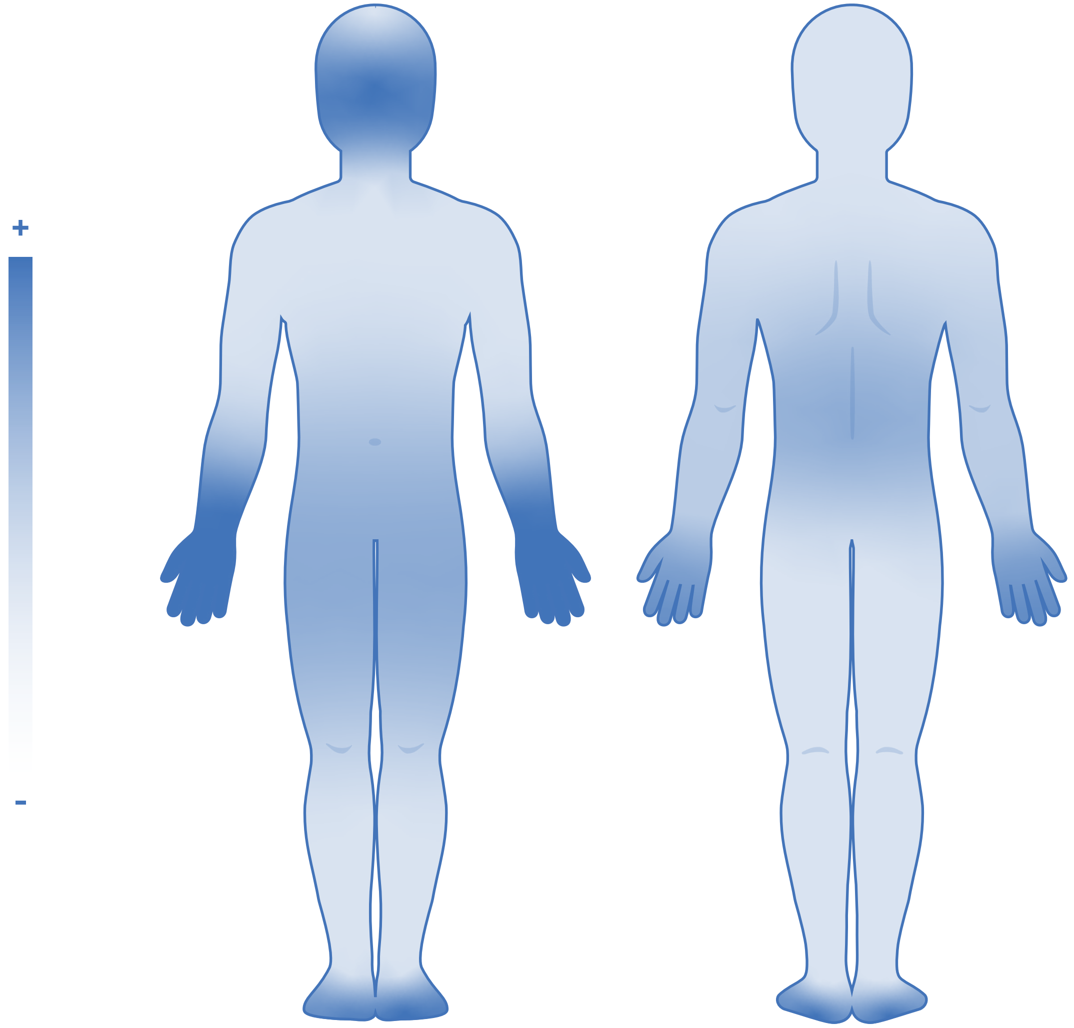


fig. 15
Body's Spatial Acuity
Adapted from: Mancini, et. al. , 2008

and 35% of FA mechanoreceptors, has a much lower spatial acuity, which translates in less precision and localization in perceiving stimuli, especially if gentle and fast. Hairy skin is generally more sensible to sustained and stronger feedbacks.

Takeaways for designers

From a designer perspective there are some takeaways that are important related to the sense of touch, that could help to design and apply feedbacks on the best possible location of the body, so that they get correctly perceived by the final user.
Generally not all human body parts are sensitive to the same type of stimuli, or at least with the same granularity; but if **glabrous skin** - the one nowadays more leveraged - **is the one with an overall higher spatial acuity** and that can detect minor changes in smaller areas, **hairy skin covers a larger body area**. This could enable different design scenarios and practices that can reduce the information overload of certain areas, or create new types of interactions and communication.

Moreover, despite the lack of a precise map of the location of the different receptors, with the estimation of the body spatial acuity, as well as the knowledge of FA and SA mechanoreceptors ratio in the different areas, **we can estimate which are the feedbacks more sensed by the specific body parts** (high frequency vibration, deep pressure, skin stretch, etc.).

Temperature

If we recall the example of the moka, among the multiple tactile cues, we were able to detect objects materials and temperature simply by touching their surface. The heat transfer between two objects with different heat conductivity or temperature - in this case the aluminum moka, or the hot mug in contact with the hand - allow us to perceive a temperature changes and so, their properties.

Our ability to sense temperature is called **thermoception** and has an important role in haptic perception. Similarly to what concerns touch, temperature variations over the skin surface, are sensed by dedicated biological elements called **thermoreceptors**: **warm** thermoreceptors, sensing temperature increases, or **cold** thermoreceptors sensing temperature decreases. The role of thermoreceptors in glabrous skin of the palms is to distinguish objects and their materials, while their role in hairy skin is primarily for the body's thermo-regulation **(Jones, 2009)**, in order to keep the core temperature in a range of ±0.5°C. **(Jones, 2018)**.

Another property that thermoception shares with the sense of touch is spatial acuity. **Thermoreceptors have a very poor spatial acuity** and, if more than one stimuli is presented in a narrow area, the sensation is summed rather than recognized as two different sources. Increasing the number of stimuli in a skin area so, increases the overall intensity of the sensation, and not the size of it. That is because of the thermo-regulatory nature of this system, which doesn't need precise information about the location, but an overall estimation of it, so that the body response can be activated accordingly.

In addition to this, if two stimuli are presented in two areas symmetrically to the body (eg. both forearms, or both legs) and simultaneously, the sensation is perceived more intense rather than two different.

For what concerns the sensitivity for single thermoreceptors, they **can sense temperatures up to 45°C and down to 5°C**. The detection of temperature variation changes according to the body temperature, but at it's standard situation, they can detect rapid increases of 0.20°C and decreases of 0.11°C, this is because cold receptors are found right beneath the epidermis, while warm receptors are deeper. However, if the variation happens in a longer time frame, people cannot perceive it easily.

Thermoreceptors are distributed across the entire body, with a **3.5 higher number of cold receptors compared to warm receptors (Jones, 2009)**.

In general, the most sensitive parts to temperature variations are the face, the back of the neck and of the torso, the abdomen, the inner part of the arms and the back of the hand. The less sensitive parts - especially to heat - are the chest, the frontal part of the neck and the lower extremities **(Luo et al., 2020)**.
Sensitivity varies also according to cold and warm variations. Thanks to an higher number of cold thermoreceptors, cold variations are perceived more and better localized.

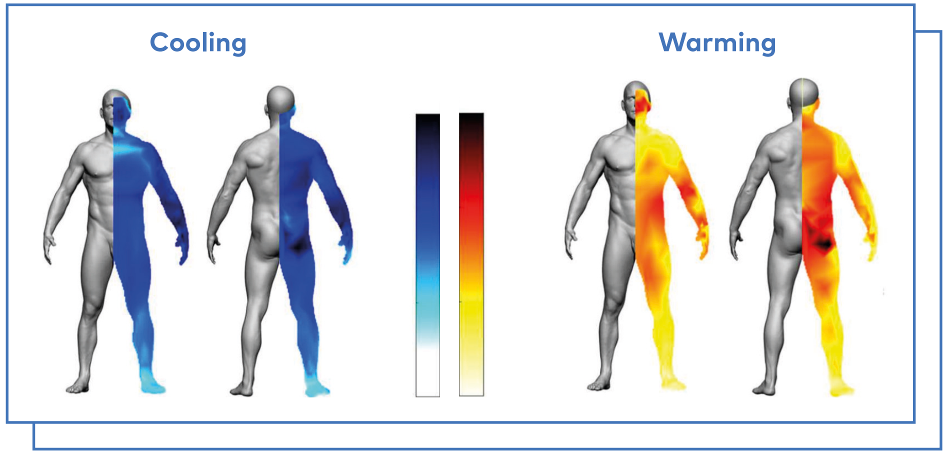


fig. 16 | Body's thermal sensitivity - Luo et al., 2020

Takeaways for designers

Thermoception has an important role in haptic sensing. Thanks to it humans can not only regulate their body temperature, but can also **recognize objects and some of their properties**, like materials or their temperature, **enriching haptic information** without using vision.

As for the sense of touch, **temperature sensing is not uniform** across the entire body, but varies according to the distribution of cold and warm thermoreceptors. It is also influenced by the body and skin temperature, with a better performance at room temperatures and with rapid changes instead of constant increases or decreases.

Spatial acuity is also low, this means that applied stimuli aren't recognized with a precise localization, but are rather summed into an overall intensity within a bigger body area.

Throughout the first part of the chapter, human haptic perception has been analyzed from a physiological point of view, describing the two main systems involved: kinaesthesia and the tactile system. Regarding the latter, touch sensing has been described trying to list the biological elements involved (mechanoreceptors), together with their properties, sensitivity and distribution throughout the entire skin surface.

With a clear and general overview of how the human body perceives haptic stimuli, **the next part of the chapter will focus on how this signals are processed and interpreted by the brain and psychology**, recognizing useful insights and guidelines that can be exploited later as the thesis develops.

1.2

Interpretation of haptic stimuli

Stimuli applied to the skin surface and detected by the mechanical deformation of mechanoreceptors are translated into electrical signals sent, through specific axons, to the central nervous system and then, to the brain where they are processed.

The haptic sense it's the first to develop in a human being and since the very beginning it plays a fundamental role not only for the perception of the surroundings, but also for interpersonal communication. Through touch and haptics humans have always communicated to a more intimate level. Our brain's interpretation of haptic stimuli, both tactile and kinaesthetic, is also able to identify emotions like affection, love, threat and injury.

This translation of mechanical stimuli into meaningful experiences and characteristics is the result of a mix of haptic inputs, but also information that come from other senses, past experience, emotions and other dimensions, like space and time.

1.2.1

Haptics and the other senses

The haptic system can be compared in terms of accuracy with audition and vision. The two main dimensions of comparison are the **spatial and the temporal resolution**: the first being "*the spatial separation between stimuli that can be detected*" **(Jones, 2018)**, while the latter is "*the time difference required for two pulses delivered ... to be perceived as successive and not simultaneous*" **(Jones, 2018)**.

Taking into consideration the two definitions, for what concerns spatial resolution, haptic perception is - in normal conditions - generally more accurate than audition, but worse than vision; while for temporal resolution, the haptic system is more accurate than vision, but less than audition. This makes the haptic system more reliable in certain situation and less in other.

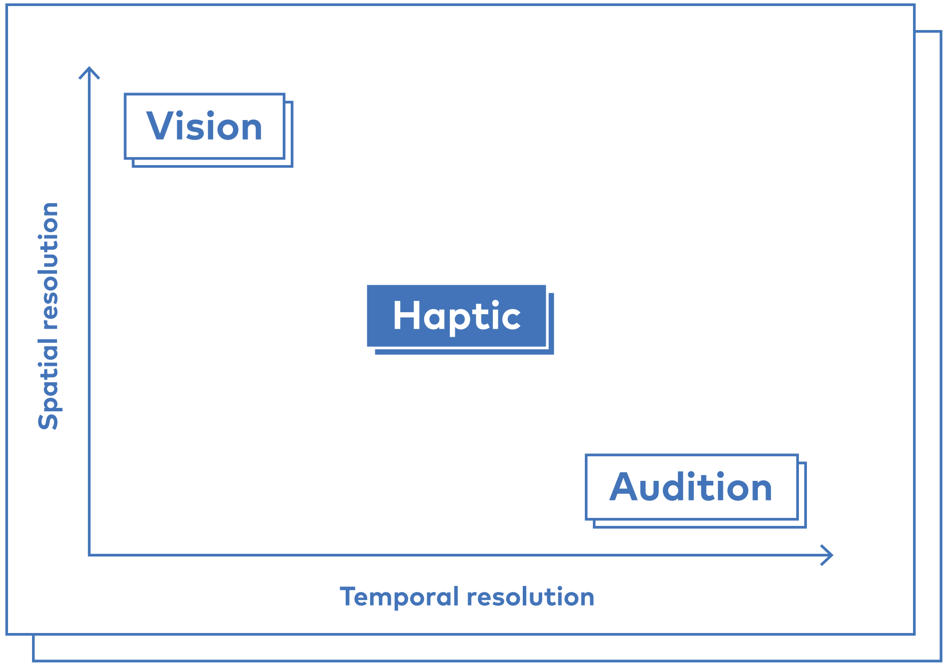


fig. 17 | Senses' resolution comparison - elaborated from Jones, 2018

1.2.2

Perception of haptic properties

Tactile properties

Tactile properties are features that the brain is capable to identify while holding an object or interacting with its surface. The characteristics that can be recognized are the **geometry** and the **materials** composing it.

For what concerns geometrical properties and estimation of weight, skin indentation and kinaesthesia are the methods used by our brain to gain these characteristics.

The identification of materials is indeed more complex, revealing a multidimensional sensation composed by objective and subjective parameters that at the end compose the feeling.

A study published in 1993, "Perceptual dimensions of tactile surface texture: A multidimensional scaling analysis" conducted by M. Hollins, R. Faldowski, S. Rao and F. Young, suggests three different axes - or dimensions - on which material are weighted and described by humans based on their perceived properties:

- **Rough - Smooth**;
- **Hard - Soft**;
- **Springiness**, or compliance (compressional elasticity of the surface).

If for the first two dimensions the main sense involved is touch - and Merkel cells, SAII mechanoreceptors - for compliance kinaesthesia has a fundamental role. **Compliance is in fact perceived as "how deformable a surface is when force is applied**, so it is defined as the ratio between displacement, or the movement of the surface, and the forces applied" **(Jones, 2018)**. Examples of compliance are keyboard's keys, a console controller button, or a balloon full of air.
For what concerns **roughness and smoothness, people perceive the difference according to the gap between imperfections present on a**

surface. Higher distance is translated into higher perceived roughness. Mechanoreceptors, however, don't have such small receptive fields to sense very fine textures, this is why our body relies on a second haptic mechanism to identify those micro-imperfections.

Vibrotactile properties

If we slide a finger on a desk surface, and later on a tablet display, we immediately notice how, despite both being visually described as smooth, the glass display is perceived as smoother once compared to the desk. Micro-imperfections and grainy textures, cause friction between the surface and the body part sliding over it; this effect generates high frequency vibrations that are processed by our brain and influence the sensation of the level of smoothness and roughness of the surface. Vibrations, are so an important dimension in human haptic perception, even if they are not always consciously perceived.

The mechanoreceptors able to sense vibrations are the Fast Adapting type: Meissner's (FAI) and Pacinian (FAII) corpuscles.

According to the Collins Dictionary, **a vibration is "*the oscillating, reciprocating, or other periodic motion of a rigid or elastic body or medium forced from a position or state of equilibrium*"**.

Vibrations can be visualized as Sine Waves on a two dimensions graph, with two physical properties that define them. These properties are:

- **Frequency** - describing "*the number of waves that pass a fixed place in a given amount of time*" **(Northwestern University)** - **measured in Hz** (events per second);

- **Amplitude** - describing "*the maximum displacement or distance moved by a point on a vibrating body or wave measured from its equilibrium position. It is equal to one-half the length of the vibration path*" **(Britannica)** - usually **measured as distance in millimeter, or acceleration from gravity G**.

For what concerns texture detection these are the two main affecting properties. Their sensing can be summarized in: **higher the frequency, or lower the amplitude, the smoother the surface is perceived**; lower the frequency, or higher the amplitude, the rougher the surface is perceived. **(Bensmaïa & Hollins, 2003)**

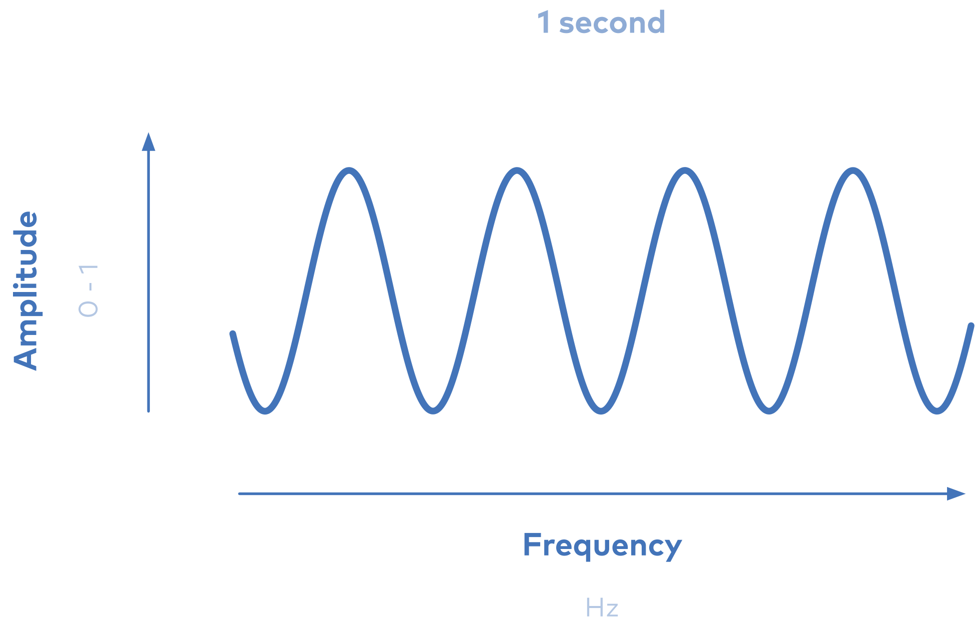


fig. 18 | Vibration graph

The role of vibrotactile stimuli in human haptic perception doesn't stop at surface sensing, but they are also a **mean of communication with the objects and the people** that surround us. When we use a blender for example, if we could remove all the other senses, like vision and audition, we would still be able to understand if the appliance is on, or even estimate the moving speed of the blades, by feeling the vibration frequency of the device. A dimension that is present and characterise vibrotactile communication is the **time in between the stimuli**, which can create patterns for more complex interactions.

It's worth to say that the human brain perceives vibrations with a frequency below 3 Hz as slow motion, from 10 to 70 Hz as rough, and from 100 to 300 Hz as smooth. Moreover, in order to detect variations between two haptic stimuli, there should be a difference of about 25% in frequency or amplitude. **(Choi & Kuchenbecker, 2013)**

Takeaways for designers

The properties that humans are able to perceive by interacting with the surroundings come from tactile and vibrotactile cues, which are a result of specific mechanical stimuli, like indentation, skin stretch, kinaesthetic movements and vibrations. Being the properties objective, and therefore measurable, implies the fact that they **can be reproduced and tweaked to reach desired effects**, also with a design goal.

1.2.3

Haptic attention

Differently from other senses, haptic stimuli have an immediate impact on the body, triggering the need of a quick analysis and response from our brain, avoiding harm and risk. This peculiarity of the **haptic system leads to a rapid change of focus** whenever also a small and insignificant stimuli is applied on the body. The low threshold of attention is also valid for haptic stimuli presented with long intervals.

According to literature **(Grunwald, 2008)**, there are some techniques that can help the brain to increase selective attention on specific haptic stimuli and make them stand out from irrelevant stimuli and background noise. These techniques can help to deliver haptic feedbacks in all the situations where the environment is not controlled and more stimuli are applied at once.

Sensory gain control

Since the neural system adapts to background levels of stimulation **(Cheadle et al., 2014)**, to increase attention towards specific stimuli, we can either amplify the magnitude of it, or decrease the one of the background or unwanted ones. The greater delta between the two allows the brain to better identify the predominant feedback.

Temporal pattern of action potentials

The second method is to create a pattern between the wanted stimuli on at least one dimension - spatial, temporal, etc. - so that this creates a popup effect easily detectable by the user. An example are songs, where the low kicks coming from percussions can be recognized in the background by noticing the temporal pattern which constitutes the rhythm.

1.2.4

Haptic illusions

Being **haptic perception an interpretation from the brain of the reality**, as for the other human senses, it can be tricked perceiving physically incorrect cues. These brain caused distortions of reality - mainly caused by time and space - are referred to as Haptic illusions.

The book "Haptics", by Lynette Jones **(Jones, 2018)**, does an in depth analysis on these illusions that can be summarised as follows:

- **Tau effect**: stimuli with a very short time interval (100-300 ms) are perceived closed than they really are;
- **Velocity of stimulation and perception of distance**: when a continuous tactile stimuli is applied and is moving, the travelled distance is influenced by its velocity. It is perceived shorter when it moves faster (velocity has little effect between 50 and 200 mm/s);
- **Weber's illusion**: the distance between two points of stimuli is perceived larger in areas with higher spatial acuity compared to ones with low spatial acuity;
- **Sensory funneling**: when very brief stimuli are applied together in a small area, the stimuli are perceived as one at the center of the stimuli, and more intense than the individual ones;
- **Phi phenomenon**: when different mechanical taps are applied sequentially, they are perceived as one stimulus moving across the skin, instead of separate stimuli. The optimal interval between stimuli depends according to the duration of the stimuli. For 100ms duration of the stimuli, the in between interval should be 70ms;
- **Sensory saltation**: short tactile pulses delivered successively at three locations on the skin is perceived as a stimulus that is moving progressively across the skin. To make the illusion take place, there should be 3-6 taps, with a time interval between stimuli of 20 to 250 ms and the spatial acuity of the skin is also to be considered. This area is known as saltation area and varies from very small are a on the finger (2-3 cm2), to a much larger area on the forearm (146cm2).

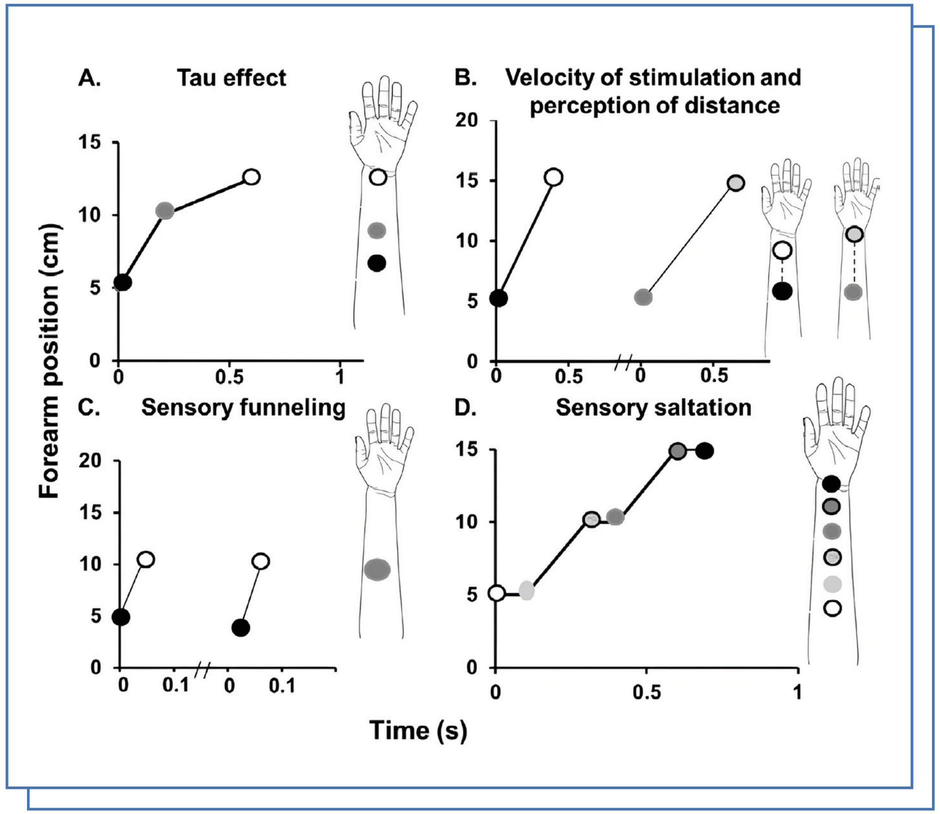


fig. 19 | Haptic illusions - Jones, 2018

Haptic communication in everyday objects

02

Human haptic perception, as presented in the first chapter is a symbiosis of physiological and psychological factors which gives meaning to external stimuli and activate adequate responses.
The bidirectional nature of the haptic system given by continuous kinaesthetic and tactile reception and production of information gives life to an always-on communication medium.

Since well before the invention of computers and therefore of HCI, people have always used their hands and skin as a way to perceive information from the world and interact with it.

Despite touch as a data transfer media is commonly perceived as a recent investigated subject, the beginning of its research has the roots in the XVII century. To create real innovation and enrich the current state of the art, I believe it is important to understand and acknowledge the past as well as its present. It is for this reason that the second chapter - focused on haptic communication in everyday objects - wants to summarise the research and Development carried on over the centuries and its current state in the Human-Computer Interaction discipline. Developed in a chronological order, the chapter begins with an "*Historic overview of haptic R&D*", from the '700 to the 2000s; moving to analyse "*The role of Touch in HCI*" field and how it is used to enhance user experience; while the last part includes a series of selected "*Case studies*", interesting from a user experience perspective.

2.1

Historic overview of haptic R&D

Haptic interfaces and devices are commonly perceived as quite recent, but their current state of research and development is the consequence of more than three centuries of experimentation, characterised by successes and some failures.
Overall, we can divide the history of haptic media and interfaces into five main parts, each referring to different and consequential historical periods with their own themes and events that influenced the future of the subject:

- The 18th century, with the first experiments of tactile stimuli through electrical shocks;
- The 19th century, the period during which scientific haptic research begun;
- The first half of the 20th century, with the first electro-mechanical haptic machines;
- The second half of the 20th century, also called the "epoch of haptic interface" **(Hiroo Iwata, 2008)**;
- The 21st century, where touchscreens took the lead and new technologies are developed.

The next pages will cover the three centuries, trying to extrapolate the most important milestones and case studies, in order to contextualise the current state of haptic knowledge and status.

2.1.1

Electro-tactile medias - 18th century

With the invention of the electrostatic generator in 1663 by the scientist Otto van Guericke, in which the movement of mechanical parts generated electrical charges, research and development efforts in the field of electricity began to increase.

Among all the human senses, the haptic system was chosen as the preferred one to describe electricity because, unlike the others, it could not only determine the presence or absence of the charges - also visible or audible through the presence of sparks - but, thanks to tactile sensation, it could also detect some of its properties, allowing people and scientists to describe and catalogue them. This perception of stimuli properties can be considered one of the first examples of human-machine tactile communication. **(Parisi, 2018)**

In the following decades the so called "electrical fluid" arose public interest, becoming the focus of performances and games: electricity was used as entertaining media.

The **Venus Eletrificata** (or Electric Kiss) is an iconic example. Developed by the German physicist Georg Matthias Bose in the late 1720s, it is a public performance consisting of a manually operated electrostatic generator, able to charge a lady standing on a non-conductive stool (made of wax). The game, presented in different environments and occasions, mostly for the middle class, challenged men to try and kiss the charged girl, feeling an electrical shock that grew stronger each time. Contestants competed until they could no longer reach the girl because of the excessive shock. **(Parisi, 2018)**

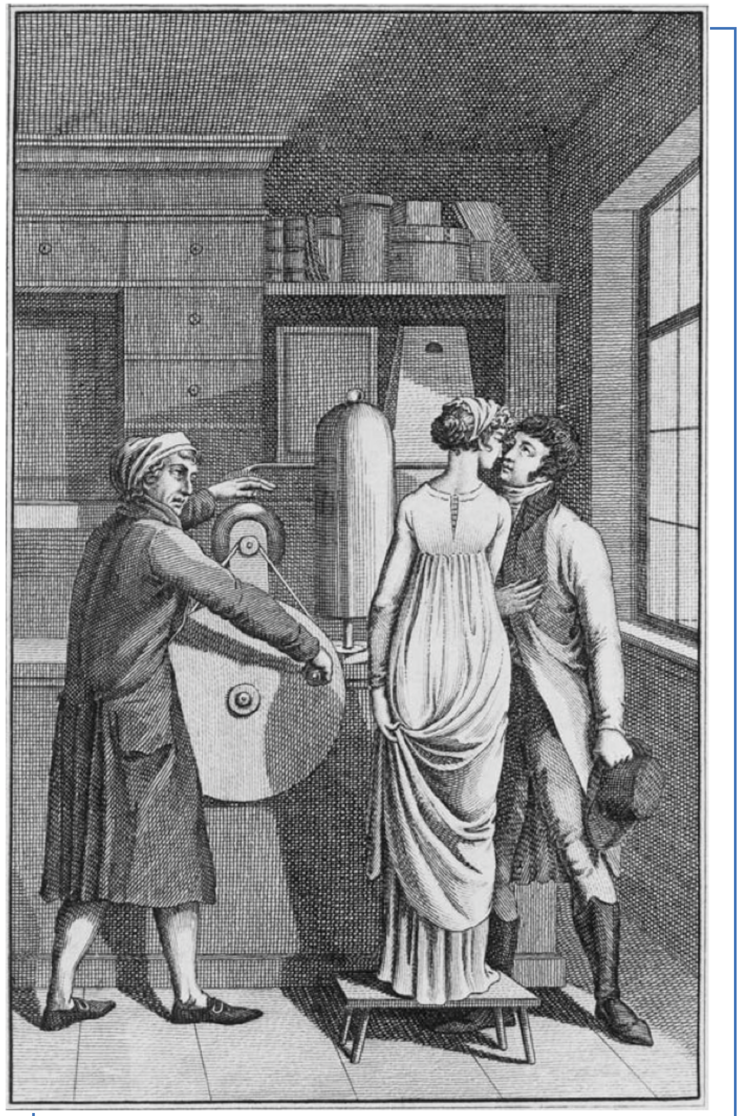


fig. 20 | 1800 reproduction of the electrified Venus

Matthias Bose, Deutsche Museum, Munich, Archive, BN09340

In 1745, the German scientist Ewald Georg von Kleist created a device able to store electrical charges generated by mechanical generators: the **Leyden jar**. Following the trend of these kinds of public performances, the electro-charged object quickly became the protagonist of a series of public experiments. Owners all around Europe generated income simply by allowing people to touch the jar and perceive the electrical current flowing into their bodies.

In 1746, the priest **Abbè Jean-Antonie Nollet** performed an experiment for the edification of King Louis XV of France, which consisted in a chain of 180 royal guards holding hands and letting the two extremities of the chain touch the previously charged Leyden jar creating a closed circuit. The discharge and the flow of electrical current between the bodies made all the guards jump and move simultaneously. The experiment has been repeated later with 900 monks in Paris connected instead with iron wires. **(Benjamin, 1898)**

fig. 21 | Nollet and the Leyden jar - Louis Figuier, 1870

Experiments of circuits with people, apart from generating entertainment, opened the door to a new kind of research. **Scientists investigated the properties of electricity and materials by constructing circuits** composed of generators or Leyden jars, different materials, and humans. Through the haptic sense, researchers were able to detect the materials' property of conduction, the speed at which electricity travels through them, and the maximum distance at which electricity can be transmitted.

In the late 18th century, researchers discovered the fundamental role of electricity in human beings and their nerves. To disprove the ongoing theory conceived by Luigi Galvani in the early 1790s, which identified two types of electricity - "artificial electricity" generated by friction or machines and "animal electricity" **(MIT Libraries)** - Alessandro Volta conducted his own experiments, concluding that electric stimulation was ultimately the result of the different metals in a circuit and the electrolyte. As a result of the experiments, the **Volta's Pile** was a device able to generate electricity by itself - unlike the Leyden jar - and release continuous and controlled shocks.

As the eighteenth century comes to an end, we can summarise the first use cases of electrotactile machines on a large scale as media merely for entertaining purposes. Beginning from the last decade of the century, electricians started to think about how the results of these experiments and the devices could be employed for practical and useful purposes, coming up with new ideas. In the medical field, electricity started to catch on, used to relieve patients' pain and for therapeutic causes. However, this use case was discredited in the early twentieth century.

The haptic sense used to perceive electrotactile information in the eighteenth century - called also electrotactile telegraphy - can be considered as a precursor of the well-known electric telegraphy of the nineteenth century, where the human body as a means to perceive electricity itself has been replaced by other mechanisms (lights and sound emitters) to be perceived by other senses: vision and audition.

2.1.2

Scientific haptic research - 19th century

From a sense mainly exploited for entertaining purposes in the past, during the 19th century touch has been rationalised and studied through the use of more modern techniques.

The main contributor of the nineteenth century was the scientist **Ernst Heinrich Weber**, who in the 1820s decided to focus his research efforts on **discovering the relationship between tactile stimuli and the human subjective perception**. Most of the outcomes from his work form the foundation of today's knowledge, with some concepts still considered up to date. **(Parisi, 2018)**

As the scientific community agreed also at the time, the human body is composed by nerves able to transmit stimuli to the central nervous system. The first Weber's goal was to go deeper into the subject understanding the structure and the role of all the physiological elements involved in tactile perception.

Due to the limited technical capabilities of instruments at the time, scientists had to find alternative ways to conduct studies and extract scientific knowledge. In the late 1920s, Weber conducted an empirical experiment to determine the minimum distance between two stimuli that the human body could detect, known as the "two-point threshold" (also described in Chapter 1).

The procedure Weber used involved placing the ends of a beam compass on the body of a subject, each time with a smaller distance between them. As the two stimuli were applied to a specific area, he asked the subject how many points they could perceive until they no longer sensed the two stimuli as separate. The distance between the two extremities defined the two-point threshold of the body area.

With the results emerged from his experiments, he elaborated and published a map of the human body's spatial acuity. At the same time, he assumed the existence of "sensory circles" on the skin that can detect stimuli with greater intensity when applied in the middle and gradually lower intensity as it moved farther away from its center. The higher density of these sensory circles translates to higher perception. With these new assumptions, he predicted the later discovery of mechanoreceptors.

As Weber prepared the procedure for the two-point threshold experimentation, aware of the empirical nature of his tests, he aimed at reducing external factors as much as possible and isolating the sense of touch in such a way that the results were not influenced, thereby assuring the reliability of them. Whilst he observed and controlled the variables around touch perception, he noted and concluded that the perception of touch was indeed influenced by other sensations under the tactile system, later framed as pain, itch, and thermal reception.

As knowledge about touch grew through experiments and discoveries of other sensations related to the tactile system, the term "touch" became increasingly constraining to refer to all things related to tactile perception. Max Dessoir, a scientist researching touch perception, proposed the word "**haptic**" in the *Dictionary of Philosophy and Psychology* **to refer to tactile perception and all related knowledge and activities performed in laboratories**. "*Haptics implied not just a new way of conceptualizing touch as a scientific object, but a new mode of doing touch through instrumentally aided experimentation.*" **(Parisi, 2018)**

In the 19th century, the scientific community's interest in touch led to rational experiments aimed at isolating the components of tactile perception (touch, temperature, pain, and itch) under the umbrella term "haptics". Tools and precise methodologies were used to increase data reliability and quantify haptic properties, some of which remain valid today.

2.1.3

From theory to practice - First half of the 20th century

Following the previous century research outcomes, the new wave of experimenters was more aware of the human ability of perceiving tactile feedbacks, together with an acknowledgment of its opportunities and limitations. The first part of the new one is marked by increasing efforts in research and development of haptic linguistic communication.

Although the use of machines in this scope was quite new for the time, during the previous centuries, people had already sought to invent ways for blind people to learn and communicate through written language using touch instead of sight. Most attempts focused on replicating the visual experience of reading, using the same pictograms and simply raising their shape in order to be perceived by fingertips and the hands, without taking advantage of the unique properties of tactile perception.

One of the pioneers in this matter is Louis Braille, who was blind from birth. He wanted to create a linguistic system specifically designed for blind people, which would exploit the characteristics and advantages peculiar of the tactile channel. Although systems to communicate language for blind people were already in use, Braille thought they were difficult to master and not very practical in everyday life, especially outside the Royal Institute for the Young Blind, the school he was studying in.

Charles Barbier's "écriture nocturne" (night writing), a linguistic system developed in 1815 to allow the French army to communicate in the dark without being noticed by the enemies, played as an inspiration for Braille. The base mechanism of this military communication system was a matrix of 12 dots where letters corresponded to a unique pattern of raised dots. Although the way it worked was effective and exploited the inherent characteristics of the tactile system, the dot matrix was higher than the index finger's pad, requiring readers to move their finger both vertically and horizontally to scan each letter, slowing down the process and resulting therefore not as effective.
Considering this limitation, in 1824 at age 15, Braille developed his own version of the linguistic system, which was easier and faster to scan compared to previous attempts. With a 6 dots matrix instead of 12 readers were able to decrypt letters and sentences by simply sliding their finger pads horizontally. The combination of 63 unique patterns of raised and unraised dots included all the letters of the alphabet, numbers and most common punctuation. **(Britannica, 2022)**
The Braille system is used nowadays to communicate in different languages. To accommodate symbols and letters required by some languages, the systems includes patterns unique to those.

A second example of substitution of vision and hearing for linguistic communication purposes is the so called **Tangible telegraph** **(Parisi, 2018)**. The morse code was a communication language already in use at the time, through acoustic feedbacks reproducing patterns of lines and dots, people were able to decode them into actual letters and therefore words and sentences.
The tangible telegraph uses the same underlying mechanisms, but replaces the acoustic stimuli with ones haptically perceivable. The two methods in used were:

- Mechanical, where the device through kinetic movement directly tapped the human body;
- Electrical, where the receiver held the telegraph's wire directly feeling dots and lines as shocks.

Despite the different nature of conveying language through haptic cues, these methods proved experimenters of the 20th century that the tactile system could somehow replace vision and hearing for communication purposes. The first half of the twentieth century focused so on finding solutions and technologies to use haptics as a communication channel.

In 1925, as telephone communication engineering challenges arose, the American Telephone & Telegraph (AT&T) company and the Western Electric company, founded the Bell Telephone Laboratories, today known to most as Bell Labs. **(Nokia Bell Labs)**

Robert Gault, at the time part of the Lab, developed the **Teletactor**, a device composed by a microphone, an amplifier and a receiver unit able to convert people's voice into vibrations detectable by the skin, leveraging the same functioning of acoustic waves for the ears. The Teletactor was described as "a new instrument that enables the deaf to hear with their hands". **(Popular Science article, 1926)**

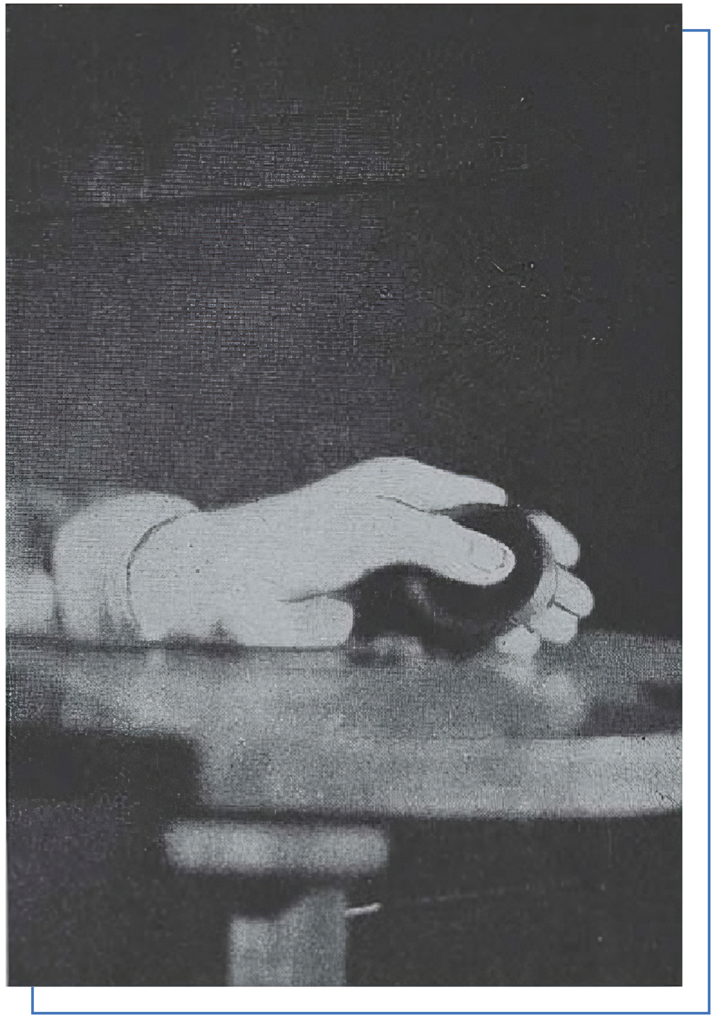


fig. 22 | Single-unit Teletactor
Robert Gault, 1927; published in Journal of the Franklin Institute 204

The vibrating membrane reproduced the entire spectrum of speech waves. The complexity and the wide amplitude of those limited the ability of user of perceiving them clearly due to the "maximum threshold of vibrotactile perception" discovered in the previous century by Ernst Heinrich Weber **(Britannica)**.

Despite the first poor outcomes, Gault truly believed in touch as a way to convey speech and as a communication media on par with television and radio, so that he devoted two decades of research into this, participating to conferences and writing articles.

The difficulty of perceiving voice vibrations through the Teletactor was not mainly due to the intrinsic limitations of the haptic system, but rather a lack of knowledge and best practices for conveying messages.

With the past experience in mind, in 1929 Gault patents a new system able to convey more easily speech, following the same mechanism of tactile vibrations: the **Multiunit Teletactor**. **(Parisi, 2018)**

The device employed an electrical filter that broke the speaker's voice into five distinct bands, each carrying a range of frequencies to a specific vibrating reed. Gault used this method to subdivide the speech vibration amplitudes into five channels, each applied to one finger: low vibrations (below 250 Hz) to the thumb, 250-500 Hz to the index finger, 500-1 kHz to the middle finger, 1-2 kHz to the ring finger, and high pitch vibrations (above 2 kHz) to the little finger.

Despite the improvement, the device still required extensive training for the user to understand the vibrations. A specific pressure and precise placement of the fingers on the vibrating parts was necessary. It could take over 100 hours to master. **(Parisi, 2018)**

The complexity of the device, and the limits it imposed, made it impossible to use outside the laboratory, resulting in the project's failure in the late 1930s. This, however, provided the basis for future experiments and demonstrated that tactile communication interfaces were possible. Furthermore, he found that haptic perception accuracy could be improved with training.

During the 1920s and 1930s, Gault's work on the Teletactor was widely recognized in the haptic field. By the late 1940s, psychologist F.A. Geldard sought to create a technology that would be beneficial not only for those with hearing impairments, but also for those struggling with the overstimulation of visual and auditory channels in their daily lives. **(Parisi, 2018)**

Morse code was effective for communicating through touch, but Geldard wanted to design a system that was not just a tactile equivalent of Morse, but was also faster in conveying messages.
He proposed a language he called "**Vibratese**", which employed five vibrating motors located on different parts of the torso. Each motor was capable of generating three levels of intensity (low, medium, and high) in three different durations (short, medium, and long).
This combination of location, intensity, and duration allowed for forty-five distinct tactile sensations, with 26 assigned to letters, 10 to numbers, and 4 for frequently used words such as "of," "and," "the," and "in". Vibratese was overall a more efficient system than Morse Code when comparing the speed of transmission - with a rate of 67 words per minute instead than 24 wpm - and also better than the Teletactor in terms of training effort - 12 hours instead of more than 100. **(Parisi, 2018)**

After these experiments and many iterations, Geltard stated that **the most fundamental and basic coding components for cutaneous communication are location, duration, and intensity** no matter the meaning or type of information to be transferred.

Vibratese proved to be successful as a code, but its associated communication device was too complex and inflexible for widespread adoption beyond the laboratory. This was especially true in the battlefield, where it was initially intended to be used.
Despite the partial failure, Geltard's efforts in Vibratese sparked interest in the field of haptic communication interfaces. In 1962, he and Carl Sherick opened the "Cutaneous Communication Lab", and many more followed suit across the US.

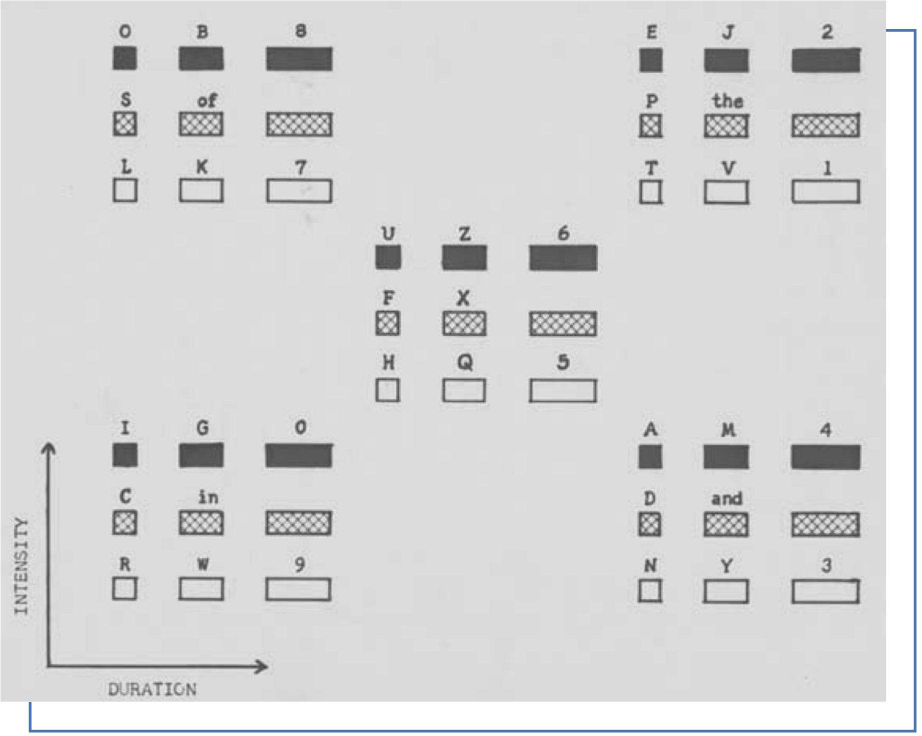


fig. 23 | Vibratese's coding scheme - Howell, 1956

In 1960, researchers in touch communication and interfaces joined forces at the US Army Medical Research Laboratory. They formed a continuous collaboration, sharing results, knowledge, machinery, protocols, etc., all with the same goal: to improve the research domain. Most of the research was funded by the army and supported by universities. **(Parisi, 2018)**

Always in the 1960s, research efforts in tactile communication as a way to substitute vision and audition - Tactile-Visual Sensory Substitution (TVSS) - arose not only for language transmission purposes, but also for haptic perception of images. Engineers, in collaboration with psychologists, worked together to understand the characteristics of human tactile perception that would enable people to virtually visualize two- and three-dimensional images in their visual cortex as an interpretation of artificial haptic stimuli, and also to create machines capable of doing so.

The neuroscientist Paul Bach y-Rita, at the time part of the Smith-Kettlewell Institute of Visual Sciences working on sensory substitution, stated in conferences and to its students that "**You don't see with the eyes. You see with the brain**" **(Bach-y-Rita, 2001)**. During his research period he developed several machines able to convey images through the haptic channel, including the **Tactile Television system in 1964**.

It was composed of a user-controllable camera capable of recording the environment, an oscilloscope that translated high-resolution images into black and white heat maps in real-time, and then into tactile pixels within a 20 x 20 matrix (totaling 400); the last component was a dentist chair with a matrix of vibrating motors mounted on the back. The blind user, by moving the camera, was able to perceive the shape, movement, and relative position of the objects in front of him through the accurate vibration of the actuators on his back. **(Parisi, 2018)**

After only 10 hours of training users were able to recognize objects and their geometric properties, movement and the position in the space. Despite the success of the experiment, the Tactile Television system had the same fate of Vibratese and Teletactor, being unusable outside controlled environments and precise experiments.

Throughout the first part of the twentieth century haptic research and development in sensory substitution proved that the tactile channel is able to perceive such information through artificially generated stimuli, however as soon as it goes outside controlled environments the efficacy decreases. Despite this, the transmission of coded messages through the haptic channel is successful and still being developed today, particularly in gaming and mobile communication devices.

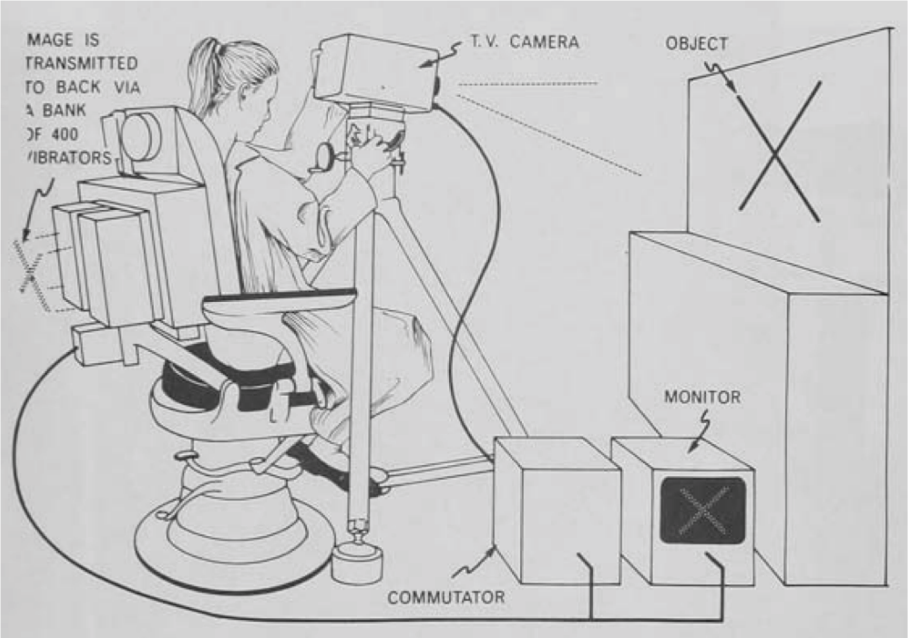


fig. 24
Schematic representation of the Tactile Television System
Paul Bach-y-Rita, 1970

2.1.4

The epoch of haptic interface - Second half of the 20th century

If in the first half of the twentieth century the efforts of researchers, scientists and experimenters funded mainly by military institutions focused on the development of alternative methods to transmit language through the tactile channel, during the second part of the century the focus shifted on the development of methods and machines able to reproduce tactile sensations typical of object's manipulation.

As the book "Archaeologies of touch" by haptic historian David Parisi **(Parisi, 2018)** highlights, **this new era of haptic research and development is based on human-machine tactile communication, enhanced by computer rendered experiences**.

Ivan Edward Sutherland, computer scientist and father of computer graphics and Virtual Reality technology **(Britannica)**, in 1965 envisions a device able to completely reproduce reality under all human senses through computer processing and rendering, stimulating a **telepresence** sensation:

> *" The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in.*
> *Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked. "*
>
> **— Sutherland, 1965**

To create a complete sensory illusion, the "ultimate display" would have been composed of an head-mounted display for vision and of an advanced kinaesthetic device for tactile perception capable to simulate all the forces within the virtual world, allowing people to interact with objects and perceive their properties.

This device - hoped since the very beginning of haptic interface R&D - is an all-in-one system able to convey all features of human haptic perception like touch, temperature, pain and itch. It was considered as an "Holy Grail" of haptic technology, which is still not available and technologically far from the current development of computer haptic interfaces. Despite this Sutherland's vision of computer powered electromechanical force-rendering machines acted as a precursor to the discoveries and experiments of the following years.

As the Cold War takes place, in the 50s and 60s, military interest into extending human body's capacity to operate in distant locations arose. The development of Project Manhattan and therefore the research in the nuclear subject, required robot hands to manipulate radioactive objects remotely in order to avoid direct exposure to harmful radiations of the personnel. The lack of a force feedback resulted in poor handling precision and so risky situations and coarse results, forcing the US military to consistently fund projects aimed at overcoming this issue.

One of the devices able to solve the challenge was the **Argonne Remote Manipulator** - or ARM -, developed in 1953 by the mechanical engineer Raymond Goertz. The machine included for the first time a force-reflection mechanism that would mimic the forces perceived by the remote hand - the slave - by means of force actuators installed on the object handled by the operator - the master - simply by using electrical current. The electrical voltage used to operate the slave arm in contact with objects, was then translated in real-time into a resistance to the master unit - heavy objects required high voltages, therefore transformed into high resistance - allowing high manipulation precision and 6 degrees of freedom. **(Grunwald, 2008)**

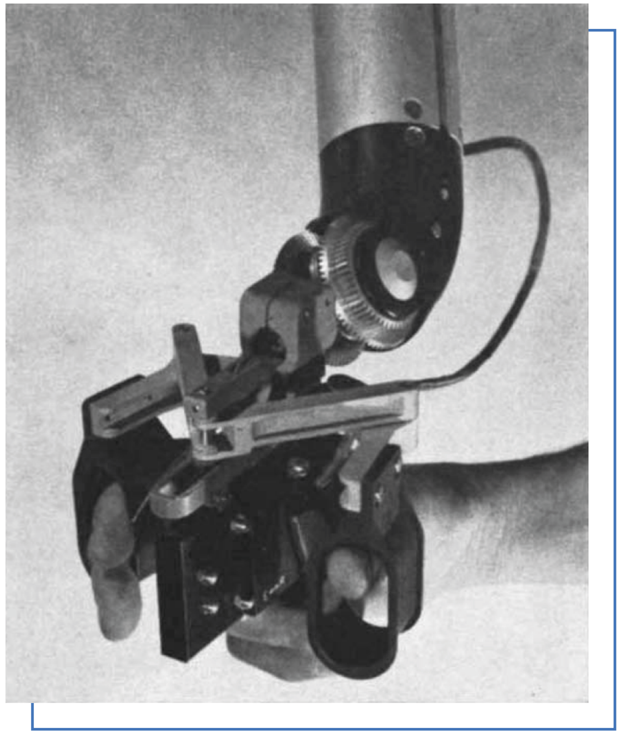


fig. 25 | Argonne Remote Manipulator (ARM) - Mosher, 1964

In 1967, at the University of North Carolina, researchers started to develop a series of haptic machines able to let users manipulate completely virtual objects under the Project GROPE. Initially bi-dimensional with the GROPE 1, with GROPE 3 they also included the third dimension in combination with a stereoscopic display to view the computer generated virtual objects. **(Parisi, 2018)**

In the late 1880s, haptic devices began to draw the interest of people from other fields as well. Computer scientists, psychophysicists, and cognitive psychologists collaborated to explore and study haptic perception.
The resulting devices were called "haptic interfaces" instead of "force displays", following a similar trend to what happened in the previous century with the term "haptics" as an umbrella term for all things related to tactile studies and activities performed into laboratories.

The 1990s were a period of immense progress and development in the realm of haptic interfaces primarily due to financial investments and advances in computer processing power. **(Parisi, 2018)** This decade was a crucial turning point in the history of this field, with researchers and developers making significant strides in furthering its capabilities. Hiroo Iwata, a prominent figure in the field of haptic interfaces, referred to the 1990s as the "**Epoch of Haptic Interface**", emphasizing the magnitude of the advancements made during this decade. The advances made throughout this period paved the way for the revolutionary haptic technology and user interfaces we experience today.

As the new discipline of haptic interfaces started to be heavily investigated, numerous figures in the research field segmented haptic studies into more specific categories to focus on smaller question and therefore increase the amount of knowledge. Mandayam Srinivasan, founder in the 1990 of the Laboratory for Human and Machine Haptics at MIT, subdivided his laboratory's research into **Human haptics, Machine Haptics and Human–Machine Haptics**. The former investigates on how the human brain interprets haptic stimuli, the second focuses on the development of machines able to sense haptic stimuli mimicking the human skin, while the latter concentrates on developing machines and algorithms capable of transferring haptic sensations, including as a subfield the discipline of "**Computer Haptics**". **(Carts-Powell, 1999)**

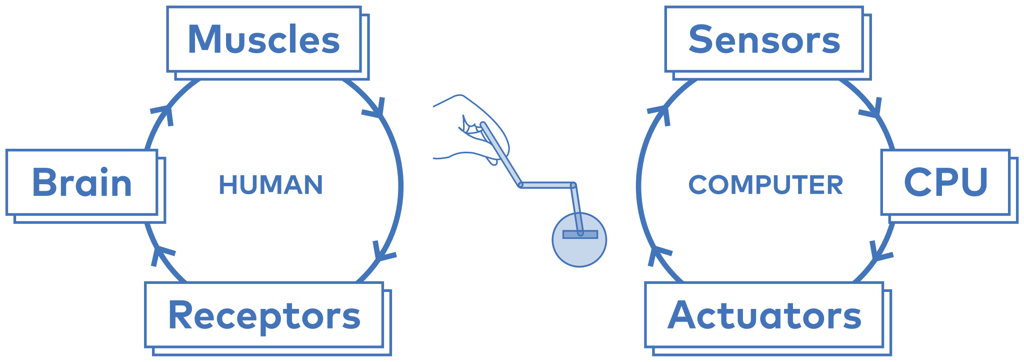


fig. 26 | Haptic HCI Loop - adapted from Carts-Powell, 1999

The high volume of experiments conducted in parallel, the number of machines produced as a result, and the varied goals of haptic illusion, create a timeline that is often unconnected. Therefore, we will focus on historically important devices, linked by a common thread.
Since one-to-one haptic sensations are impossible to reproduce, **haptic designers had the task of defining the type of haptic properties to include and contend with the limitations imposed mainly by:**

- **Technology**: lack of processing power, high latency, low speed;
- **Neurophysiology**: complexity of human perception;
- **Commercial viability**: cost, market, ergonomics, etc.

Devices with high fidelity were in fact hard to build and therefore expensive, while easy to build and cheap machines, performed poorly when convincing users of haptic illusions. **(Parisi, 2018)**

Due to the constraints previously mentioned three main types of devices have been developed to reproduce these object interaction's macro sensations: **shapes and textures** (single-point of contact), **surfaces**, and **grasp and interaction with objects** (without grounded forces).

Shapes and textures

To perceive shape and texture properties of virtual objects, the most popular devices developed during the 90s where the tool-based devices: force displays able to transmit haptic stimuli to the users by means of a machine simulating a single point of contact between the virtual surface and the user.
One of the first successful examples is the **PHANToM**, developed in 1993 at MIT by Thomas Massie and Ken Salisbury. It is a device in which the operator inserts their fingertip into a thimble. The machine is then able to detect its 3D movement and track it in a virtual environment. When the virtual representation of the fingertip makes contact with a virtual object, the mechanical arm precisely replicates a force resistance, giving the operator a realistic sensation of grounded forces like weight and also texture and stiffness. **(Parisi, 2018)**

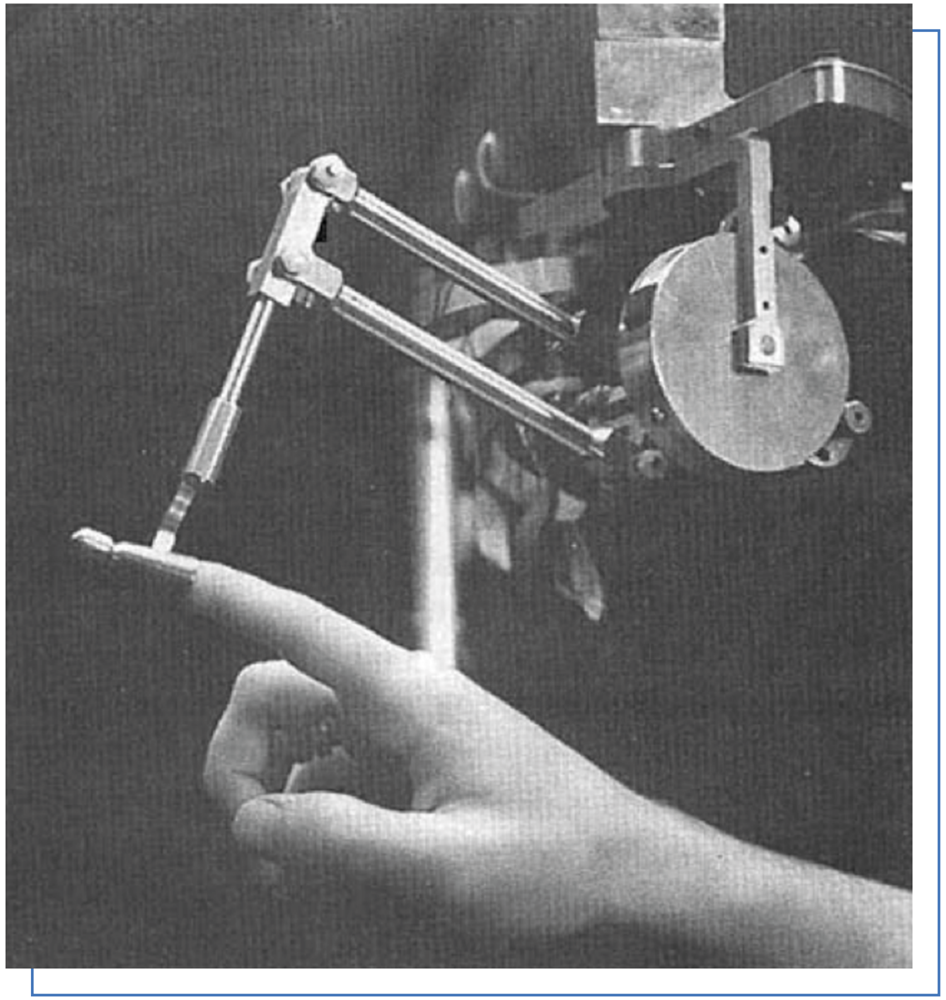


fig. 27 | Original version of the PHANToM - Massie & Salisbury, 1994

Future versions of the PHANToM, as well as for competitors, replaced the thimble with a pen shaped grip, allowing for greater precision and lower complexity of the machine.

Due to the nature of these types of devices, users had to rely on intermediary tools to interact with virtual objects, restricting the experience of a thorough and unrestricted exploration of the objects.

Surfaces

To overcome this limitation haptic researchers developed starting around 1994 object-oriented machines, where the devices themselves move and deform in order to reproduce the shape of the virtual object, enabling users to directly interact and feel them with more points of contact.

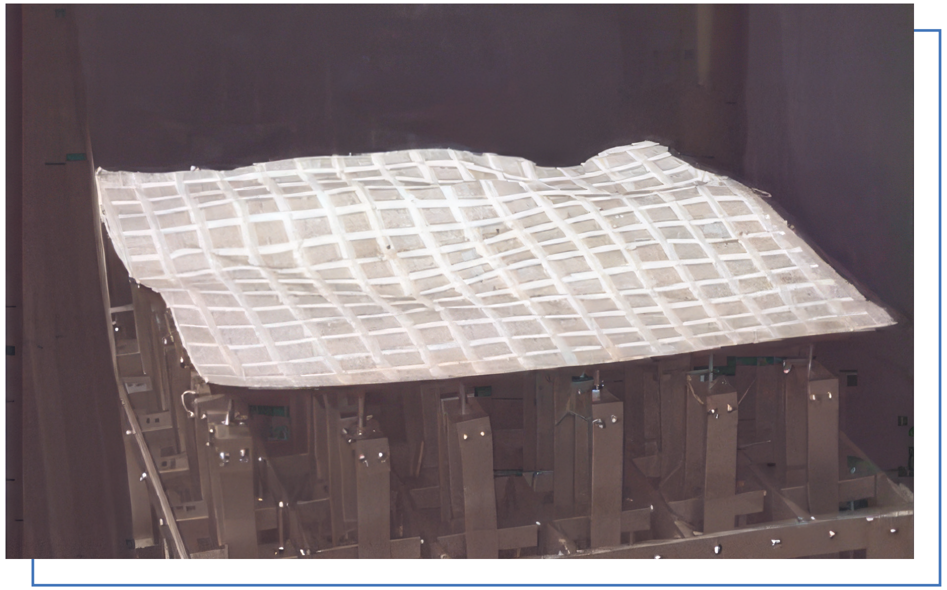


fig. 28 | FEELEX with test image projection - Iwata et al. , 2001

FEELEX, created in 1997 by H. Iwata, H. Yano, F. Nakaizumi and R. Kawamura, aimed at adding haptic surface feedbacks to graphic images. The device consisted in a matrix of pistons 24x24cm. Depending on the projected image, individual pistons were moved individually on their vertical axis deforming a sponge display to replicate the surface of the virtual object. Not only was the device able to recreate the object's geometry, but also its stiffness when the user pressed the surface with their hands. Softer objects caused a larger movement compared to harder objects when a specific force was applied. **(Grunwald, 2008)** Later versions of the device reduced the dimension of the pistons allowing for a better spatial resolution.

Grasp and interaction with objects

In the 1990s, a third type of device was developed, allowing users to not only feel the geometry and stiffness of simulated objects, like in the FEELEX, or create stimuli to perceive texture, like with the PHANToM, but also providing greater freedom of interaction with both hands and feeling haptic sensations with all ten digits. The machines, positioned on the user similarly to gloves, captured real-time data of arms, hands and fingers' movement through twenty-two sensors. The signals, later transmitted to a computer, were used replicate the user actions in the virtual environment. Through the use of joints and actuators the device rendered realistic resistance and force feedback to simulate the interaction with the virtual objects, like grasping an apple, or squeezing a ball. **(Parisi, 2018)** Devices using this technology are the **CyberGrasp**, developed by Virtual Technologies Inc. and funded by the US Office of Naval Research; and a lightweight and simplified version: the **Rutgers Master**. **(Grunwald, 2008)**

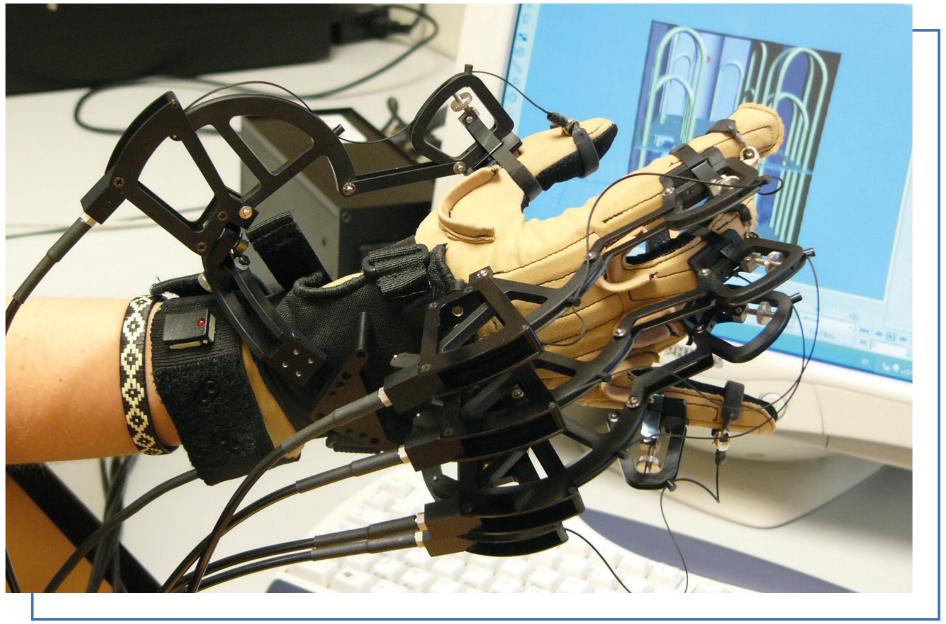


fig. 29 | CyberGrasp glove - CyberGlove Systems

Devices such as these are still being developed nowadays for virtual reality purposes. Their main limitation however is that, without a ground connection, they cannot transfer forces necessary for perceiving weight and mass (grounded forces).
At the end of the 20th century and of the "Epoch of haptics" (Hiroo Iwata, 2008), no Holy Grail or "ultimate display" had been discovered. This posed a challenge to researchers and engineers, who sought solutions and developed machines to recreate individual aspects of haptic perception.

In parallel to professional and research solutions, in the consumer market game manufacturers used the haptic sense as one more way to immerse players inside the storyline and the virtual environments. Console peripherals included vibration feedbacks generated by eccentric rotating mass motors precisely activated according to the visual and sound cues.

Examples of **consumer grade applications in the late 90s** are **Nintendo's N64 Rumble Pak** - an add-on device for the N64 controller launched in 1997, which once connected enabled vibration stimuli at specific moments, eg. when firing a weapon **(Nintendo 64 fandom)** - **Sega's Tremor Pack and Jump Pack** by 1999 - based on Nintendo's add-on concept - and **Sony's DualShock controller** for the original PlayStation in 1997 - an all-in-one controller with embedded vibration motors. **(Teslasuit.io)**

fig. 30
Playstation 1 controller
Wikipedia

fig. 31
Nintendo 64 Rumble Pack
Nintendo 64 fandom

2.1.5

Touchscreens and new challenges - 21st century

The last decade of the XX century saw many advances in the field of haptic interfaces, leading to the development of a variety of devices that could reproduce different tactile sensations enabling virtual object manipulation and interaction. However, the reduced interest into virtual reality in the early 2000s and the end of the Cold War resulting in a reduction of military funding, led to a decline of haptic interfaces research. **(Parisi, 2018)**

With the slowdown of novel advances in computer haptics, the focus shifted to integrating knowledge developed in previous decades into consumer-grade devices. This opened up new opportunities for marketing and user experience design.

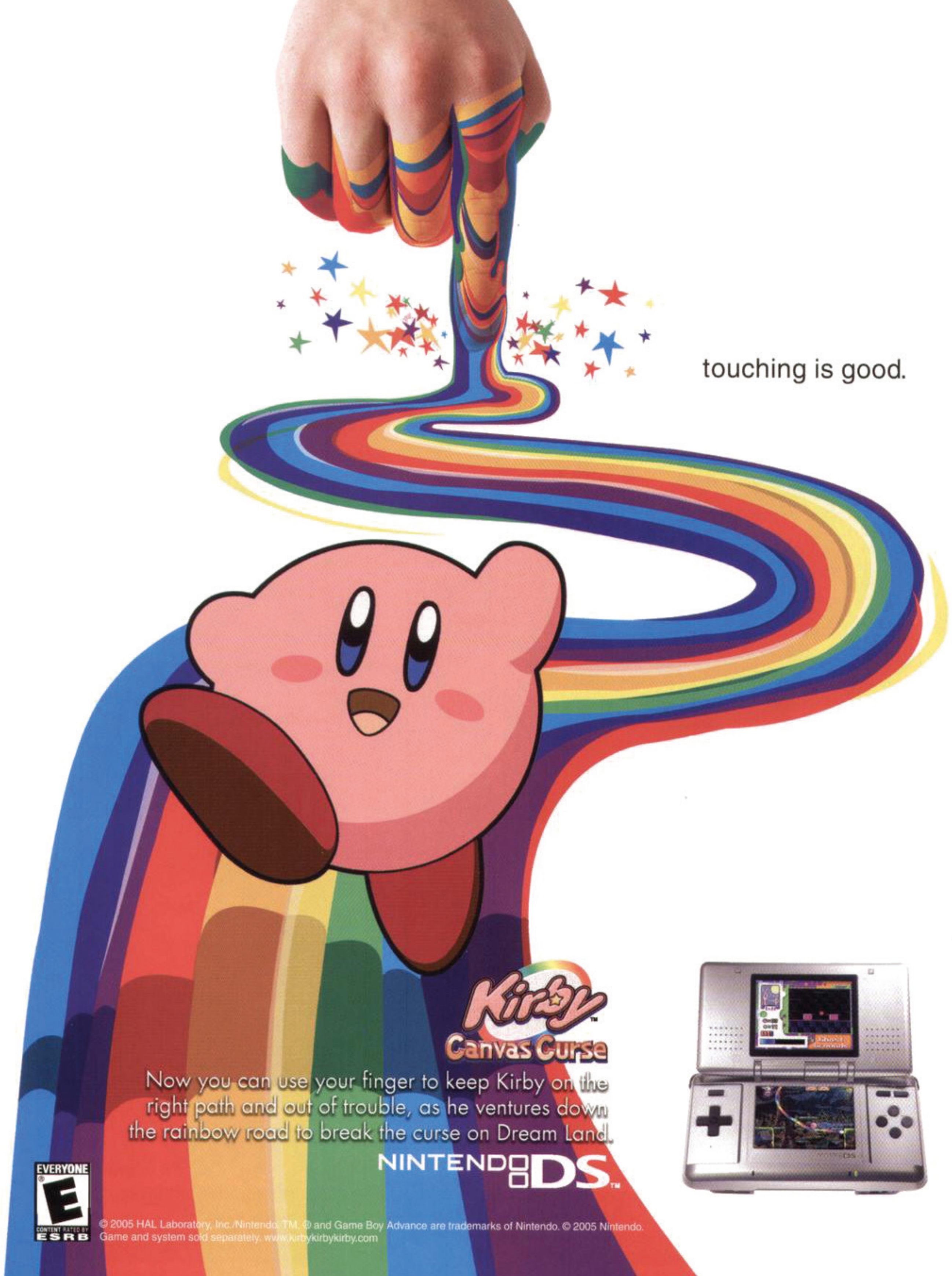
From a Human-Computer Interaction perspective, the first decade of the 21st century was a period of widespread adoption of computers and mobile technologies. This was largely due to a decrease in hardware costs, and the introduction of graphical user interfaces, which made these devices accessible and easy to use for everyone.

If computers had keyboards and mice to interact with the operating system, for portable devices a new technology took over:
the touchscreen.

The **Nintendo DS** - released in 2004 - was a pioneer of touchscreen gaming. It featured two displays; the upper one showed most of the graphics and gameplay, while the lower one enabled a new way of interacting with the storyline, characters and virtual objects through a capacitive touchscreens able to recognize both fingers and the included stylus. Along with traditional physical buttons, the DS brought innovation in the game industry enabling new game mechanics, through direct taps, swipes, drag, etc.

To advertise this new technology available in the new console, Nintendo carried on an extensive marketing campaign aimed at touching the deeper level of gamers: Touching is good. The new Nintendo DS, according to the company, aimed at rediscovering the sense of touch hitherto forgotten in favour of GUIs and sometimes demonized in the computer industry. **(Parisi, 2018)** Thanks to it's hardware people could have a completely new tactile experience:

> " *Touching is not good.*
> *Or so we're told. Please do not touch... yourself, your nose, wet paint, that zit, grandma's best china. You name it, you can't touch it. We think that's wrong. Why shouldn't you touch what you want? What if you could touch the games you play? What if you could make something jump or shoot or run just by touching it? Let's face it, touching the game means controlling the game. And when we say control, we mean precision control. One right touch and you're master of the universe. One wrong touch and you're toast. Forget everything you've ever been told and repeat after us. Touching is good. Touching is good.* "
>
> **— Print ad for the Nintendo DS portable gaming system**



Now you can use your finger to keep Kirby on the right path and out of trouble, as he ventures down the rainbow road to break the curse on Dream Land.

© 2005 HAL Laboratory, Inc./Nintendo. TM, ® and Game Boy Advance are trademarks of Nintendo. © 2005 Nintendo. Game and system sold separately. www.kirbykirbykirby.com

fig. 32
Nintendo DS ad serie - Kirby
Nintendo. , 2004

During the iPhone reveal (San Francisco, January 9, 2007) Steve Jobs dedicated an important section of its presentation on the role of touch as the unique way to interact with the new breakthrough device, discrediting solutions implemented by competitors like the physical keyboard or the stylus, intermediaries and therefore obstacles between users and the virtual content.
On the same line of Nintendo's DS advertisement, in 2007 for the launch of the **iPhone** and of the **iPod Touch**, Apple releases its campaign: **Touching is believing**. With its manifesto, the American company wanted to remark the importance of the tactile system as a medium to interact with the digital world. Retracting an index finger protracted towards the bright iPhone screen intent on interacting with a virtual world, the image recalls famous paintings from the past like Michelangelo's "The Creation of Adam" and Caravaggio's "The Doubting of Saint Thomas". **(Parisi, 2018)**

Despite the involvement of the tactile system, touchscreen devices heavily rely on graphical user interfaces (GUIs) to navigate digital information and perceive feedbacks. Moreover, although some consider the touchscreen as an improvement from an haptic perspective since users interact with the device directly with the fingers, **the one-way communication** - mostly through just a single finger pad - **and the lack of tactile cues and reactions from the screen, mark the de-facto death of haptic communication and displays**, going against the aim and vision of researchers involved in haptic research over the past centuries. **(Parisi, 2018)**

Over the course of the first two decades of the 2000s haptic development and research didn't stop at solving touchscreen's tactile limitations, indeed they continued to raise and solve challenges throughout many different sectors like VR, wearable technologies and medical devices. Despite that, none of the discoveries and devices radically solved the intrinsic property of haptics of being complex and for some aspects unknown. Consumer companies and research entities are still working on haptics trying to improve current devices and invent new technologies tackling the different aspects of haptic perception (eg. touch, kinaesthesia, temperature).

fig. 33
Original iPhone print ad
Apple Inc. , 2007

2.2

The role of touch in HCI

> *" Our eyes and our ears are assaulted so continuously, such frequent and insistent demands are placed on them, that the visual and auditory channels are seriously overburdened at times. Such oversaturation leads quite naturally to the question of whether it is only vision and hearing that can serve in communication. "*
>
> **— Frank A. Geldard, "Adventures in Tactile literacy"**

Despite the technological advancement and research, haptic sensations able to convince the human brain are still hard reproduce and it's therefore impossible to recreate an haptic experience in its completeness. During the last decades of human-computer interaction, most individuals working in Human-Machine Haptics or Computer Haptics disciplines aimed at integrating a physical dimension into digital interfaces in order to overcome issues and fulfill needs specific to each use case rather than create a new movement with common practices within HCI, envisioning new interaction scenarios with digital information. Therefore there's no such thing as structured knowledge and extensive guidelines for haptic HCI in the broader term, as there is for other human senses in HCI (eg. GUI, Voice interactions, auditory feedbacks etc.). **(Parisi, 2018)**

For this reason, to understand the benefits and constraints of haptics and how this sense is involved in today's human-computer interaction, I decided first to **understand the general purposes for which the tactile sense is utilised**, focus on the most relevant ones for the scope of the thesis, and then, **I explored the HCI research fields that employ tactility as the primary interaction modality**.

2.2.1

Sensory substitution, augmentation and reproduction

As of now, research and development efforts of haptic human-computer interfaces are divided based on the perceptual goal for which they exploit the tactile sense. According to the literature, the main categories are sensory substitution and sensory augmentation **(Macpherson, 2018)**, with a third one often included under sensory augmentation: sensory reproduction.

In the case of **sensory substitution**, the haptic sense is used to "replace a missing sense by delivering some or all of the information usually gathered by one sense to another sense." **(Macpherson, 2018)**. Use cases involving sensory substitution are the Tactile Television system presented previously, where visual information like shapes, motion and position are translated and transferred to the user through tactile actuators; or the braille system, where language is transmitted through the tactile channel.

For what concerns **sensory augmentation**, devices are used to "create a novel sense or enhance an existing sense. Deliver information to a subject via a sense that does not usually deliver that information" **(Macpherson, 2018)** . In smartphone and wearable devices this modality is extensively used to notify and communicate with users through vibration cues, or again in the automotive field to convey spatial information alerting the driver when approaching roadway lines through vibration or force feedback on the steering wheel.

Finally, when devices aim at reproduce realistic tactile sensations with machines and technological techniques, we are in front of **sensory reproduction**. Extensive research in this area is still being carried on in the area of virtual reality in order to reach the much aspired feeling of telepresence **(Sutherland, 1965)**, for example by replicating the grasping sensation through haptic force feedback gloves; or for remote manipulation.

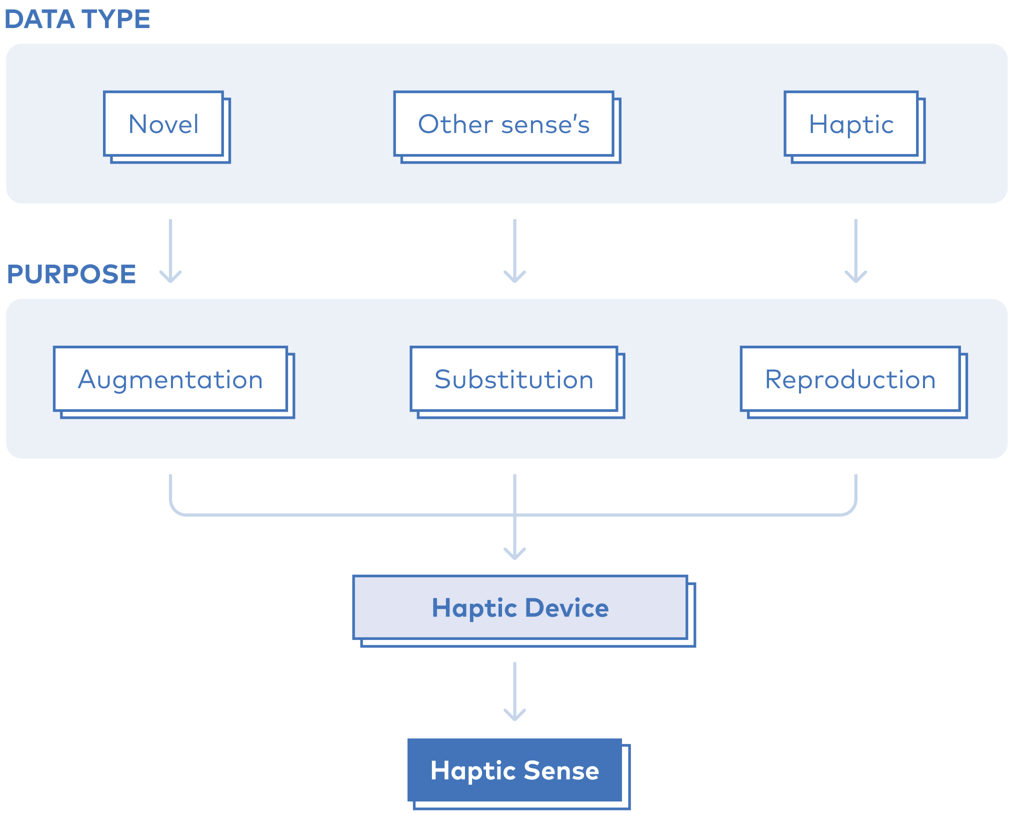


fig. 34 | HCI perceptual goal - elaborated from Macpherson, 2018

Key takeaways

If the reach of a good sensory reproduction - useful to immerse people in virtual worlds - is mainly related to technological challenges that can be solved with device advancements, on the other hand, sensory substitution and augmentation serve different purposes. Rather than trying to realistically replicate existing tactile sensations, the goal of applying these two models to digital interfaces is to convey messages that are not typically associated with the haptic channel. This opens up opportunities and new scenarios in HCI that are worth exploring. Given the main research question of the thesis - **How can haptic technology be used to improve Human Computer Interaction?** -, it is for this reason that I will be concentrating on **sensory augmentation and substitution through haptics as a way to enhance HCI**.

2.2.2

Graspable, Tangible and Natural User Interfaces

With the development of personal computers and the birth of GUIs in the 1980s, the majority of data exchanged between people and the digital world has been confined to two-dimensional screens, a mouse, and a keyboard. Despite the emergence of mobile computing and touchscreens in the new millennium, the core of **the whole experience even now mainly relies on a flat graphical user interface**. **(Ishii & Ullmer, 1997)**

We can think about our daily habits and how we interact with our smart devices and digital life. From sending a message to a friend, starting a workout session on a smartwatch, playing a movie on a TV, to input the destination on a car infotainment system, or writing code for a prototype, the scope of the interaction changes, but the modality and kind of interface remain the same in every scenario. The visual component, therefore still plays a key role in human-computer communication.

The centrality of displays, auditory feedbacks and of GUIs in modern devices has lead to a continuous **overstimulation of the visual and auditory channels**. Moreover, in situations where our eyesight is already engaged - like when we are driving - or is not in optimal condition to operate - eg. at night, underwater, etc. - opportunities open up for new ways of interaction with digital products. **(Jones, 2018)**

To offload the visual and auditory senses, researcher are trying to elaborate different ways to communicate with digital devices, receive information and manipulate data involving also the other human senses.

We can find three major currents that have been chronologically developed aimed at including the haptic channel to feel and manipulate digital information. Starting from the mid '90s with Graspable UI and Tangible UI, moving to the more recent Natural UI, the tactile dimension in interfaces is continuously been explored and implemented in more devices.

Graspable User Interfaces

The concept of Graspable User Interfaces originated in 1995 at the University of Toronto, from the Ph.D. research work of George W. Fitzmaurice. Although GUIs often try to attach semantic meaning to digital features and elements by taking inspiration from the physical world and our natural interaction with it, one of their greatest limitations is the sequential way of input via a single generic and multifunctional device, such as a mouse or keyboard. This requires continuous selection and deselection of software features to achieve desired goals that results in an inefficient **time-multiplexed interaction**. **(Fitzmaurice et al., 2002)**
When we are creating a screen in a design tool, for example, we select and use different functions (eg. frame, create shape, scale, colour picker, pen, etc.) by clicking on their representing icons (or through shortcuts), clicking on the canvas or dragging the cursor. All the actions are therefore performed via a single input device one after the other, resulting in a temporal timeline of events.

The goal of Graspable UIs is to move **from a time-multiplexed interaction, to a more efficient space-multiplexed one**, creating a sort of direct manipulation of virtual applications, by means of specialised physical objects. Providing graspable elements that are spatially aware and individually attached to specific virtual features, Graspable UIs enable a new way to manipulate digital information through physical affordances that by their natures "*are inherently richer than what virtual handles afford*" **(Fitzmaurice et al., 2002)**.

A fundamental element of the Graspable UI concept are the so called "*Bricks*": physical devices tracked in the virtual software to specific functions - eg. the corner handle of a shape - which allow the user to manipulate the virtual environment simply by reflecting the movements happening in the real world (ie. moving a brick attached to a virtual square, moves it on the digital canvass). Moreover, the **spatial awareness of "*Bricks*" allow for manipulations of digital assets involving the relative position of more elements**.

By adding two or more "*Bricks*" is in fact possible to increase the complexity of features, like scaling a shape by dragging two cubes apart involving a **two-handed manipulation**, or create a spline in real-time by positioning the control points with a specific position, rotation and distance between each other.

"*From the user's perspective, the bricks act as physical handles to electronic objects and offer a rich blend of physical and electronic affordances.*" **(Fitzmaurice et al., 2002)**

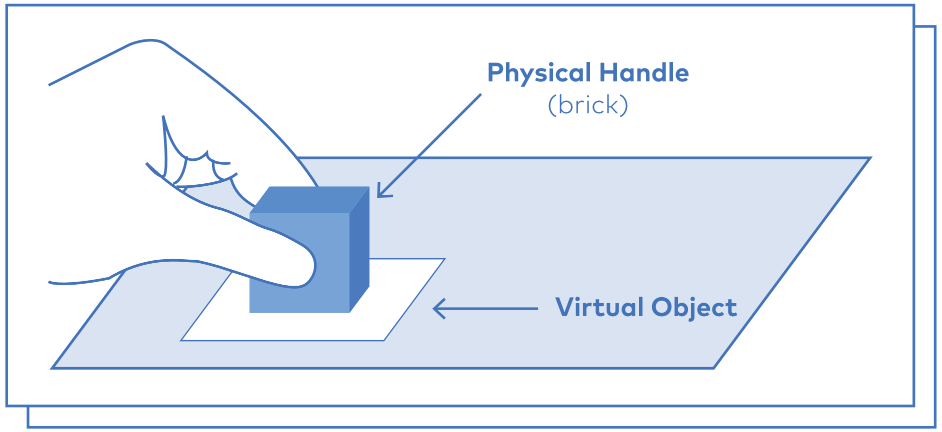


fig. 35 | Graspable UI concept - adapted from Fitzmaurice, 2018

According to Fitzmaurice, using physical intermediaries - the "*Bricks*" - instead of only the hands or fingers (as for touchscreen devices), is more desirable for two reasons. First of all the tactile feedback is essential: by providing physical objects users have a tactile and visual confirmation of their actions and of the interface status. Lastly hand gestures are not precise, the affordance of grabbing an object and releasing it set up a clear starting and ending point of the interaction.

This HCI theory has several advantages for the user: it **replaces single generic input devices with multiple specialised and context specific ones**, **enabling multi hand manipulation**, and **exploits inherited haptic skills** making **interactions more tangible and direct**.

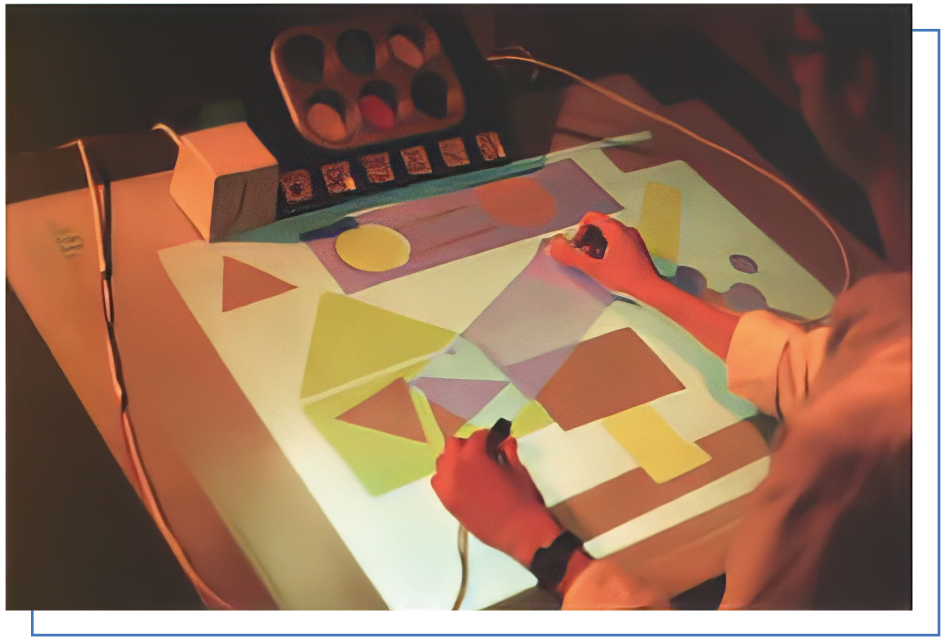


fig. 36
Graspable User Interface prototype
Fitzmaurice, 2002

Tangible User Interfaces

Inspired by the concept of Graspable UI and Ubiquitous Computing, the idea of Tangible User Interfaces, published in 1997, is to "*computationally augment physical objects by coupling them to digital data*" **(Shaer & Hornecker, 2010)** and "*take advantage of [their] natural physical affordances to achieve a heightened legibility and seamlessness of interaction between people and information.*" **(Ishii & Ullmer, 1997)**.

The goal is therefore to move part of the information usually located behind screens and place them directly in the physical world, allowing for a more tangible experience from all the senses.

The "*Tangible Bits*" concept developed by Ishii, which form the components of the Tangible UI, can be viewed as an evolution of Fitzmaurice's "*Bricks*". Unlike the "*Bricks*", Ishii's "*Tangible Bits*" were not (only) intended as a medium used to directly manipulate the digital world on a GUI - inputs- , but they were also designed to store and communicate information to users, representing virtual content and states through physical cues - outputs.

An example coming from the original research group of TUI include **SandScape**, by Tangible Media Group at MIT, 2002: a urban planning surface where users can move constructions and manipulate soil to see in real time their effect on elements like road planning, water flow and caused shadows. This is done by sensing the elevation of sand and objects' position, that is computed in real-time and then the simulated effect is projected on the surface itself.

Despite the focus of TUI theory and case studies wasn't relegated to a specific human sense, the haptic dimension (both tactile and kinaesthetic) plays an important role in terms of input modality exploiting its space-multiplexing and direct manipulation properties, and also in terms of feedback reception, including tactile sensations coming from direct manipulation, passive and active exploration.

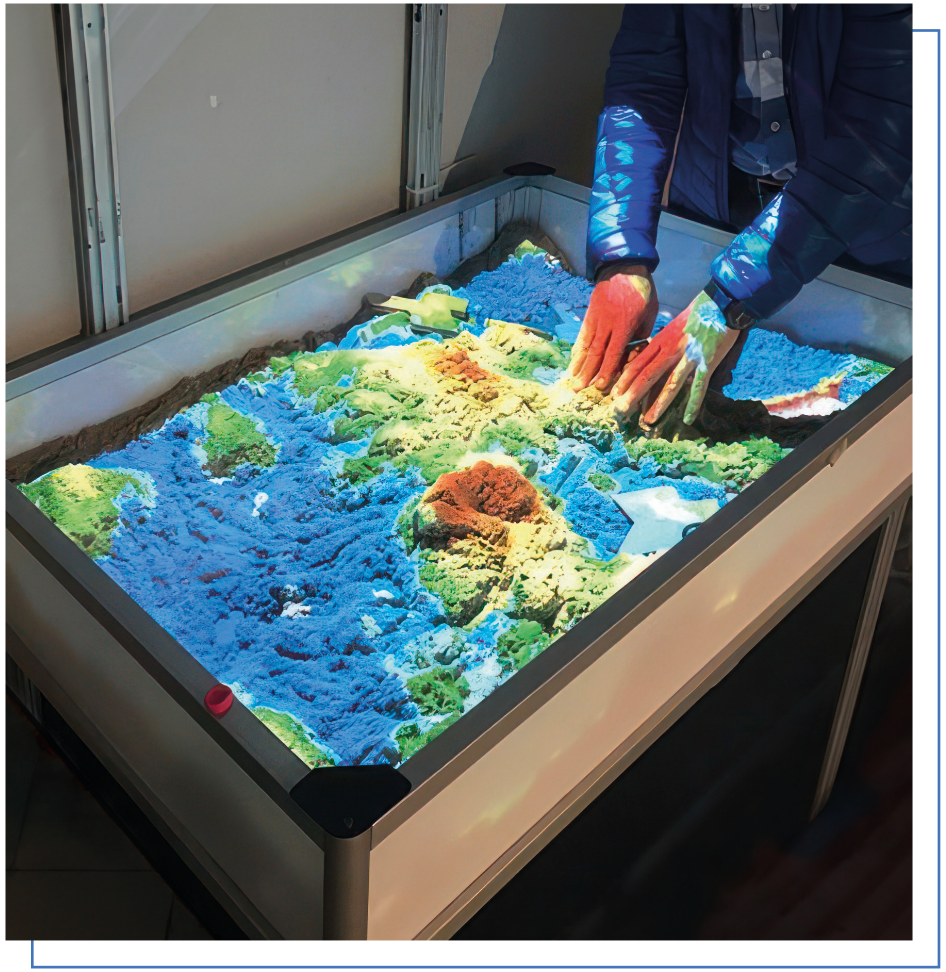


fig. 37
SandScape - Tangible User Interface
Ishii et al. ; Tangible Media Group, 2002

Natural User Interfaces

The reduction of levels of abstraction of digital information typical of Graphical User Interfaces aimed at creating more tangible, intuitive and therefore natural ways to interact with the virtual world, is what links the previously presented design fields to a much more recent and broadly accepted one: Natural User Interfaces.

In a world where interacting with an interface means to embrace a set of rules dictated by the machine - eg. click on the forward icon to advance a YouTube video, or to follow a precise directory to find a file through a series of clicks - **the concept of Natural User Interfaces relies on "*exploiting skills that we have acquired through a lifetime of living in the world*"** **(Mortensen, 2020)**. This means that instead of making the user understand the limits of the technology and teaching how he should behave in order to use it, the device itself adapts to his behaviour, providing a natural way of interaction that is already embedded in its mindset.

Although also in this case, the concept of NUI does not focus on specific sensory channels, but rather on the behaviour of the interfaces and on the way the user interacts with them (eg. exploiting the naturalness of voice), the haptic system plays a significant role in many applications. Major trends in Natural User Interfaces, in fact, include multi-touch and gestures. **(Kaushik & Jain, 2014)**

Examples of devices involving a tactile dimension that are considered as Natural User Interfaces are the Microsoft Kinect, that by recognising body movement allows people to directly interact with games' digital worlds and interfaces; the Apple Pencil that makes users draw and paint on the digital canvas of the iPad simulating the analog experience with an high fidelity level; and the multi-touch gestures used for example in Navigation apps to zoom-in and zoom-out the map.

All these case studies highlight a fundamental intrinsic property of NUIs: **Direct interaction**. In a NUI, the interface reaction happens at the same time as the user action (directness), there is a constant flow of action and reaction between the user and the interface, without waiting times or repeated starting triggers (High-frequency interaction), and finally the system should show only relevant information to the user taking in consideration the overall context (contextual interaction). **(Mortensen, 2020)**

Thanks to the direct interaction property and the exploitation of skills already embedded in our mind, the communication between the user and the machine becomes tangible and natural, opening the way to an exchange of digital information through the haptic channel, effectively enabling haptic sensory augmentation.

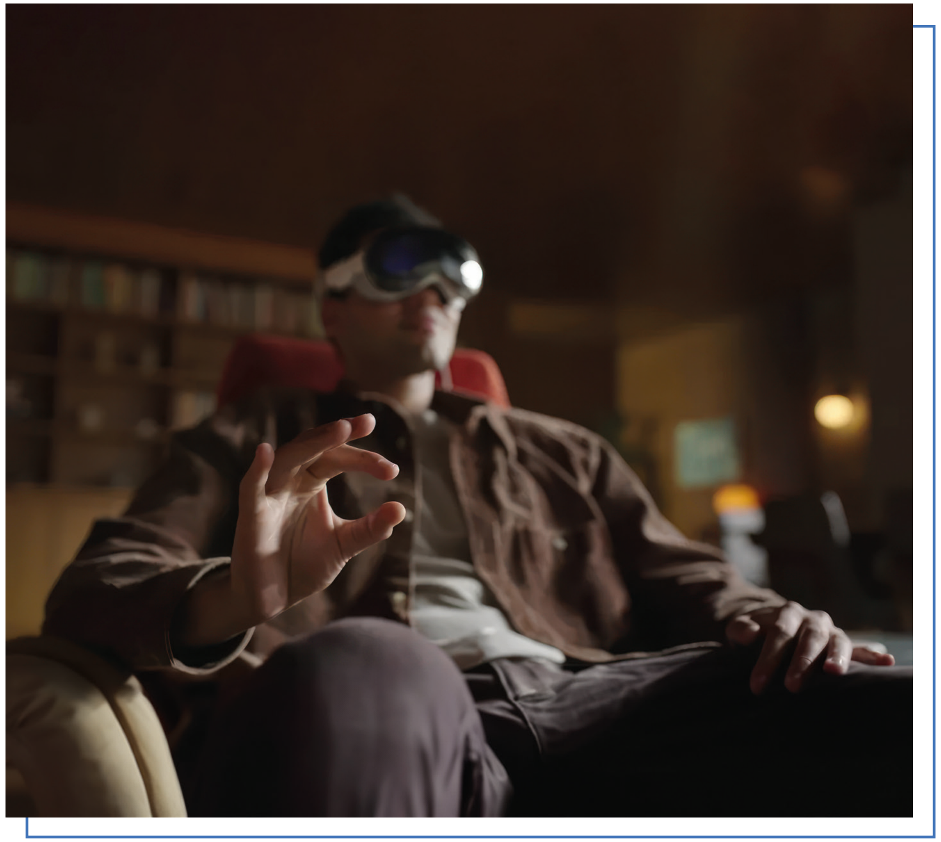


fig. 38 | Apple Vision Pro input gesture - Apple, 2023

2.3

Case studies

As we have seen, in the past decades researchers and people working in the HCI field started to push towards a world against the visual centricity of digital interfaces, where more senses are involved in order to reach more intuitive and natural interactions with information.

In the HCI concepts presented earlier, the tactile dimension appears to play a fundamental role in this mission. This is due to its inherent capabilities and high level of affordance. From a design perspective, exploring haptic-centric solutions or coupling the tactile sense with other senses (such as haptic-visual or haptic-auditory) can improve the way we experience interfaces or even open up new ways of interaction with the digital world.

In recent years many devices have tried - and sometimes succeeded - to disrupt the way we perceive and communicate with everyday objects. To showcase the potential of the introduction of haptic technologies as a way to improve HCI I decided to present some selected commercial case studies, each of which exploits different aspects of tactility to convey information and sensations through the haptic sense.

ROLI Seaboard

Haptic interaction: touch and kinaesthesia
Way of communication: input
Type of input: pressure, direction and position (gestures)
Type of interface: embodied
Application field: music

The ROLI Seaboard is an innovative Midi controller that aims at exploiting the haptic sense to create music and sound effects. The main feature of the Seaboard is the 5-Dimension tactile input sensing. Instead of considering just the key strike and hold (as for other keyboards), the music and sound creation experience is enhanced, registering also other "**organic gestures**" (ROLI), like glide (to bend the pitch), the slide on one single key (to add brightness or texture to the sound), but also from one key to another to create a seamless transition from a note to another, and finally the lift, modifying the sound resonance according to the lifting speed.
The keyboard allows users to create new types of music and sound effects, recognising natural gestures and instantly mapping these to also the finest notes and sound distortion. In this Tangible User Interface, the touch sense is involved to feel the keys' shape, while the kinaesthetic dimension is used to perceive the surface compliance and also to perform the gestures. The keyboard comes with a companion software to edit each key sound, note and effect, but most of the interaction happens physically.

Technology

The Seaboard's hardware is pretty simple. It is composed by a matrix of **force sensing resistors (FSR)** underneath a rubbery membrane. When the keyboard is been touched by the user, it transform the mechanical movement of gestures into electrical inputs which are then mapped into sound through a proprietary algorithm. **(Lamb & Robertson, 2023)**

fig. 39
Roli Seabord Block
Roli, 2017

PS5 DualSense

Haptic interaction: touch and kinaesthesia
Way of communication: input and output
Type of input: pressure
Type of output: vibration, force
Type of interface: embodied
Application field: gaming

With the new version of their console, Sony launched the PS5 DualSense controller. It is the main input device for PlayStation 5 games. Similarly to its predecessor it features a series of buttons, triggers, a touch surface and levers. The most interesting elements regarding haptics that affects the user gaming experience are the **vibrotactile feedback** and the **adaptive triggers**. Thanks to these two elements, game developers can further engage players into the gameplay through the tactile channel, without trying to realistically reproduce physical sensations, but rather, conveying information and sensation about the environment and actions using sensory augmentation and substitution.
For what concerns the vibrotactile feedback, users are able to sense HD haptic vibrations that can simulate rain drops, explosions, the opponent relative position, or the terrain texture. The adaptive triggers, indeed, dynamically modulate their stiffness to share real-time information through active exploration about tools, vehicles, weapons etc. shown in the game like a car's braking smoothness, or a gun trigger resistance. They also actively reproduce force feedback to simulates effects like a loading gun, or street defects while driving.

Technology

The PS5 DualSense haptic experience is powered by two main technologies. The HD vibrotactile feedback is rendered in real-time by the console following the game action and is produced by two **Linear Resonant Actuator (LRA)** positioned on both sides of the controller. The Adaptive triggers use a **custom developed solution that modulate the trigger stiffness or makes it move through mechanical gears** and a DC motor at the opposite end of the mechanism. **(Actronika)**

fig. 40
PlayStation DualSense 5
PlayStation, 2017

Apple Watch

Haptic interaction: touch and kinaesthesia
Way of communication: output (and partially input)
Type of input: kinaesthetic
Type of output: vibration
Type of interface: GUI support
Application field: wearable

Starting in 2015 with the MacBook Pro with Retina display, Apple introduced vibration feedback into their main products. One of the most meaningful executions where vibrotactile feedbacks are used to communicate with the user is the Apple Watch.

The device uses the tactile channel to deliver information and receive inputs from the user. Through the digital crown people can navigate through the interface by scrolling or clicking it. In the presence of lists, the watch reproduces a firm vibration feedback synchronised with the graphical animation to support the interaction.
Vibrotactile stimuli are also used as a communication channel for notifications (eg. when a message arrives), but also to inform the user about the current system status (eg. low battery, to guide the breath in the Mindfulness app, to confirm the zoom limit, etc.).

The quality of the experience is mainly due to the quality of the hardware, but also to the **natural metaphors** the vibrations patterns try to elicit in the user's mind, which most of the times result in tap sequences with specific amplitude, frequency and intervals instead of classic vibrations.

Technology

The haptic feedback are reproduced by a custom Linear Resonant Actuator (LRA) designed for quick and precise taps, called **Taptic Engine**. Modifying the frequency and the pattern, the device is able to convey specific messages. (iFixit)

fig. 41
Compass on Apple Watch Ultra
Apple, 2022

BMW gesture controls

Haptic interaction: kinaesthesia
Way of communication: input
Type of input: kinaesthetic
Type of interface: GUI support
Application field: automotive

With some of the new vehicles delivered after 2017, BMW offered the gesture control optional. The driver and the front passenger are able to control some functions of the iDrive infotainment system by using **mid-air hand gestures**, without touching the head unit display.

This way of input is particularly safe when driving, since it doesn't require the user to lean forward to touch the screen, without looking for the right interactable UI component, however, it acts only as a support for the GUI, since there's no haptic feedback.

Examples of the gestures are: a circular motion to increase or decrease the volume, move the hand to the right to dismiss popups or decline calls, move the thumb left or right to skip song.

The gestures that the system recognise are predefined, and therefore it requires a previous training or knowledge by the user, who has to remember which gesture to use for a specific control, losing the naturalness of the interaction.

Technology

The car registers the gestures through a **3D Time of Flight (ToF) camera** positioned on the roof and directed towards central console. Through an algorithm the system recognises them and are then transformed in GUI inputs. **(BMW blog)**

fig. 42
BMW iDrive 5 mid-air gestures
BMW blog, 2017

Part II

Focused Research

Haptics are used to create tangible, natural and direct interactions

Narrowing down the research

As shown throughout the second chapter, the world of haptic interfaces has a long history and encompasses a wide range of use cases, involving various technologies, aims, and applications. With the knowledge collected we can now answer to the initial research question - How can haptic technology be used to improve Human Computer Interaction? - The haptic sense is an always-on, personal and immediate channel. In HCI, haptic sensations have been used to create more tangible, natural and direct interactions delivering new and meaningful information to the tactile sense, augmenting its potential and bringing the users closer to the machine.

Despite the benefits of haptic interfaces, the popularity in the design field is still limited and so are the devices available in the market. Considering the insights collected during the general research, and the width of haptic sensation, technologies and goals applied to a variety of markets; we can say that it's impossible, or at least improbable to intervene in only one way to improve the field of haptics in general. It's for this reason that I decided to narrow down the research efforts to a precise aspect of haptic interaction that in my opinion is worth to explore, that has potential to improve HCI and that is already partly acknowledged by the design community: **Dynamic vibrotactile stimuli** (input modulated vibrations) as a bi-directional Human Computer interface for sensory augmentation.

When we look at the market right now and try to see what is the current state of haptic sensations while interacting with digital devices, we can notice how vibrotactile technologies are the ones that are mostly present. After initial growth in the late 20th century, applications now range from smartphone notifications and lane departure alerts in vehicles to in-game action enhancements. Vibrotactile sensations per se are a one-way communication channel that allow machines to notify people, since they do not require active tactile exploration and are not affected by user inputs. However, when they get directly triggered by an action, or are modulated according to it through separate actuation modalities (eg. PS5 DualSense), they can act as a real-time and tangible interface able to further engage the user and support bidirectional and direct human-computer communication typical of Graspable UIs, TUIs and NUIs.

Other arguments in favour of vibrotactile interactions that are fundamental for the democratisation of these on a large scale, are that the technology is significantly cheaper compared to the one involved to recreate other types of stimuli (eg. kinaesthetic, thermal, etc.), and that the prototyping experience and implementation is easier, due to the lower complexity of the hardware and smaller space occupied in the final device.

Looking at vibrations in the HCI and design fields, much more content has been produced in terms of research and case studies, although there's not an extensive repository of guidelines or common best practices, and there are still some open and unexplored directions.

In order to determine how dynamic vibrations for sensory augmentation can be further developed and showcased, and to understand what would be most beneficial for designers to consider, envision, and evaluate this type of interaction, it is necessary to understand what's behind vibrotactile HCI, the state of the art and also the designer's perspective.

The second part of the thesis will therefore develop as follow: **chapter three will analyse how vibrations are defined by its most basic building blocks**, how these can be perceived as informations, together with other sensory stimuli and finally what are good examples of dynamic vibrotactile experiences; **chapter four will focus on the tools through which designers can explore and prototype with haptic technologies**, going deeper into the hardware and software that allow them to include dynamic vibration feedbacks into products, and the overall experience using them; concluding with **chapter five where a focus on the state of the art of design and vibrations will be presented**, including insights coming from a field research (survey and interviews).

Vibrotactile stimuli

03

3.1

Vibration properties

While in the first chapter vibrations and their properties have been described as a fundamental aspect for humans to perceive object's information through haptic exploration (active touch) and passive touch, in this chapter, their properties will be analysed in order to understand how they can be modulated and exploited to transfer meaningful information to the users through semantic.

3.1.1

Basic building blocks

As partly seen in the first chapter, vibrotactile stimuli are quite easy to analyse. They are in fact the result of periodic motion of a mass that can be visualised in a bi-dimensional waveform.

The basic building blocks of a vibrotactile stimuli that are used to recreate unique haptic sensations are **frequency**, **amplitude** and **duration**. By modifying each of the properties, we can obtain different stimuli that can be used to convey specific information to the user. (Jones, 2018)

In the design field, frequency and amplitude are often referred to as sharpness and intensity, respectively, due to their more intuitive nature. Vibrations with higher frequency are perceived as sharper and more rigid stimuli, while lower frequencies are perceived as softer. Modifying the amplitude of a vibration, changes the perceived intensity of it.

3.1.2

Transient and Continuous Vibrations

The second building block of vibrotactile stimuli is linked to the duration of these. We can in fact distinguish two types of haptic vibrations: transient and continuous. **(Apple Developer, n.d.)**

Transient vibrations are feedbacks that last a very short amount of time (usually 1/100 of a second) **and are perceived as taps or impulses**. They can be easily experienced using Apple devices, eg. when feeling the click of the Trackpad on a Mac, or as a result of a long press on an App icon on the iPhone. This type of feedback usually requires more precise and fine controllable actuators to be reproduced.

Continuous vibrations on the other hand, **are feedbacks that last longer and are perceived as sustained feedbacks**. These are the most popular types of stimuli and can be experienced by using a game controller, feeling a notification of a smartphone, etc.
Unlike transient feedback, **continuous feedback can have varying amplitudes and frequencies within the same event** generating ascending and descending vibration feedbacks.

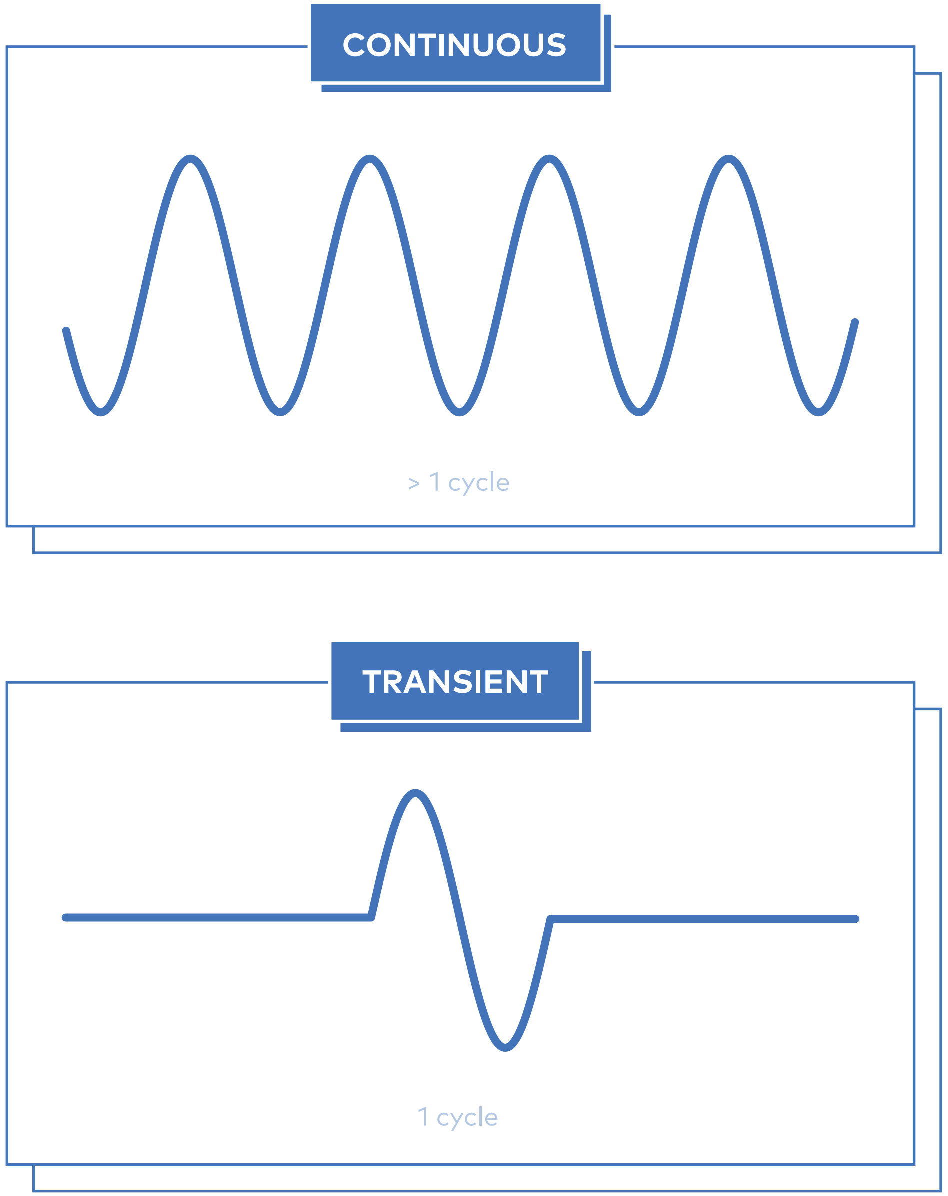


fig. 43
Transient & Continuous Vibrations
adapted from Apple, 2019

3.1.3

Haptikós app

With a theoretical knowledge of the vibration's properties and its building blocks, I decided to test their role in real life, in order to understand how they affect the perceived sensation.

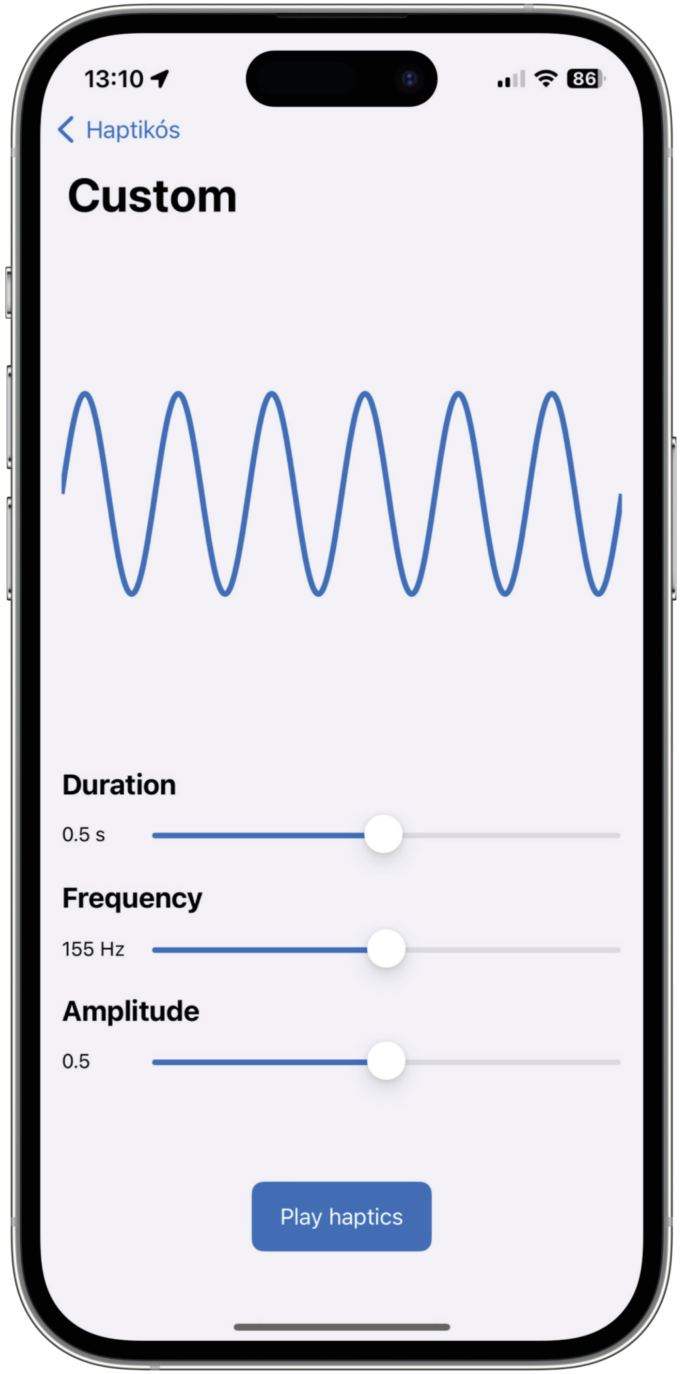
Although there are many ways to do it - eg. by using a microcontroller and some actuators, or by trying different devices - I wanted to have something much simpler, accessible and that could have been used on the go, also by other designers. It's for these reasons that I decided to develop a simple iOS application aimed at manipulating vibrations and experience the results, by exploiting the high-quality actuator embedded in the iPhone (Taptic Engine).

The name of the app, Haptikós, comes from the original old Greek term from which the word haptic is derived. **(Jones, 2018)**

The first feature of the app is dedicated to the customization of the vibration feedback. By editing the frequency, amplitude and duration through sliders, users can see in real time the effects on a graphical representation of the waveform. Tapping the play button reproduces the custom effect using the vibration motor in the iPhone.

The goal of **the second feature is to demonstrate the potential of compound vibrotactile feedbacks** by showcasing the native patterns in iOS along with an explanation of their intended usage to communicate specific information to the final user.

The app is **available on the App Store** and can be downloaded by everyone on iPhones.

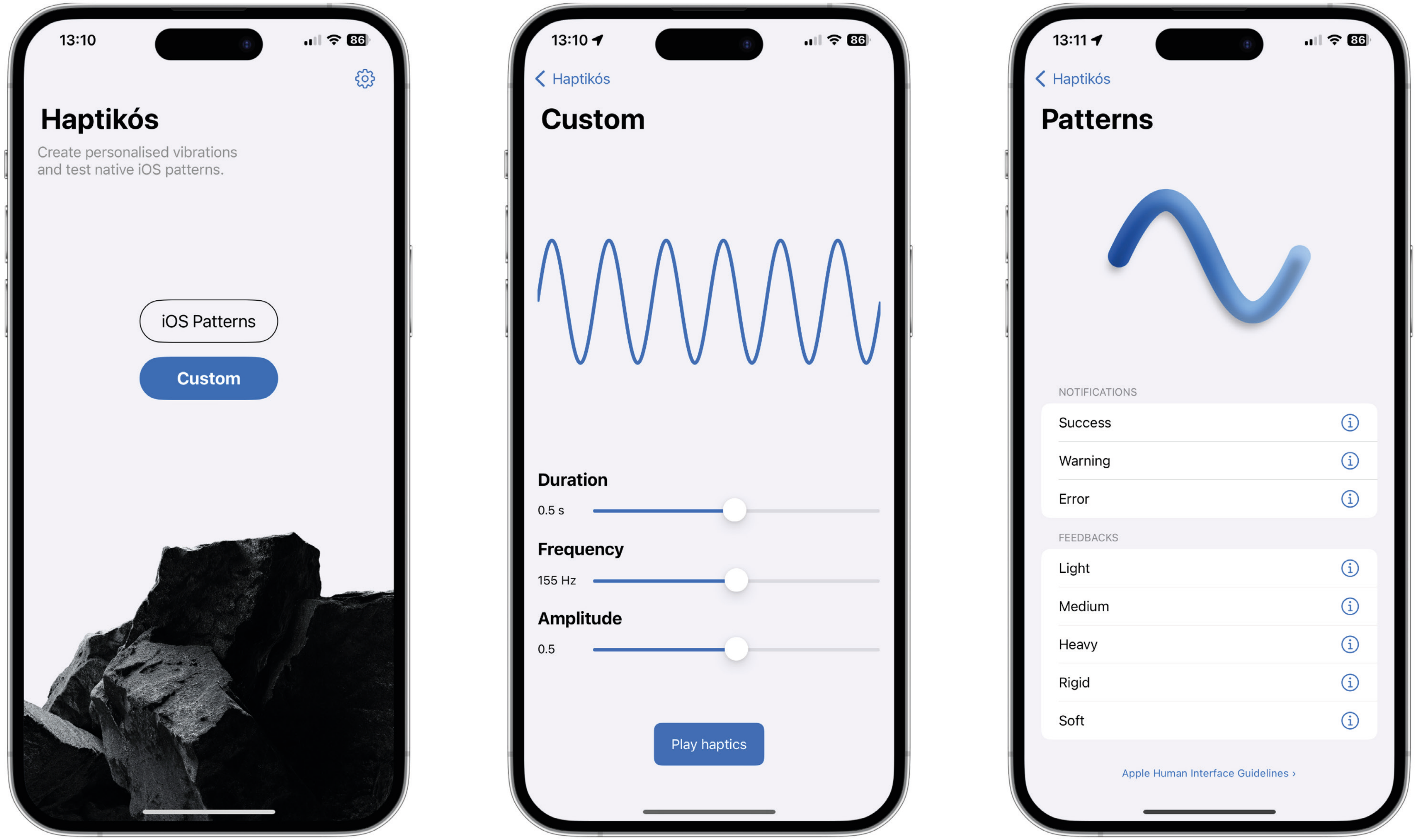


Duration
0.5 s

Frequency
155 Hz

Amplitude
0.5

fig. 44
Haptikós "Custom" feature and app icon
Raineri, 2023



Create personalised vibrations and test native iOS patterns.

Duration 0.5 s

Frequency 155 Hz

Amplitude 0.5

fig. 45
Haptikós app
Raineri, 2023

Final takeaways

While the basic properties of vibrotactile feedbacks are relative simple, by playing with them we can achieve different haptics that have a completely different character. Lower Frequency results in a softer sensation especially if the amplitude is also low; while higher ones result more rigid and urgent. If we also consider the division between transient and continuous vibrations, and we combine multiple to create patterns, we can easily recreate a large variety of distinct stimuli.

Haptic feedbacks do not have a meaning by themselves, but when they are delivered in a specific context, in response of an action, or in combination with other sensory inputs, they can communicate precise information and support user's interaction with products and interfaces.

3.2

Haptic patterns and metaphors

Single vibration blocks, are often combined into temporal sequences forming patterns able to communicate more complex information. When haptic patterns elicits a specific meaning into the user's mind - as icons do for the visual sense - we can call them **Tactons**: "structured, abstract messages that can be used to communicate complex concepts to users non-visually." **(Brewster & Brown, 2004)**

Haptic patterns and tactons can be composed by both transient and continuous vibrations, where they can have different amplitude and frequency, and different duration and time intervals.

iOS Success notification   iOS Error notification

Apple Watch notification   iOS Error notification

fig. 46 | Native iOS haptic patterns - adapted from Apple, n.d.

Metaphors can be used to communicate digital information through physical representation perceivable by the sense of touch

3.2.1

The concept of metaphors

If haptic feedbacks are not utilised to reproduce realistic sensations (sensory reproduction), but to communicate with the user through the sense of touch, is important that the message is clear and understandable.
Haptic interactions for sensory augmentation must therefore be designed so that single haptic stimuli and patterns can be recognised and linked to a meaning. This is done by using metaphors.

Metaphors have always been used in HCI. If we think about GUIs, the concepts of desktop, folders, and the way the interaction is structured, want to somehow simulate the way people lived in a working environment before the computer was adopted by the mass. Because of these metaphors, complex information are easily delivered to the user, which can manipulate them and achieve its desired goals.

Going back to haptics, **metaphors can be used to communicate digital information and events through physical representation perceivable by the sense of touch**. (Baker, 2019)

A high frequency and amplitude transient vibration can make the user feel a virtual object that is impacting with another one more rigid and with a harder material, compared to when the haptic has a lower frequency and amplitude (often perceived as softer and therefore more deformable).

Metaphors can also be used for real time and bi-directional interactions: when locating an AirTag using the Find My app for example, transient vibrations are reproduced on the iPhone; the time interval between individual stimuli increases or decreases depending on the distance between the user giving a tangible feedback that helps him in the action.
In both cases, the haptic dimension involves a new sensorial layer supporting and enriching the overall interaction in a direct, tangible and natural way, without requiring any training or explanation.

3.2

Multisensory perception

If the scope of this chapter is to present how vibration and its properties can be used to communicate meaningful information to users, when interacting with the environment around, we rarely make use of just one of our senses at the time. While we are driving, for instance, we make use of sight together with haptics and audition; when we play an instrument, indeed, haptics and audition are the main involved senses. The combination of different sensory systems allows us to have a greater perception of the situation and also a better performance - both in terms of accuracy and speed.

Haptics in multisensory interaction can be either **complementary**, in case through the tactile sense new and different information are transmitted, enriching the overall perception of the stimuli (eg. the haptic simulation of the heartbeat of a virtual character while playing a video game); or **redundant**, when the input provide the same type of information, strengthening the final stimuli perception and interpretation (eg. an ascending haptic pattern in combination with a positive sound or visual cue). **(Grunwald, 2008)**

In both cases, there are some principles that have to be taken into consideration to make sure haptic cues support the interaction by making the experience tangible, direct and consistent.

Causality

The first principle of multisensory perception is causality. When haptics are coupled with stimuli coming from other senses, **to be perceived as connected** and so to trigger the complementary or redundant role of these, they must meet two prerequisites: **temporal synchrony and spatial coincidence** - also referred to as causality **(Apple Inc., 2021)** - otherwise they would be interpreted as separate stimuli coming from different sources, or temporally disconnected.

The first characteristic means that the stimuli must be synchronised, or presented in a very short period of time, while the latter refers to the spatial proximity from which the two stimuli come from, the closer, the more probable the source is unique. **(Grunwald, 2008)**.

A practical example of redundant connected stimuli, are smartphone notifications, where sound together with vibration feedback are presented at the same time - temporal synchrony - and both stimuli come from the same source (the device) - spatial coincidence.

Harmony

The second principle is harmony. **Tactile stimuli, when delivered in combination with other sensorial outputs, must be consistent with these**, creating a sense of naturalness similar to what he would expect while interacting with physical objects in the real world.

For example, calm auditory feedbacks should be coupled with lower amplitude and frequency vibrations, compared to urgent sounds.

fig. 47
Causal and harmonic multisensory experience
Apple, 2019

3.2

Dynamic vibrotactile experiences

Sony, with its PlayStation DualSense 5 controller, and Apple with its mobile devices, are two companies at the forefront of vibrotactile technologies for sensory augmentation. In some of their experiences, the tactile channel plays a vital role in delivering meaningful information or immersing the user further as a consequence of their actions.

When the properties of vibration feedback are modulated in real-time according to the user's input, they become dynamic. To better understand the value of dynamic vibrotactile experiences, two relevant examples will be analysed from the perspectives of user experience (UX) and technology. Specifically, this analysis will examine how the experience creates value for the user and how it is made possible by the underlying technology.

Playstation 5 - Astro's Playroom

Astro's Playroom is a game launched in 2020 from PlayStation, specifically designed to showcase HD Haptics, Touchpad and Adaptive Trigger capabilities of the newly released PS5 DualSense controller. **(PlayStation, n.d.)**

The UX

Since the first welcome screen, players can feel a multisensory experience, where **animations are enriched by sounds and high quality custom haptics**, where harmony and causality are perfectly respected. Vibrations are used to convey multiple kinds of information like the use of specific tools, the texture of surfaces the character is walking on, the tension of objects the character is pulling, impacts and object's stiffness. Overall the haptic feedback gives not only a satisfactory experience, but **allow the player to perceive an whole new layer of information** that engages him more in the gameplay, while allowing him to perform better at the different tasks.

Technology

Despite The PS5 DualSense is highly recognised also for the Adaptive Triggers, for the scope of this analysis, only the HD Haptics will be covered. The UX described in the previous paragraph is made possible by the extensive and meticulous work of the game's developers and designers. **The system modifies the character's state within the virtual environment according to the player's movements and interactions**.

Depending on the type of surface the character is walking on, or the type and state of the interaction with in-game objects, the controller reproduces defined haptic effects that are modulated in real-time. For instance, the difference between walking on a steel surface, compared to a sand one, is rendered by modifying the basic vibration's building blocks: sharp and transient stimuli for steel (high amplitude and frequency), while loose and continuous stimuli for sand (lower amplitude and frequency). **(MP1st, 2022)**

fig. 48
Astro character pulling a cord
PlayStation, n.d.

Apple Watch - Directions

From the first model launched in 2015, the Apple Watch features haptic feedbacks in all parts of the UI, due to the small screen's real estate and the always-available direct contact with the user's skin. Vibrotactile feedbacks are extensively used in the Maps App.

The UX

The Maps app offers two types of experiences: free navigation and directions. The former includes searching for points of interest and starting navigation towards them, while the latter is activated when the user sets up navigation on their iPhone or directly on their watch.

To tell users where to go without looking at the screen while driving, walking or riding a bike, the Watch gives **vibrotactile feedbacks able to guide the user's movements through unique dynamic pattern** (eg. turn left, turn right, etc.). The stimuli acquire a natural meaning when the user finds himself in this specific scenario.

Technology

Each message has its own pattern, but to help users understand their distance from the turning point, the real-time location is sensed **through the iPhone's or Watch' GPS; the interval between each pattern is then modulated accordingly** - higher when they are far and lower when they are near.

fig. 49
Apple Watch Maps app - Directions

Prototyping haptic experiences

04

To better understand how we can actually make use of the theoretical knowledge and reproduce dynamic vibrations to create metaphors that guide and transfer information to the user, I decided to go for an hands-on approach. By testing the hardware and the software currently available on the market I had the chance to map the current designer experience. This chapter will focus on the prototyping workflow, by analysing the hardware part of it - actuators, sensors and microcontrollers -, and the digital one - software, APIs, development environments, etc. -. At the end, some final considerations about the designer's prototyping journey will be presented.

4.1

Haptic hardware

For every user interaction with a product or interface we can identify three basic elements that are necessary for the interaction to happen: input, processing, output.

fig. 50 | Basic interaction elements

When considering tangible interfaces that include dynamic vibrations as feedback to communicate with users, this interaction loop is more specifically enabled by:

1. **Sensors**: register and track the user interaction with the system;
2. **Compute unit**: elaborates the inputs and triggers the response;
3. **Actuators**: reproduce the system feedback.

These elements are usually decided after the type of interaction and the scope of it have been defined in the design process. In cases where the interface is going to run on a third-party device, like an app, a console video game, etc., sensors, compute unit and actuators are already defined and their properties must be taken into consideration when designing the experience.
For what concerns the sensors that can be used to trigger and modulate vibrations, these are many and can be either related to the haptic sense - like force and touch - or other input modalities - like GPS, ultrasonic and temperature (as seen in the case studies presented in chapter 3). For the scope of the thesis **I will concentrate on the two variables that are relevant for reproducing vibrations: actuators and microcontrollers**.

4.1.1

Actuators

Haptic actuators have the role of reproducing the vibration stimuli that are perceived by the user. **By receiving the trigger from a compute unit, they activate the physical periodic motion defined as vibration**. The quality of feedback and its properties are for the largest part influenced by the technology and the quality of the actuator. Its choice therefore takes an important role when delivering a desired vibrotactile stimuli.

If the most popular type of haptic actuator until a few years ago was the ERM technology (Eccentric Rotating Mass), thanks to the increased interest in the field in the last two decades, the variety and quality of actuators have improved. **(Precision Microdrives, 2021)**

By reading the datasheets provided by the manufacturer or the descriptions coming from others, we can only understand part of the actuator's properties (the quantifiable ones). It is for this reason that, in addition to the objective characteristics, I decided to test them personally in order to give also a subjective summary.

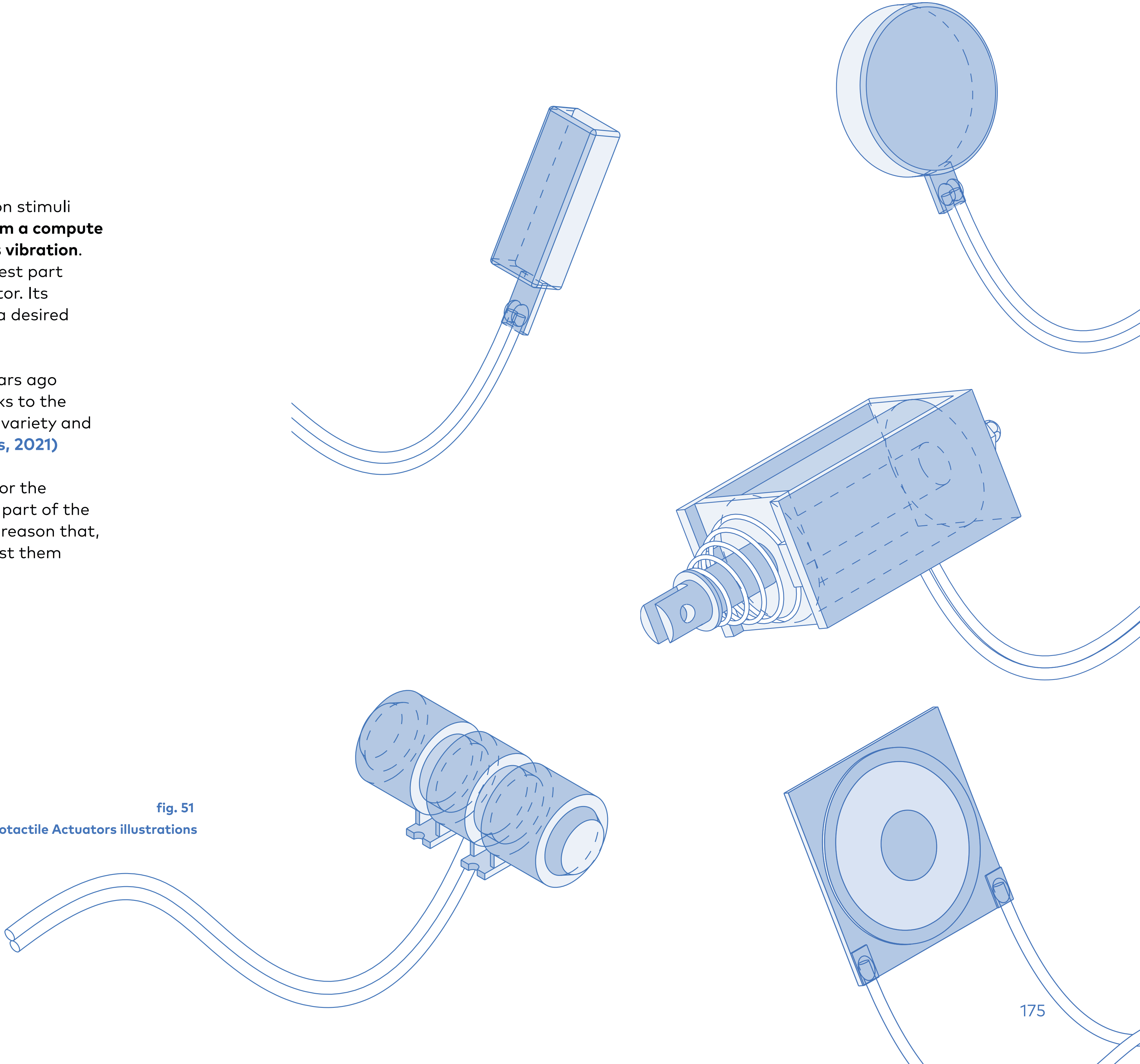


fig. 51
Vibrotactile Actuators illustrations

ERM

Eccentric Rotating Mass

An ERM "is a DC motor with an offset (non-symmetric) mass attached to the shaft". **(Precision Microdrives, 2021)**
By delivering a constant current the motor rotates, and the off-centered mass causes the vibration. **(Choi & Kuchenbecker, 2013)**
Because of how they are built they require a direct signal and the **amplitude of their vibration is proportional to the frequency**: the faster the mass rotates (frequency), the strongest the vibration is perceived (amplitude). Finally, ERM actuators have a low rising and falling time, resulting **unpractical for transient sharp feedbacks**.

They are a **good and cheap choice for stimuli that require continuous and rumbling vibrations** that don't need instant changes (eg. phone calls notifications, engine vibrations in a car simulator, Nintendo's Joy-Con controllers).

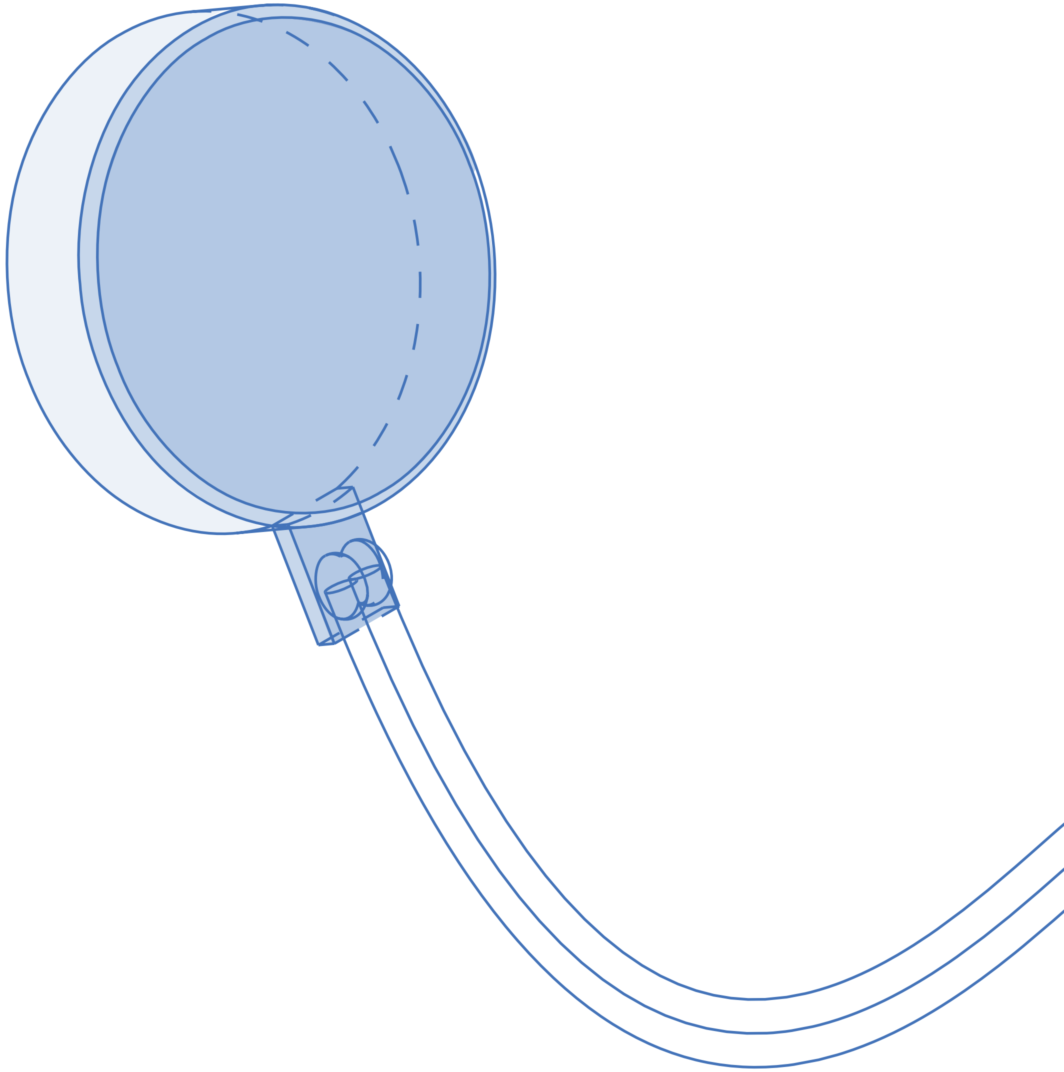


fig. 52
ERM Actuator illustration

LRA

Linear Resonant Actuator

Linear Resonant Actuators (LRA) create the stimuli through an oscillating force across a single axis. "*It consist of a mass on a spring and an electromagnet (Voice Coil). The electromagnet is alternately charged and discharged, which results in the mass vibrating at a specific frequency.*" **(Immersion Corporation, 2020)** In this case amplitude and frequency are individually controllable. Its rising and falling times are fast precise allowing for **very sharp vibration effects**.

Differently from ERM actuators that produce vibrations through a continuous movement of a mass in one direction driven by constant current, LRAs require alternate signals to make the mass move in both directions, requiring an external driver controller. **(Texas Instruments, 2016)**

Despite being more expensive and complex, they are used when better performance and more **precise and realistic stimuli** are fundamental in a small space (eg. Mac trackpad, wearables, latest high-end smartphones). Apple devices include the Taptic Engine, which is a proprietary and high quality version of LRA able to convey very precise feedbacks while occupying a very small real estate in the device.

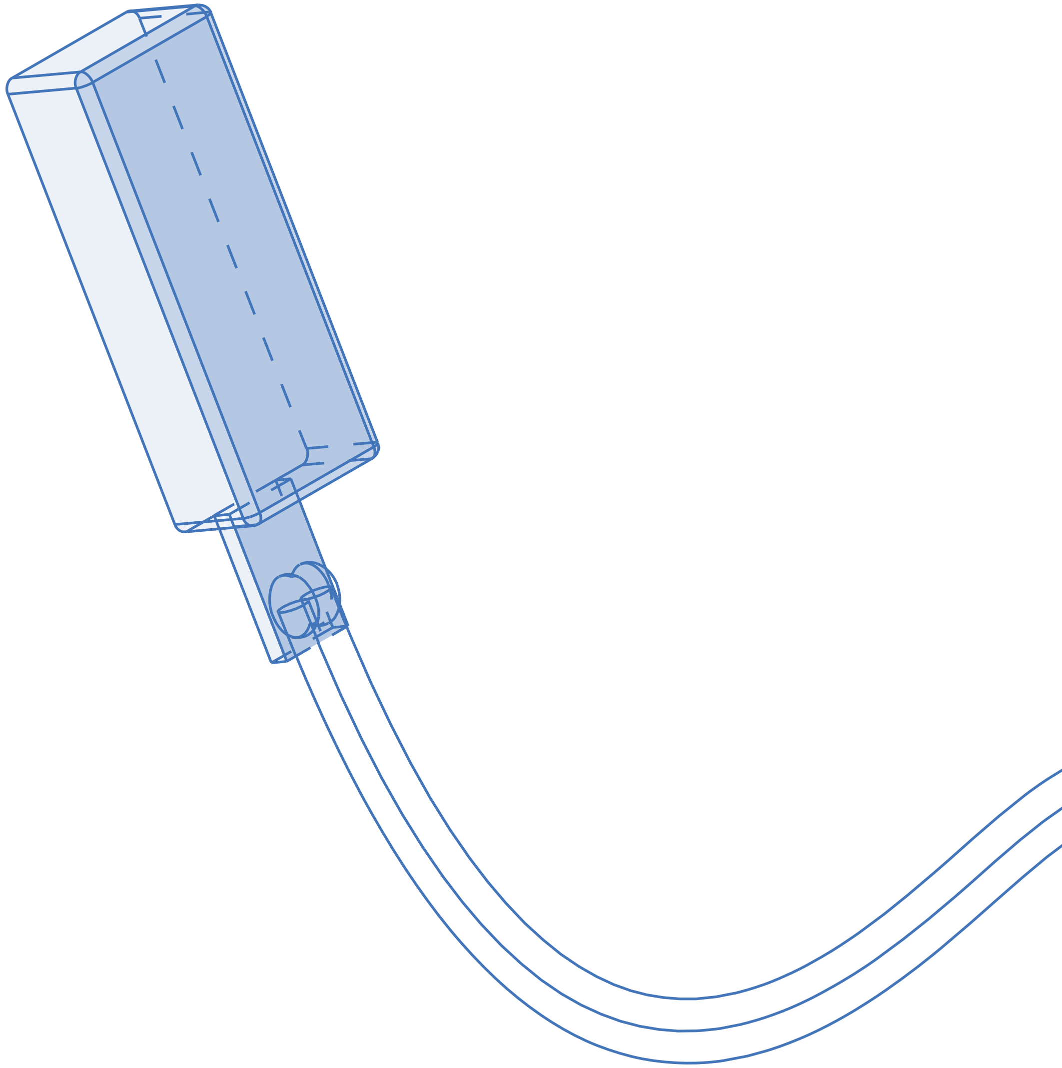


fig. 53
LRA Actuator illustration

LMR

Linear Magnetic Ram

Linear Magnetic Ram actuators (LMR, also called Voice Coils) are almost identical to LRAs except for the spring that is missing, in favour of an electromagnetic mechanism, which moves the mass back and forth on one axis. **(Titan Haptics, nd.)**
The **feedback it produces can be influenced by the dampers positioned at the end of the mass chamber**, which is impacted when the mass reaches the end stop; their material can sometimes be customised in order to create very precise and iconic vibrotactile events.

Compared to LRAs, LMRs generally have a **larger dimension, which increases the intensity and the impact force** of each vibration cycle. They are however more expensive and require more energy.

Use cases include VR controllers, automotive screens and situations where a "click effect" is desired.

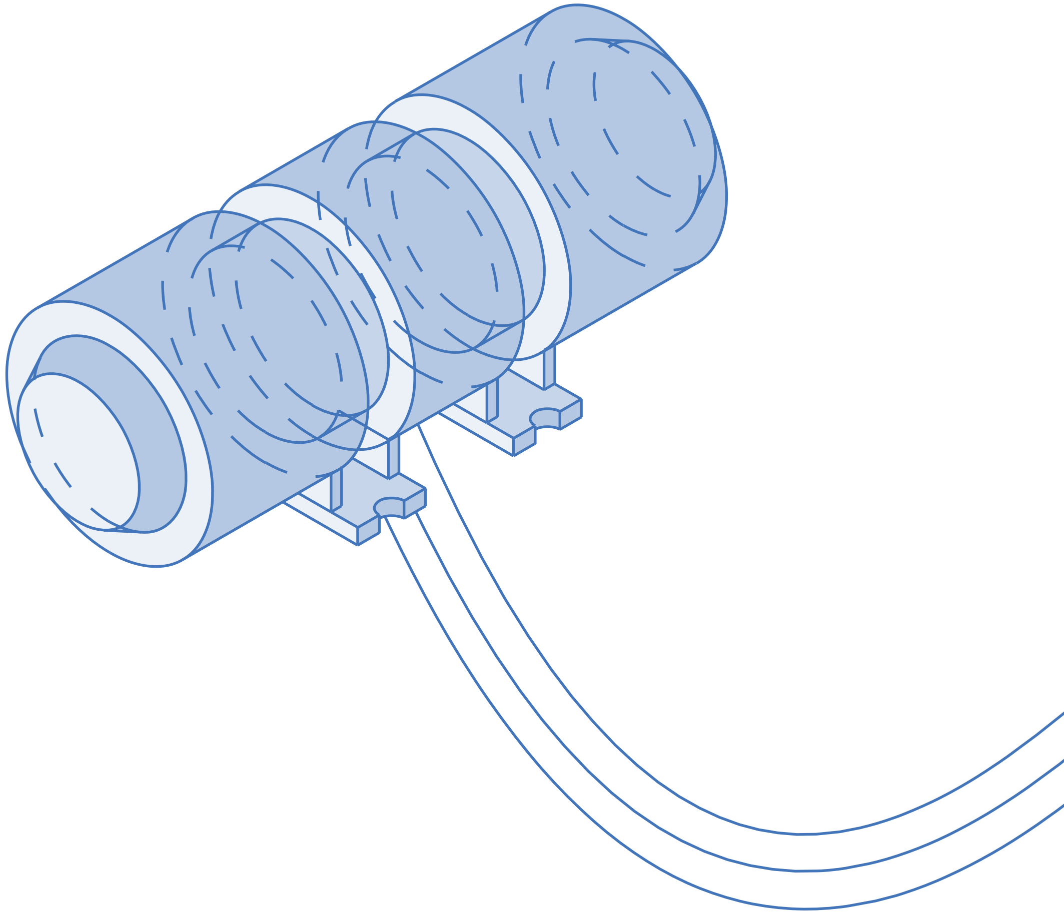


fig. 54
LMR Actuator illustration

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Solenoid

Solenoids are electromagnetic actuators composed by a mass mounted on a spring on one end and a coil. By charging the coil with direct current, the mass compresses the spring; when the coil gets discharged, the spring pushes the mass back to its original position. **(Immersion Corporation, 2020)** The end opposite to the spring can feature a dent that emerges from the actuator's housing **tapping directly on an external surface**.

This type of actuator generates **transient feedbacks with high fidelity, very strong impact forces**, that sometimes can touch directly an external surface or indent the user's skin. Their technical functioning however limits solenoids to **specific use cases**, requiring also a **considerable amount of energy** and a large space.

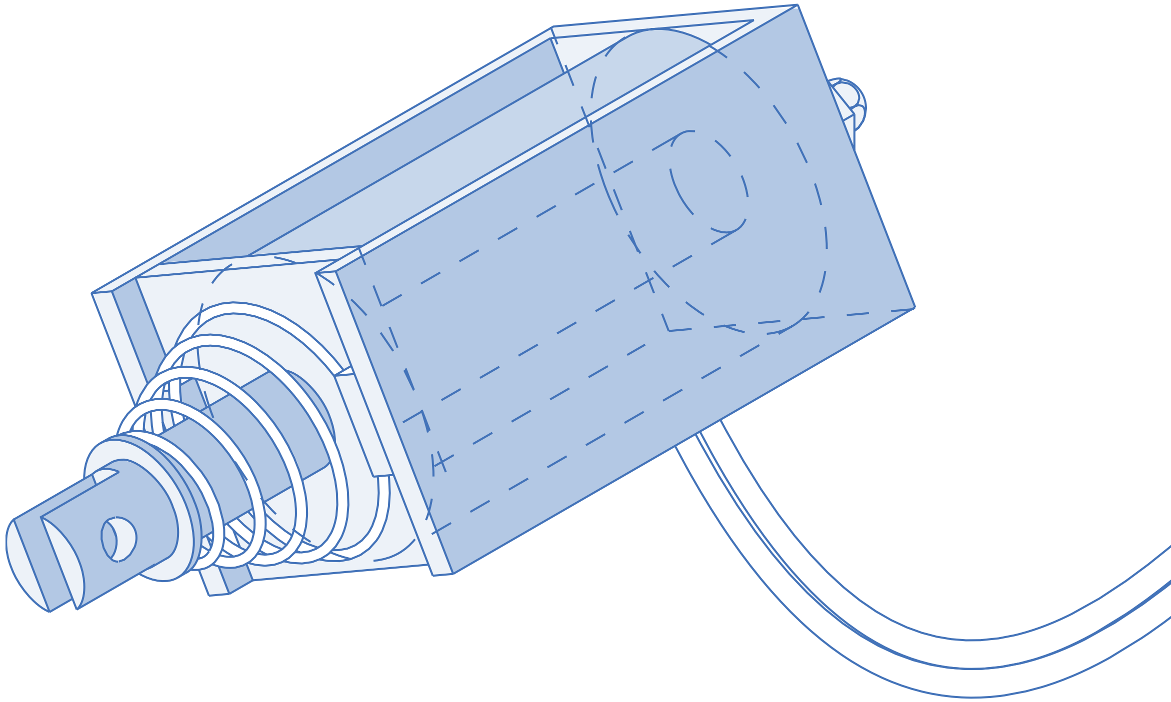


fig. 55
Solenoid Actuator illustration

PZT
Piezoelectric Actuator

Piezoelectric actuators are the most recent type of actuators among the ones presented. Instead of moving a mass by means of an electromagnetic effect, they work by "*deforming a solid crystal structure - usually ceramic - when a charge is added or removed*". **(Immersion Corporation, 2020)**

Thanks to their electro-mechanical actuation, PZTs can hold their position, simply by removing or modulating the voltage and the vibrotactile sensations can be very localised. They are developed in **multiple shapes and dimensions, as well as very thin**.

Because of how they work the have a **great controllability** with very low rising and falling times, **suitable for applications where HD effects are required**, together with low energy consumption and space limitations. They can also act as pressure sensors while keeping their actuator properties.

Commercially available use cases are still limited, but they can be used in automotive, VR controllers and mobile devices.

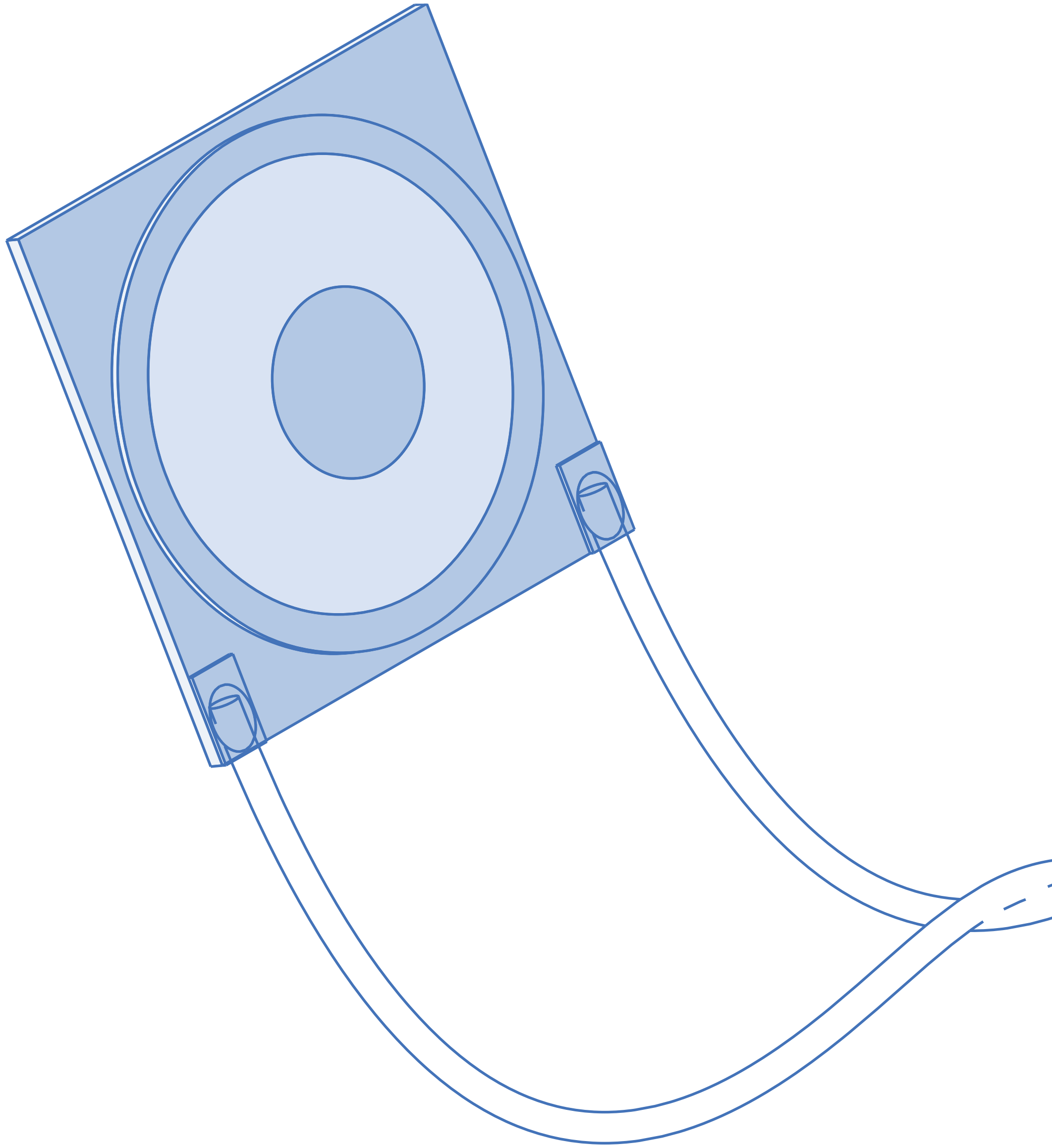


fig. 56
PZT Actuator illustration

Notes

As a result of the actuator's testing I decided to create a quick comparison table aimed at supporting prototyper's decision while looking at the actuator's landscape. The comparison integrates both quantitative data coming from their datasheets and from subjective perception of their vibration feedbacks coming from the tests.

fig. 57
Actuator comparison

Acronym	Type	Signal	Consumption	Controllability	Type of vibration	Dimensions	Price	Best for
ERM	Electro-Magnetic	Continuous	Medium	Low	Continuous	Small to large	Low	Inexpensive continuous vibrations
LRA	Electro-Magnetic	Alternate	Low	High	Both	Small (More shapes)	Medium	High precision in small devices
LMR	Electro-Magnetic	Alternate	Medium	High	Both	Medium	High	Very high precision, high intensity, impact forces
Solenoid	Electro-Magnetic	Continuous	High	Low	Transient	Large	Medium	Strong transient stimuli, direct surface contact
PZT	Electric	Alternate	High	High	Both	Small to large	High	Very high precision, pressure sensing, specific needs

3.1.2

Compute Unit

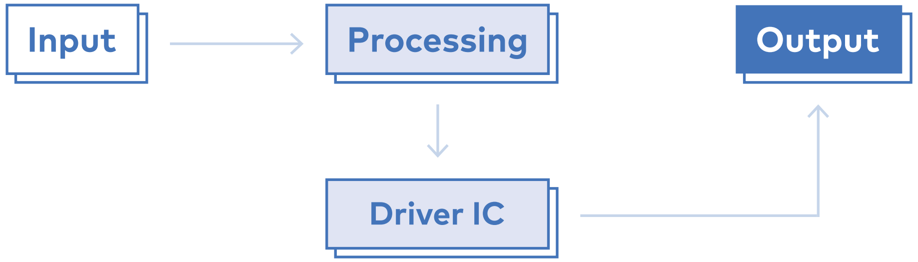


fig. 58 | Interaction processing elements

To elaborate inputs coming from sensors and control haptic actuators, a compute unit is needed, and must be composed by a microcontroller and a driver IC. The latter is needed to convert triggers coming from the microcontroller into direct current for ERMs and Solenoids; or alternate current for LRAs, LRMs, PZTs; and reproduce the desired haptic patterns.
There are three possible choices I found to prototype with vibrotactile hardware:

1. Develop a **custom circuit board** with an integrated microcontroller and driver IC;

2. Connect a **separate microcontroller and driver IC**;

3. Use **off-the-shelf circuit boards**.

The first option is more flexible because it allows to create a personalised layout and eventually already integrate the sensors and actuators on the board, however it takes a lot of effort and technical knowledge; the last one is plug and play and therefore user friendly and quicker, on the other hand it has less room for personalisation and sensors/actuators support could be limited. The second option is a trade-off, allowing for a good personalisation of sensors and actuators while using accessible components with extensive resources.

During the research process, I used the last two options, which allowed me to quickly prototype and test with sensors and actuators. To be more specific, an **Arduino Uno and an Adafruit DRV2605L** (separate microcontroller and driver IC), and a **hapticlabs satellite** (off-the-shelf circuit board). The hapticlabs board, resulted very efficient. Being a plug and play device, it allows to change frequency, amplitude and create haptic patterns simply by using their GUI software. The Adafruit DRV20605L, however, was better to pair with sensors, since all the processing is managed by a single Arduino board.

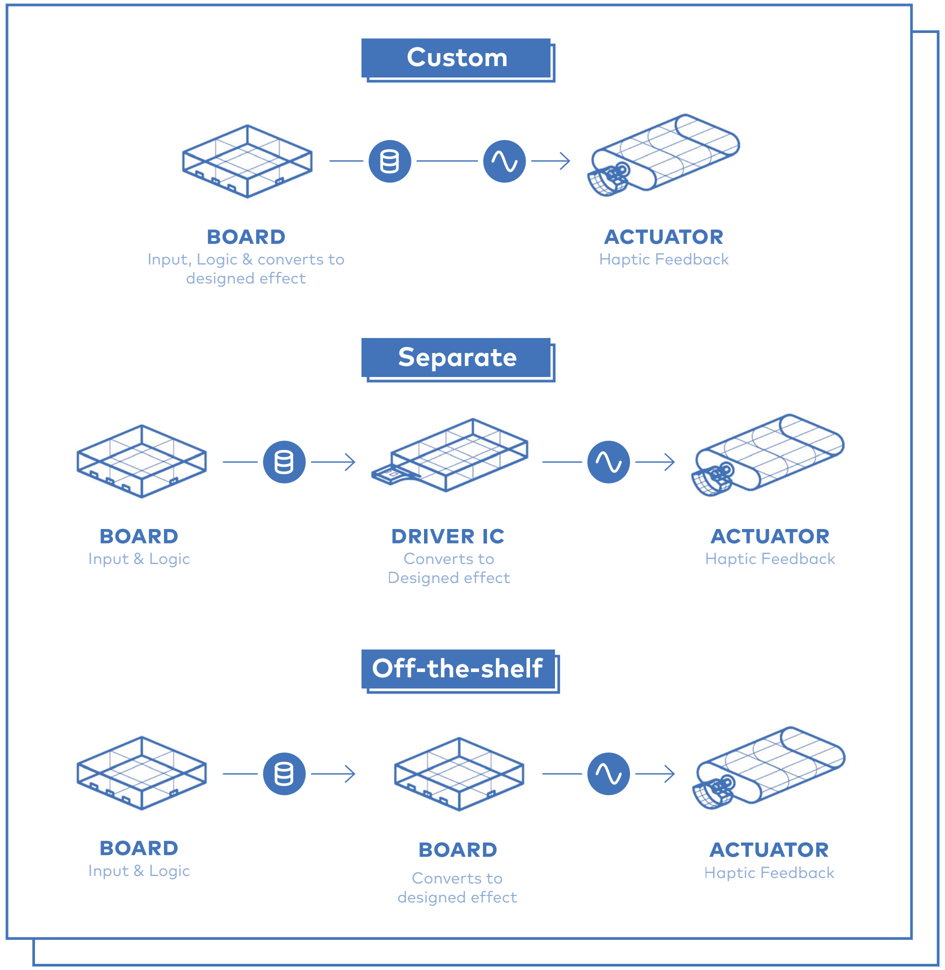


fig. 59 | haptic prototyping boards - adapted from Immersion Corp.

4.2
Software

If the hardware part is crucial for haptic experiences, when we have to design and prototype patterns, changing vibration properties and trigger them according to precise inputs, a software that programs all the requirements into the actual behaviour is needed.

From the analysis of the solutions available at the time I'm writing this thesis, three possible ways to prototype vibrotactile interactions emerged: **code**, **no code** and a mix of the two which I'm going to call **low code**. The preferred approach heavily depends on the level of coding experience and the amount of time and flexibility the designer has.

Another aspect to take into consideration that can influence the software to use, is the type of interface and the device the haptic experience will rely on. If we want to create a vibrotactile experience with a physical product, then we are very flexible. If it is instead going to run on third party device, we are limited to the device's prototyping software choices.

4.2.1
Code

The first option is the one that **requires more technical and coding experience, but that allows for more flexibility** throughout the entire prototyping process. Development environments allow for the integration of multiple kinds of sensors, actuators, and behavior, with fine-tuned control. However, this option can be very time-consuming when compared with the others.

The programming language and development environment vary according to the target device (processing unit) the experience will run on, which also impacts the available sensors and actuators. Most of integrated development environments (IDEs) include libraries or APIs to support designers developing prototypes faster, while obtaining high quality results. Some examples are Swift, Xcode and Core Haptics APIs for Apple's devices; C#, Unity 3d, and OpenXR APIs for VR applications; C++, Arduino IDE and InterHaptics Library for Arduino boards, etc.

Excursus - Haptikós App development

To create the Haptikòs App presented in Chapter 3, Xcode and Core Haptics APIs have been used. Despite the application development relied exclusively on code (apart from the UI that has been realised using the Storyboards feature), the APIs and the clear documentation made the creation process easy and straightforward. This highlights the fact that among the "Code" options, the experience can be very different according to the API availability and the documentation quality. The prototyping process must then also consider this variable.

4.2.2

No-code

The second option is to use software that offer a graphical user interface for all aspects of the haptic prototyping experience. These solutions, when compared to the "Code" ones, allow for **quicker prototyping and enlarge the designer's audience**, since no or little programming and technical knowledge is needed.

Their similarity to other design tools and their easy learning curve make possible to create a functioning prototype in just a few minutes. On the other hand, these software are limited to the set of features they provide, to the kind of sensors/actuators supported and mostly handle only the input (sensing) or output (vibration) aspect of the interaction. Moreover, most of the "No code" solutions available on the market are close source, have little documentation and support, and offer a subscription model.

The number of "No Code" haptic design tools is very limited and none of them has a strong leading position. In the last few years however, with the increased interest in haptics, new ones have been teased and released. A quick overview of the most popular haptic prototyping software will be presented in the following paragraphs.

hapticlabs.io

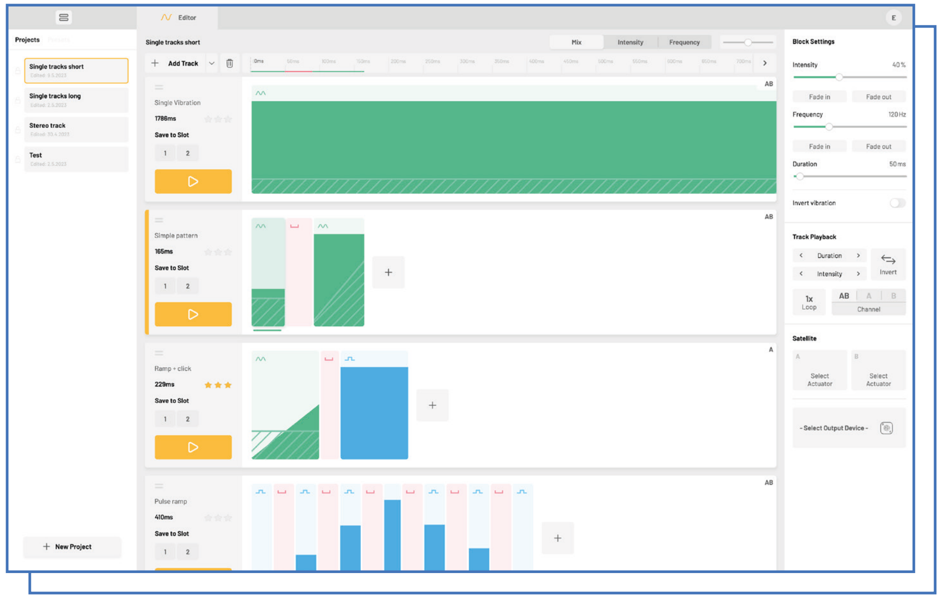


fig. 60 | hapticlabs.io Studio UI

Hapticlabs is a powerful and user-friendly prototyping software that is designed specifically for designers. With its proprietary hardware that is a plug and play solution, it supports most of the actuators and allows for a good level of customization of patterns with continuous and transient stimuli, although it does not support export (only works with Hapticlabs satellite). Despite it has limited input capabilities and no modulation support, it is the most recent and one of the best "No code" haptic prototyping software available on the market.

Macaron Editor

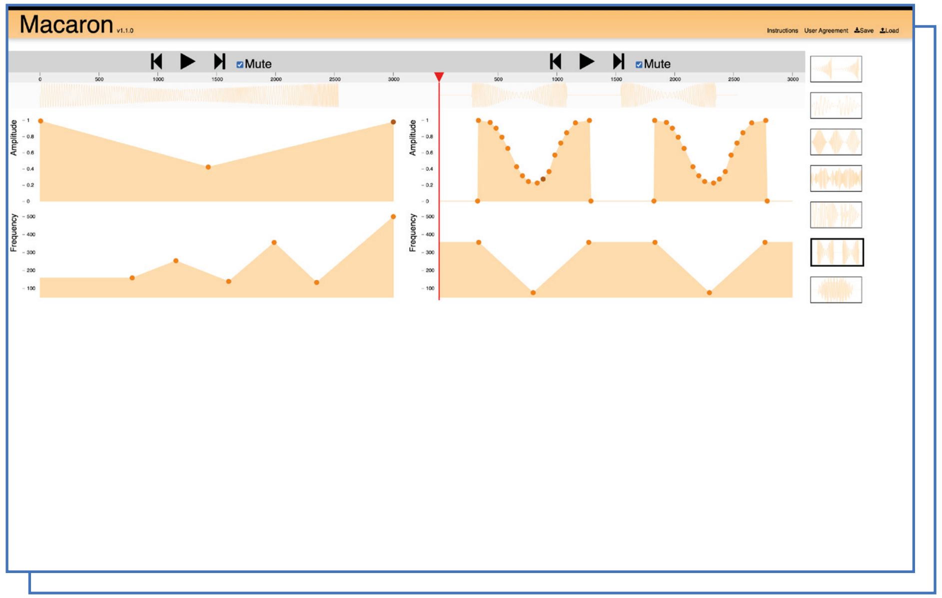


fig. 61 | Macaron Editor UI

Macaron Editor is an online tool that was developed in 2016 as a result of university research. It allows users to create continuous vibrotactile patterns that can be tested by attaching an actuator to the headphone jack of the device. The UI is very simple, although not particularly flexible, since the maximum duration of the pattern is set to 3 seconds. It is possible to export a Json or wav file, which can be imported in other prototyping tools. Despite it has some limitations, Macaron Editor is a good option if we want to use a free online and open source tool.

Haptic Composer

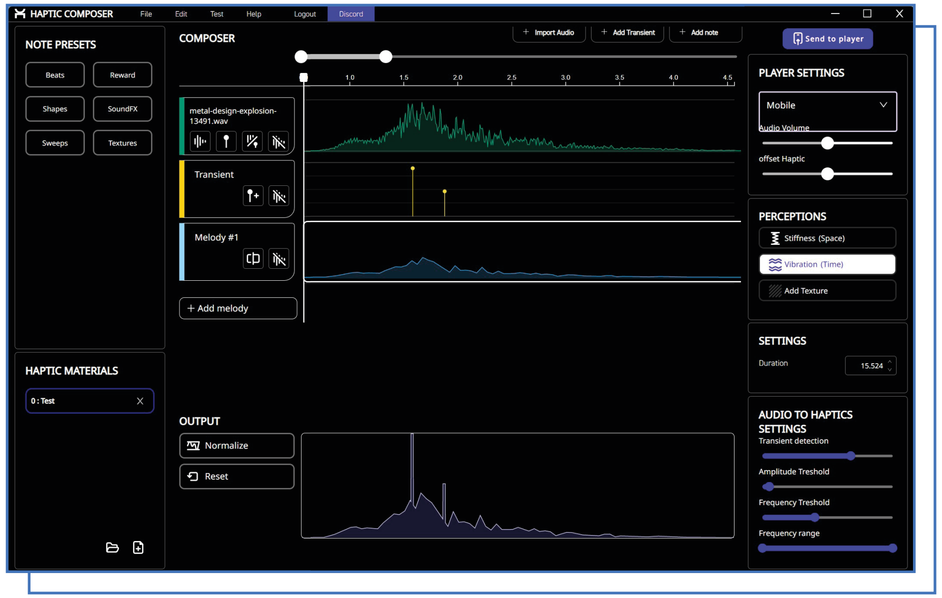


fig. 62 | Haptic Composer UI

Haptic Composer is a haptic prototyping software acquired by Razer that is **mainly designed for game developers**. Although it has some useful features, it falls short in some areas. For instance, it only supports feedback and has no input or modulation support. However, it does offer a good level of customization of patterns with continuous and transient stimuli, that can be tested with Android and iOS devices and PS5 DualSense. The timeline-based UI is similar to video editing tools, making it easy to use for those who are familiar with these programs. Haptic Composer is only available for Windows and offers .haps export (JSON based).

4.2.3

Benchmarking

In order to compare the different options and the software within the two, a benchmarking activity has been performed. This involved identifying some **key factors to consider**, such as **flexibility**, **programming skills required** and the **ability to process both input and output**. I then gathered data on these factors, which have been used to create some illustrations that visually show the comparison between the different software programs.

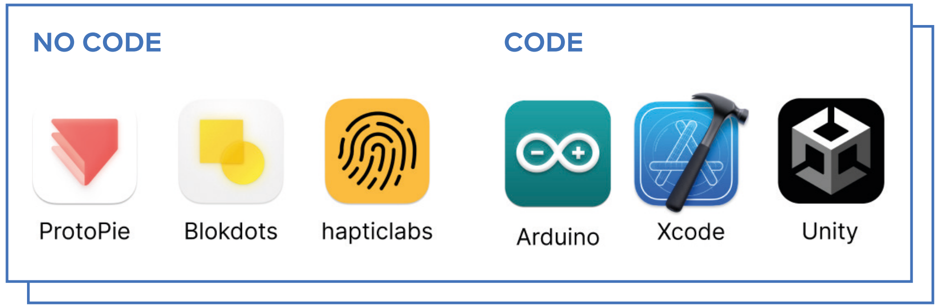


fig. 63 | Haptic prototyping software analysed for the benchmarking

By exploring the "Code" and "No Code" options we can once more confirm the fact that **software that require programming skills are definitely more flexible**, since they allow designers to personalise the prototype in every minor detail; however they are more time consuming when compared to "No Code" solutions, since all processes and logic are not automised and therefore must be declared - becoming more prone to errors and bugs. On the other hand **"No code" options are definitely easier and quicker to use**, especially for simple and common scenarios (eg. push to feel a "click"); but they are usually mainly focused on the feedback creation, rather than on the whole interaction (input, processing, output).

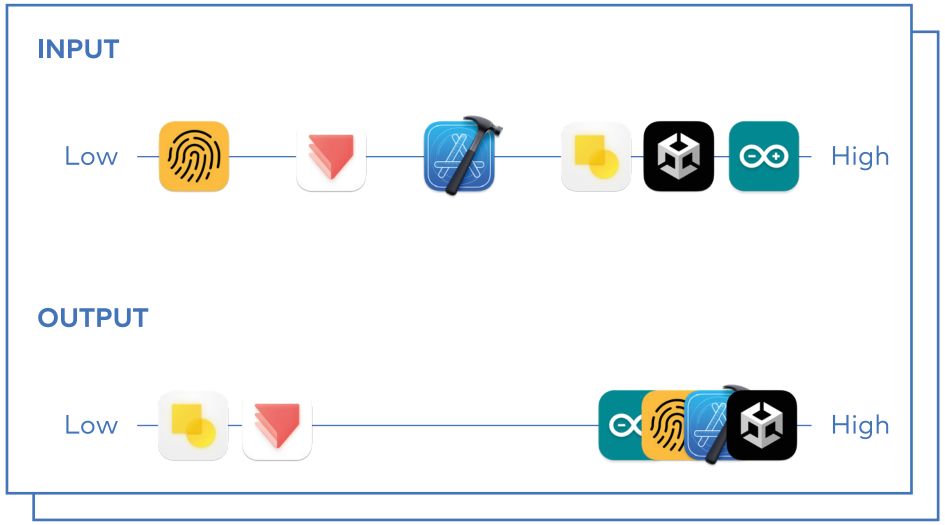


fig. 64 | Haptic prototyping software I/O management

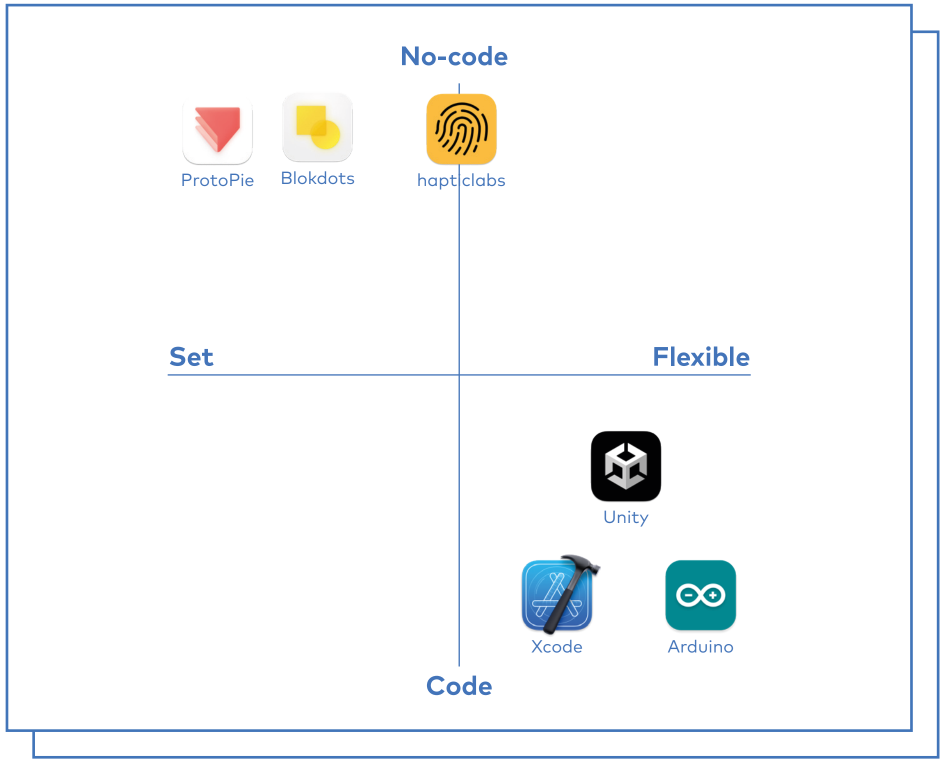


fig. 65 | No-code vs Code software benchmarking

4.2.4

Low Code

While trying to create dynamic vibrotactile interactions, **I found very effective to use both types of software, relying on an hybrid "Low Code" solution**. By exploiting flexibility, logic and input support of development environments, I was still able to obtain high quality feedbacks and high actuators' control of "No Code" programs. This workflow turned out to be very quick, without sacrificing the fidelity of the interaction.

Here is a new benchmarking illustration that takes into account, instead of single software, set of tools able together to manage the entire interaction.

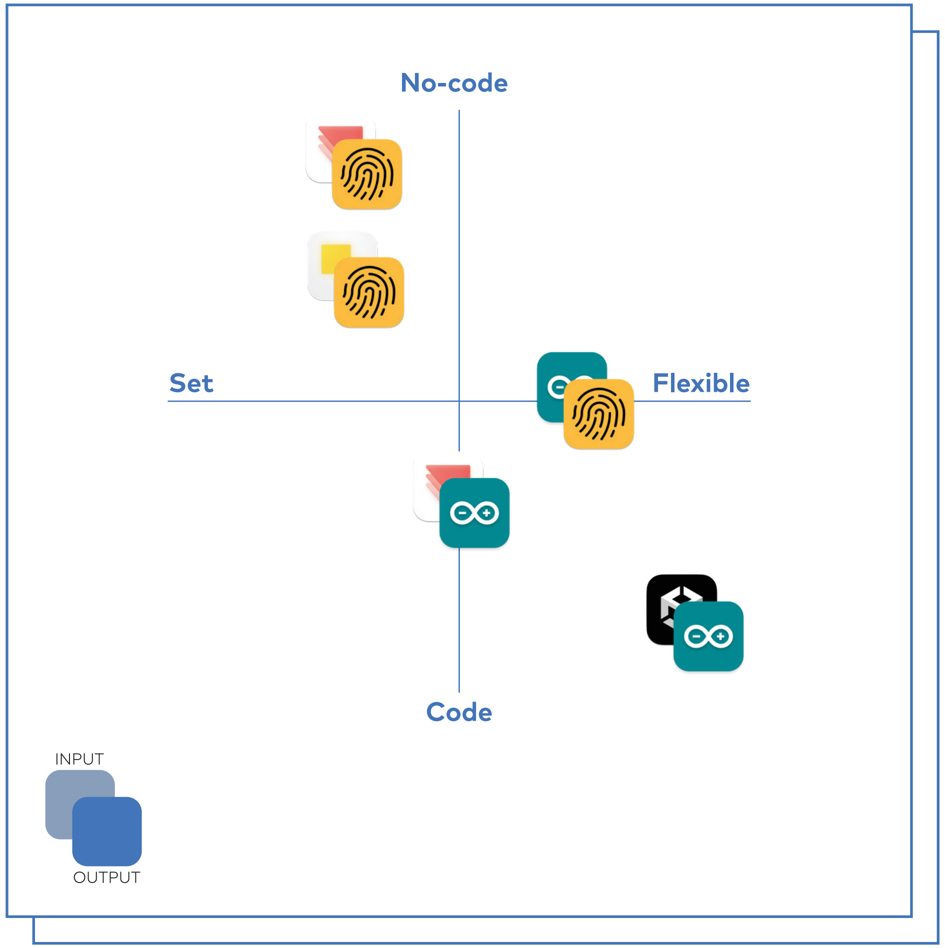


fig. 66 | No-code vs Code software benchmarking

Final takeaways

From the experience I had analysing haptic prototyping software during this phase of applied research, I want to highlight the fact that **there's no best overall solution**. The choice is highly influenced by the designer's technical and programming knowledge, as well as the time available for prototyping; and most of all by the type of interaction, the sensors and actuators needed, and the device the experience will run on. This type of consideration must be taken into account as soon as the prototyping phase begins. Finding the most suitable set of tools and workflow to manage input, processing and output creates a smooth prototyping experience.

4.2
User Journey

Throughout this chapter we have seen how complex is prototyping haptic interactions; from choosing the right actuator and board, to deciding which software tool to use to program the interaction logic, the designer's experience can be overwhelming. To conclude, I've tried to sum-up the entire journey of three distinct types of designers that are approaching this field in separate Journey Maps:

- **Expert designer**: who is familiar with code and electronic hardware;
- **Beginner designer**: who has little or no experience with hardware prototyping and programming;
- **Intermediate designer**: is a mix of the two. He has already some experience (both from hardware and coding perspective), but feels more comfortable using tools that offer good online resources and support.

To create comparable User Journey Maps, I confronted them using the same goal and steps.

Scenario

Three designers - each with a different level of expertise - want to recreate the parking assistance experience by replacing classic alert sounds and graphics with haptic feedback, to offload the visual and auditory senses and creating a more private communication with the vehicle.

The interaction to achieve

As soon as the driver gets closer to an object, the steering wheel has to reproduce transient vibrotactile stimuli that become more frequent according to the distance.
The interaction follows this flow: through an **Ultrasonic sensor**, the distance with objects is registered, which is in turn processed by a **board (flexible)** and mapped to dynamic transient vibrotactile stimuli delivered by an **LRA**.

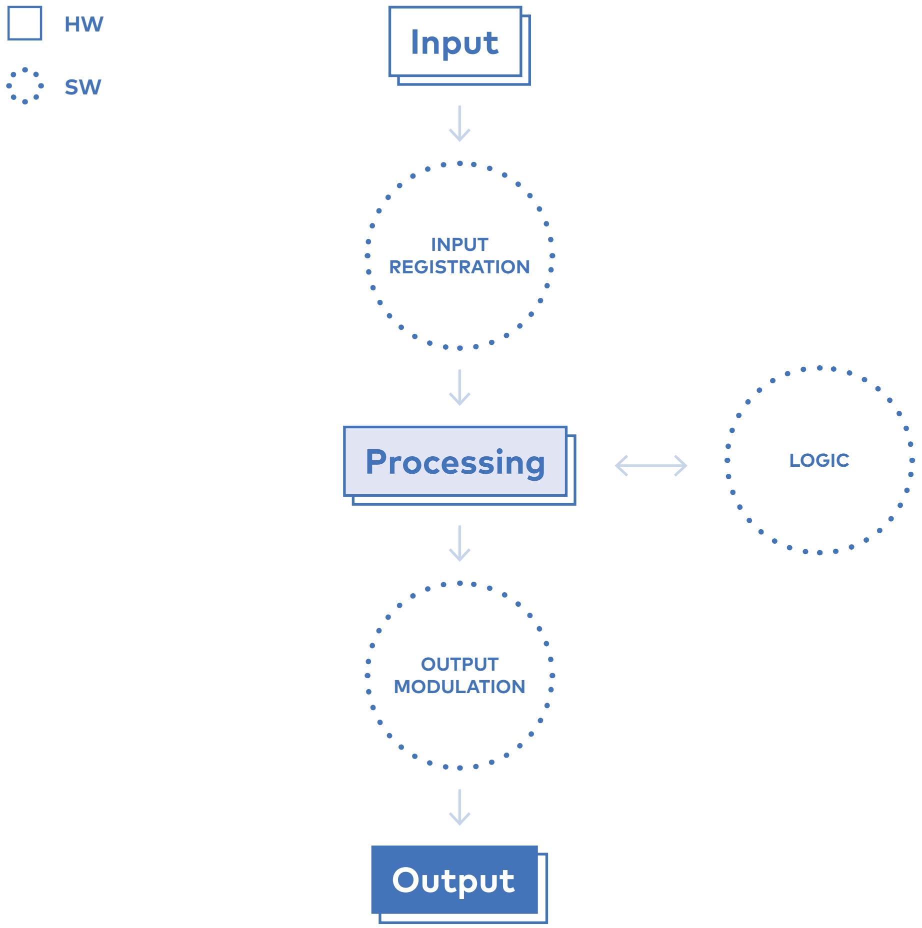


fig. 67 | User Journey Map interaction flow

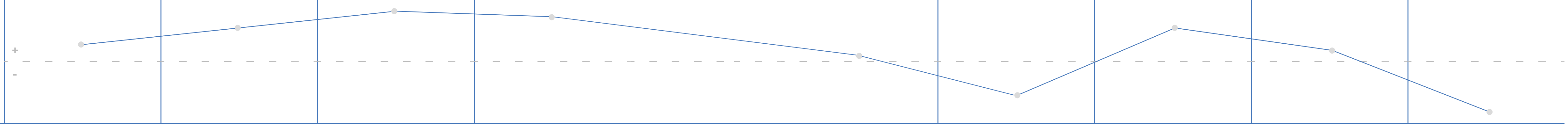
4.2.1

Expert User

fig. 68
Expert User Journey

The expert designer decides to use an Arduino microcontroller with a Driver IC and an integrated development environment (Arduino IDE) to manage the entire interaction.

Action	Tools selection With the metaphor decided, the **expert designer** identifies the hardware and development environment to program the interaction of the prototype.		Input set-up As first action to create the prototype he sets up the input part.		Output set-up To manage the haptic feedback he prefers to continue using the flexibility of code.		Logic creation To make the actuator vibrate with a variable interval between each stimuli, according to the distance registered by the ultrasound sensor, the **expert designer** uses his programming skills on the Arduino IDE. He has to think about the entire logic of the interaction going through some debugging, but at the end he's able to trigger the Hapticlabs Satellite with a variable interval according to the distance detected by the ultrasonic sensor.	Testing Once the prototype is complete, the **expert designer** tests it to understand if the result is similar to what he intended at first and finds out that the default frequency of the stimuli is too high.	Iteration To change the frequency he goes back on the Arduino IDE and looks for a possible solution online, finding out that to change the frequency to one that different from the resonant frequency of the actuator, he has to manually write the code to deliver the right voltage. After some time and iterations he's successful.
Detail	Hardware From experience, he picks up the ultrasonic sensor and an Arduino board. For the haptic feedback he looks on specialised forums and manufacturer's websites and datasheets selecting the right actuator and Driver IC.	Software He decides to recreate the entire experience by using Arduino IDE, exploiting the Driver IC library.	Hardware He wires the ultrasonic sensor with the Arduino board from experience.	Software Through the Arduino IDE he is able to program the ultrasonic sensor and calculate the correct distance.	Hardware To actuate the LRA, he needs to connect it to a Driver IC, which is in turn connected to the Arduino board.	Software To design the transient feedback he uses the driver's library and, by reading the documentation, he is able to set the right amplitude. To change the frequency he has to look at the Driver IC's datasheet and specialised forums, when he decides to keep the default one			
Touchpoint	**Forums, manufacturer's websites & documentation**	**Forums, manufacturer's website & documentation**	**Ultrasonic Sensor & Arduino**	**Arduino IDE**	**Arduino, Driver IC & LRA**	**Arduino IDE, Driver IC Library, manufacturer's website & forums**	**Blokdots, Arduino & Hapticlabs Satellite**	**Sensor, Actuator, Arduino & Driver IC**	**Online forums, manufacturer's datasheet, Arduino IDE**
Emotions									
Insights	No single source of knowledge To find information about hardware's properties, the designer has to look at multiple websites and sources.					Complexity of haptic HW Libraries for Arduino don't support frequency change of LRA and LMR, which is set to the resonant frequency by default			No support on haptic On specialised forums and websites, there's just a few content and discussions on haptics.

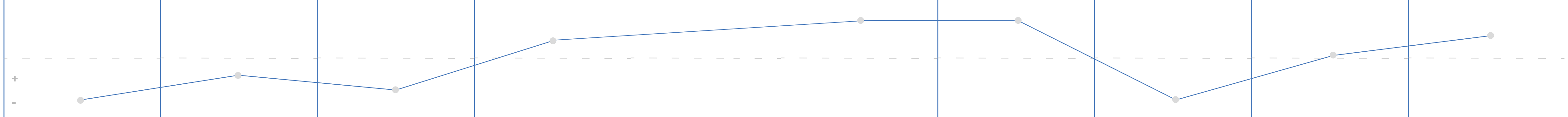


4.2.1

Beginner User

fig. 69
Beginner User Journey

The beginner designer decides to use an Arduino microcontroller and an Hapticlabs Satellite. To manage the logic he uses GUI software: Blokdots for sensing, mapping the distance with triggers, and Hapticlabs Studio to design the transient stimuli.

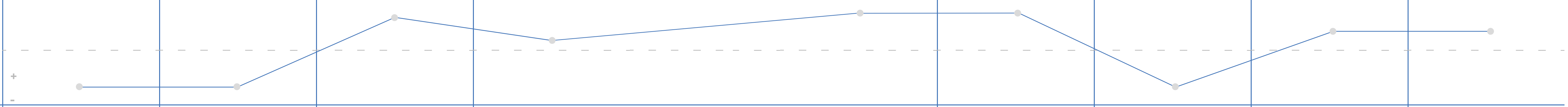
Action	Tools selection With the metaphor decided, the **beginner designer** tries to identify plug and play hardware and an easy software needed to prototype the interaction.		Input set-up He initially tries to set up the input part of the interaction by assembling the hardware and connecting it to a computer.		Output set-up Similarly to the input, he sets up the output part and tests it by using the design software.		Logic creation To make the actuator vibrate with a variable interval between each stimuli, according to the distance registered by the ultrasound sensor, the **beginner designer** uses Blokdots. He can trigger the actuator, but the interval between stimuli is not smoothly mapped to the distance.	Testing Once the prototype is complete, the **beginner designer** tests it to understand if the result is similar to what he intended at first and finds out that the vibrotactile stimuli is too sharp.	Iteration He goes back on Hapticlabs Studio and changes the feedback frequency to something lower and reuploads the track to the Satellite.
Detail	Hardware He finds a list of sensors, actuators and boards without a precise detail on the real assembly and management experience. He is also not aware about the real feedback difference between each type of actuator.	Software Without having programming knowledge he tries to look for ready-to-use and GUI softwares. He finds out that most of them are subscription based and don't offer all the features he needs. He also tries to find for hardware compatibility.	Hardware Once he gets the hardware he purchased, he links the ultrasonic sensor to the Arduino board by looking at online tutorials.	Software Using the GUI software, he is able to receive and visualise the distance values coming from the sensor.	Hardware The hardware is plug-and-play and he can immediately attach the LRA actuator to the driver board.	Software To design the transient feedback he opens Hapticlabs Studio and finds an intuitive interface. He sets the duration, frequency and amplitude of the tap very easily and uploads it on the Satellite to immediately feel the feedback.			
Touchpoint	Search engine, forums & online stores	Search engine, forums & online stores	Ultrasonic Sensor & Arduino	Blokdots	Hapticlabs Satellite & LRA	Hapticlabs Studio	Blokdots, Arduino & Hapticlabs Satellite	Sensor, Actuator, Arduino & Satellite	Hapticlabs Studio & Satellite
Emotions									
Insights	Too much choice Online we can find many different hardware options, however actuators stimuli are difficult to perceive without testing them, and is very difficult to understand what the real prototyping experience is going to be due to missing guidance and opinions.	Not enough information The GUI tools available on the market are expensive and don't have a solid customer base that can help.					Lack of features of GUI haptic tools Current plug-and-play hardware and GUI software are very limited in terms of features when programming the interaction logic.		

4.2.1

Intermediate User

The intermediate designer uses a mix of both code and no code solutions to control the ultrasonic sensor and the Hapticlabs Satellite: Arduino IDE for the input registering, mapping and output triggering, and Hapticlabs Studio to design the actual vibrotactile feedback.

fig. 70
Intermediate User Journey

Action	Tools selection With the metaphor decided, the **intermediate designer** goes on specific forums and websites to identify sensors, boards and actuators.		Input set-up The **intermediate designer** goes immediately to set up the input part of the prototype.		Output set-up Once the input part is on place, he moves to the output one, which is delegated to an off-the-shelf solution.		Logic creation To make the actuator vibrate with a variable interval between each stimuli, according to the distance registered by the ultrasound sensor, the **intermediate designer** uses his programming skills on the Arduino IDE. He has to think about the entire logic of the interaction going through some debugging, but at the end he's able to trigger the Hapticlabs Satellite with a variable interval according to the distance detected by the ultrasonic sensor.	Testing Once the prototype is complete, the **intermediate designer** tests it to understand if the result is similar to what he intended at first and finds out that the interval between vibrotactile stimuli is too short.	Iteration To solve the issue he goes back on the Arduino IDE and remaps the distance values with the interval.
Detail	Hardware Having previous experience with hardware prototyping, he already knows what type of sensor and board he want to use. He's unfamiliar with haptic actuators and find just a few information on specialised forums and websites.	Software To be more control on the interactive experience he decides to rely on code for the majority of the prototype, apart from the feedback design which will be delegated to a GUI software. He has hard times deciding which one fits better, due to lack of info.	Hardware To link the ultrasonic sensor with the Arduino board, he goes on Arduino forum finding the right wiring.	Software Through the Arduino IDE he is able to program the ultrasonic sensor after some iterations, receiving the correct distance.	Hardware The hardware is plug-and-play and he can immediately attach the LRA actuator to the driver board.	Software To design the transient feedback he opens Hapticlabs Studio and finds an intuitive interface. Thanks to his technical experience he already knows the role of frequency and amplitude. Once he's done creating the feedback, he tests it.			
Touchpoint	Search engine, forums & online stores	Search engine, forums & online stores	Ultrasonic Sensor & Arduino	Arduino IDE	Hapticlabs Satellite & LRA	Hapticlabs Studio	Blokdots, Arduino & Hapticlabs Satellite	Sensor, Actuator, Arduino & Satellite	Arduino IDE
Emotions									
Insights	Doubts about Haptic actuators' properties Despite the number of data available on the datasheet, subjective information about perception are hard to find and sometimes too abstract.	Close source software Most GUI softwares are close source and don't offer interoperability since there is no standard in the field.					Low flexibility of GUI haptic tools Despite being very easy to use, GUI haptic design tools (eg. Hapticlabs, Haptic Composer, etc.) don't offer any kind of real-time modulation feature.		

Design for touch

05

Since the inception of the thesis research, the primary objective has been to comprehend why the majority of contemporary products and interfaces lack the incorporation of touch as a means of interaction. Consequently, it holds significant value to ascertain the perspectives of designers and the design industry concerning haptics, vibrations, and the tactile channel in general. To address these inquiries, a three-tiered research approach on this matter was undertaken.
Firstly, an investigation was conducted to determine the availability of theoretical knowledge in a format accessible to makers and designers. Secondly, an exploration was carried out to understand how designers consider haptics, if at all, and the reasons behind its frequent oversight. Lastly, insights were gathered from experts actively engaged in the field of haptics and design.

5.1

Haptic guidelines

The desk research on haptic guidelines reveals a lack of comprehensive guidance and best practices for designers who aim to incorporate tactile elements into their products. Existing information on this topic is scattered across multiple sources, requiring designers to search and cross-reference various content. This fragmentation makes it challenging for designers to find reliable and authoritative resources that can inform their haptic design decisions effectively.

One notable example of haptic design guidelines can be found in Apple's Human Interface Guidelines (HIG). Apple's HIG includes a dedicated page regarding haptics, which provides principles on how to design custom haptic feedback and an overview of system haptics that can be utilized by third-party developers as part of the iOS design system. **(Apple Developer, n.d.)** To enhance the understanding of these principles, Apple also offers recorded sessions from their Worldwide Developers Conference (WWDC) in which designers explain the concepts outlined in the documentation **(Apple Inc., 2019; Apple Inc., 2021)**. By showcasing real examples and demonstrating dynamic vibrotactile interactions in real-time, these sessions emphasise the value and potential of haptic design.

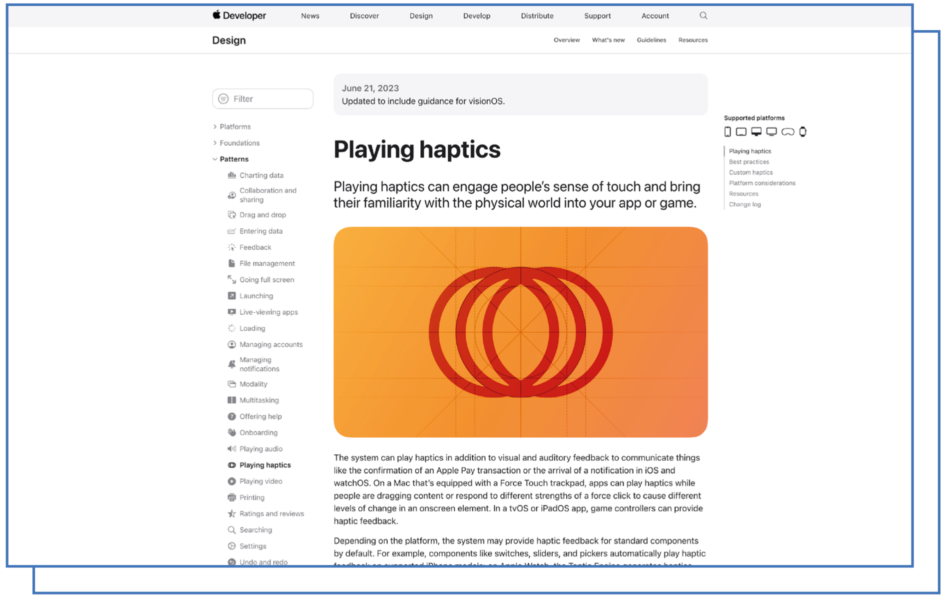
In contrast, Google's Material Design documentation **(Google, n.d.)** provides some guidelines for implementing haptics in Android applications. However, these guidelines are relatively vague and concise compared to Apple's resources. While they offer a starting point for designers, they lack the depth and specificity required to address the intricacies of haptic design effectively.

Beyond the official documentation from Apple and Google, other sources such as Immersion's blog, Medium, and design agencies' websites share additional principles, guidelines, and experiences related to haptic design. Although these sources may draw inspiration from the established guidelines provided by Apple and Google, as well as commercial experiences, their effectiveness and reliability must be evaluated and validated through further research and practical application.

The available guidelines and resources primarily focus on specific platforms within design systems. While the fundamental principles of haptic design are applicable to both physical and digital applications, the existing guidelines assume that the user interacts with a device equipped with a screen for visuals and a speaker for audio content. This limitation overlooks potential applications of haptic design in contexts where screens and audio are not the primary means of interaction. Consequently, designers working on haptic interfaces for unconventional devices or novel experiences face additional challenges in translating and adapting existing guidelines to suit their unique requirements.

Due to the broad nature of haptic guidelines and the platform-specific design considerations, designers working on any type of haptic interface need to envision, prototype, and test the entire tactile interaction. This process allows them to evaluate and iterate their designs based on user feedback and objective observations. However, this iterative process, although a standard part of design, demands significant time and effort from designers. Moreover, the lack of detailed guidance often leads to avoidable mistakes that could be prevented with more comprehensive instructions.

In conclusion, **while some official guidelines exist from prominent companies like Apple and Google, the current state of haptic design lacks comprehensive, consolidated, and cross-platform guidance.** Designers must navigate multiple sources and adapt existing guidelines to suit their specific needs. This fragmented landscape emphasises the need for further research, standardisation, and the development of best practices that consider haptic design in its entirety. By establishing a comprehensive framework, designers can reduce trial-and-error, optimise their design process, and deliver more consistent and effective haptic experiences across various platforms and contexts.



June 21, 2023
Updated to include guidance for visionOS.

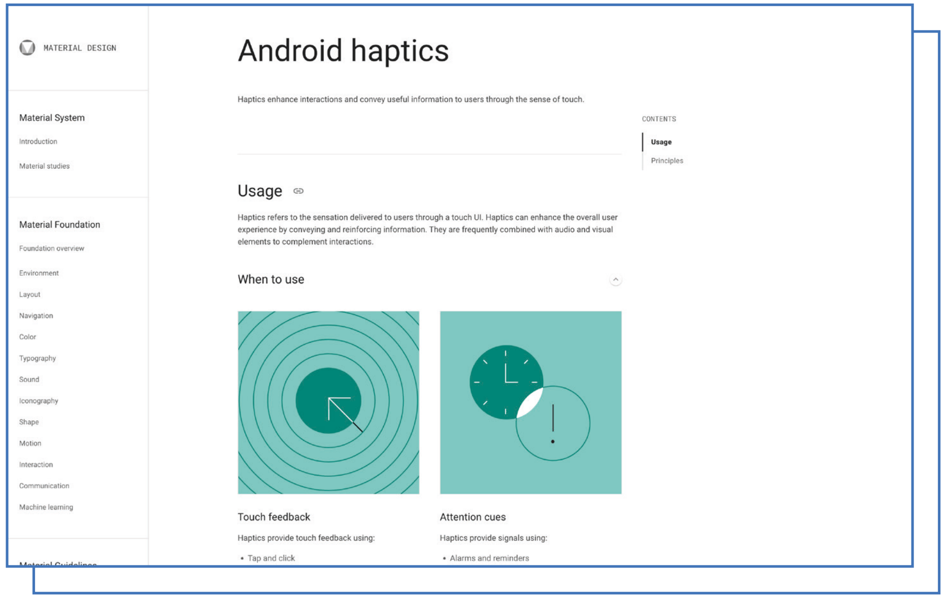
Playing haptics

Playing haptics can engage people's sense of touch and bring their familiarity with the physical world into your app or game.

The system can play haptics in addition to visual and auditory feedback to communicate things like the confirmation of an Apple Pay transaction or the arrival of a notification in iOS and watchOS. On a Mac that's equipped with a Force Touch trackpad, apps can play haptics while people are dragging content or respond to different strengths of a force click to cause different levels of change in an onscreen element. In a tvOS or iPadOS app, game controllers can provide haptic feedback.

Depending on the platform, the system may provide haptic feedback for standard components by default. For example, components like switches, sliders, and pickers automatically play haptic

fig. 71 | Apple Human Interface Guidelines - Apple, 2023



Android haptics

Haptics enhance interactions and convey useful information to users through the sense of touch.

Usage

Haptics refers to the sensation delivered to users through a touch UI. Haptics can enhance the overall user experience by conveying and reinforcing information. They are frequently combined with audio and visual elements to complement interactions.

When to use

Touch feedback

Haptics provide touch feedback using:

- Tap and click

Attention cues

Haptics provide signals using:

- Alarms and reminders

fig. 72 | Google Material Design Guidelines - Google, nd.

5.2

Haptics and designers

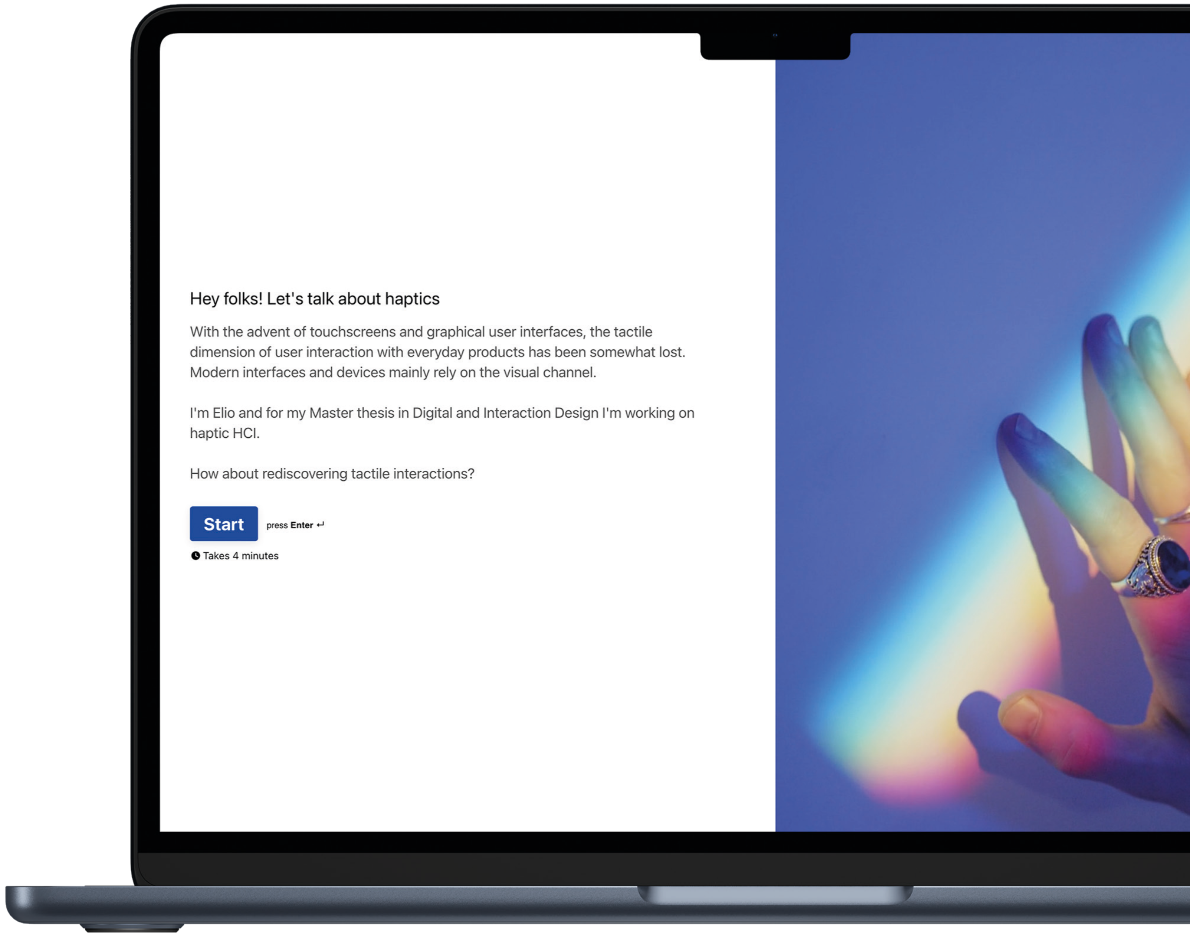
In order to gain insights into the awareness and involvement of designers regarding haptics and vibrotactile interactions in digital interfaces, a survey was conducted during this part of the research. The survey was specifically designed to explore the reasons behind the limited integration of the tactile channel in the design of digital interfaces from the perspective of designers and was shared with a selected target audience of design students and design professionals.

The survey consisted of three distinct categories, each with a specific goal. The first category focused on the designers' experience as users, aiming to uncover their familiarity with haptics, their personal enjoyment of haptic interactions with digital devices, and the impact of tactile feedback on their overall interface experience. By understanding how designers perceive and engage with haptics as users, valuable insights could be gained into the potential significance and value of haptic interactions in the design process.

The second category of the survey aimed to delve into the designers' experience from the perspective of their role as creators. It sought to determine whether designers had considered the tactile channel as a communication medium for their products and interfaces. Additionally, it aimed to uncover the types of haptic feedback designers had explored or implemented in their designs. Furthermore, the survey sought to identify any challenges or obstacles encountered by designers during the prototyping phase of haptic experiences.

Finally, the last part of the survey focused on discovering the needs and opportunities perceived by the designers themselves. Participants were asked to provide their insights on what they believed was necessary to increase their awareness of haptic potential and to support them in the design process of haptic experiences. By gathering these perspectives, the survey aimed to uncover potential areas for improvement, identify gaps in knowledge or resources, and find ways to foster a greater integration of haptic interactions in digital products and interfaces.

Overall, this survey was designed to provide a comprehensive understanding of designers' awareness, involvement, and challenges related to haptics and vibrotactile interactions. By analyzing the results, valuable insights can be gained to inform strategies for increasing the adoption and integration of haptic feedback in digital interfaces.



Hey folks! Let's talk about haptics

With the advent of touchscreens and graphical user interfaces, the tactile dimension of user interaction with everyday products has been somewhat lost. Modern interfaces and devices mainly rely on the visual channel.

I'm Elio and for my Master thesis in Digital and Interaction Design I'm working on haptic HCI.

How about rediscovering tactile interactions?

fig. 73 | Survey on haptic designer's awareness

Results

The survey was completed by a diverse sample of 22 individuals, including design students and professionals. The participants represented various design specialisations such as UX, Interaction, Service (digital), Industrial, and Automotive design (physical). The deliberate inclusion of this diverse range of design specialisations was a conscious decision to gather insights from individuals across different sectors of the design industry.

The initial findings from the survey were intriguing. When asked about their knowledge of haptics in Human-Computer Interaction (HCI), the majority of respondents (20 out of 22) indicated that they were aware of its meaning. Furthermore, all participants acknowledged experiencing tactile interactions at least once. Notably, popular scenarios mentioned by testers involved interactions with Apple devices (iPhone, Apple Watch, and Mac), gaming consoles (PlayStation and Nintendo Switch), and wearable devices. Vibrotactile technologies emerged as prominent, with 20 participants mentioning them, while 5 mentioned tactile resistance, and 3 mentioned force feedback.

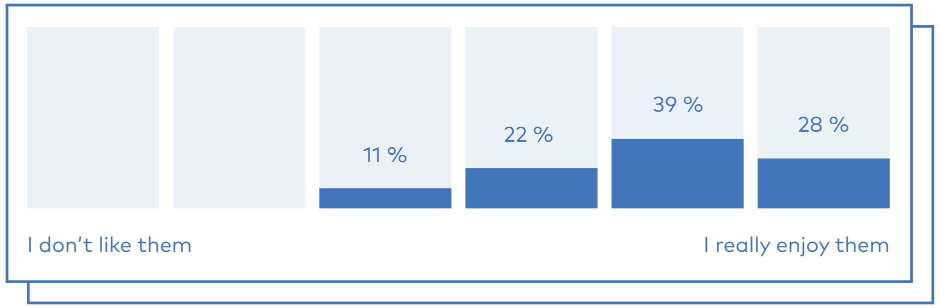


fig. 74 | Level of enjoyment of haptic interactions

Regarding their experiences with haptic interactions, most testers described them positively, highlighting how the tactile channel increased the immediacy and tangibility of their interactions, effectively bridging the digital and physical realms.
In gaming contexts, haptics were praised for enhancing gameplay and overall immersion.

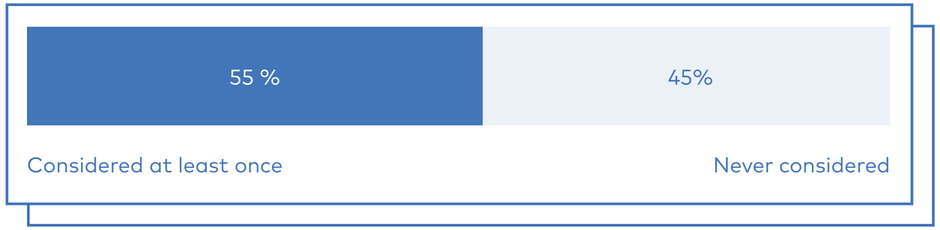


fig. 75 | Designers who have ever considered designing with haptics

Despite these positive responses, it was interesting to note that only 12 out of 22 participants had ever considered haptics in their product design work or university projects. Moreover, only 9 individuals had successfully implemented and delivered haptic features, with the rest facing challenges in haptic prototyping.

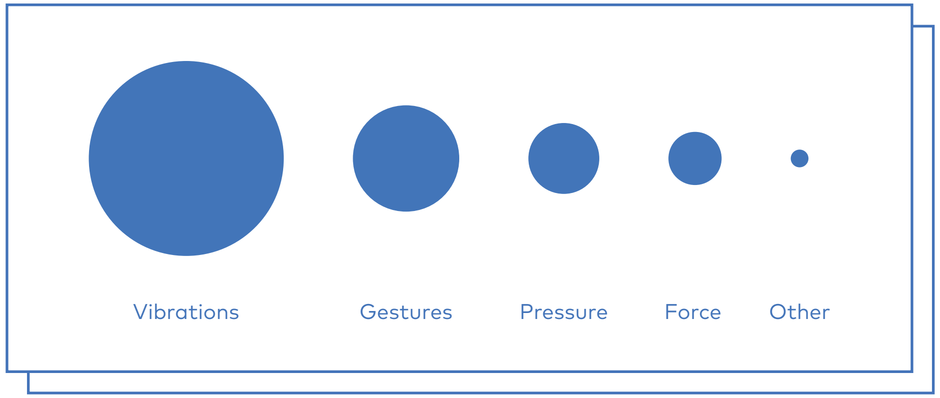


fig. 76 | Type of haptic technologies employed by participants

Vibrations emerged as the most commonly utilised technology (10 cases), but other technologies, such as gestures (5 cases), pressure sensing (4 cases), and force feedback (3 cases), were also considered. The reasons cited by the remaining 10 participants for not involving the tactile channel in their products primarily revolved around knowledge gaps. Many expressed unawareness of the potential of haptics (6 cases) and the absence of instruction or education on the topic (5 cases). These findings further confirmed the substantial lack of awareness surrounding haptics.

In line with these findings, the final section of the survey revealed that nearly all participants (21 out of 22) would consider incorporating haptics in their design process if there were ways to evaluate their potential and benefits. When asked directly, participants emphasised the importance of both theoretical support, such as clear design guidelines (rated 3.7 out of 5) or case studies (rated 3.6/5), and practical support, like user-friendly prototyping tools (rated 4.2 out of 5). This emphasised the significance of comprehensive guidance throughout the entire haptic design process.

In conclusion, the survey findings highlight the benefits that users derive from the inclusion of haptics in their interactions with physical and digital products across various dimensions. However, due to the lack of knowledge, awareness, and guidance, designers often overlook the potential of haptics and hesitate to embark on a haptic design journey.

5.3
Market insights

To further understand the market of haptic technologies and design, I decided to look at it in first person and to directly hear the opinions coming from experts working in the field.

5.3.1
Immersion Corporation

According to Parisi **(Parisi, 2018)**, Immersion Corporation, founded in 1993 in San Jose, California, has established itself as a leading company in haptics and vibrotactile technologies since the inception of haptic applications in HCI. In fact, their tagline, "Immersion. We are haptics," emphasizes their strong position in the field. The company operates with a business model focused on developing and acquiring thousands of patents related to haptic technologies, which they then license to various brands and manufacturers. Their technologies have been integrated into over 1 billion devices, and they have forged partnerships with industry giants such as Sony, Samsung, Huawei, Kyocera, LG, Motorola, BMW, Microsoft, and Apple.

Despite Immersion Corporation's closed-source philosophy, which may appear intimidating to smaller players, they contribute to the expansion of the market by creating innovative solutions that are subsequently implemented in consumer devices. Furthermore, the company occasionally shares part of its knowledge publicly through articles on haptic technologies and best practices in haptic HCI.

5.3.2
The community

During the research on the haptics community, what has been discovered is that, despite the small dimension of it, due to the limited awareness and recognition of haptics in the market and design practice, experts in the field tend to support each other and share their knowledge through articles and online content.

One notable example is "The Haptics Club", a podcast founded by experts working in various companies and roles, including academia, consumer products companies (e.g., Razer, Unity), and technology companies (Titan Haptics, SenseGlove). The podcast invites other experts in the field of haptics to discuss insights, future predictions, and conduct interviews. Additionally, they publish written editorials to further share information.

The overarching goal of The Haptics Club is to increase awareness and create a network among professionals working in the field. By fostering collaboration and facilitating knowledge exchange, they aim to enhance the overall understanding and advancement of haptics.

5.3.1
Interview with hapticlabs.io

During this phase of the research, I had the opportunity to engage in a discussion with the creator of hapticlabs.io, the design tool introduced in Chapter 4. The purpose of this conversation was to gain insights into the market, identify opportunities, and understand the obstacles faced during the development of the tool.

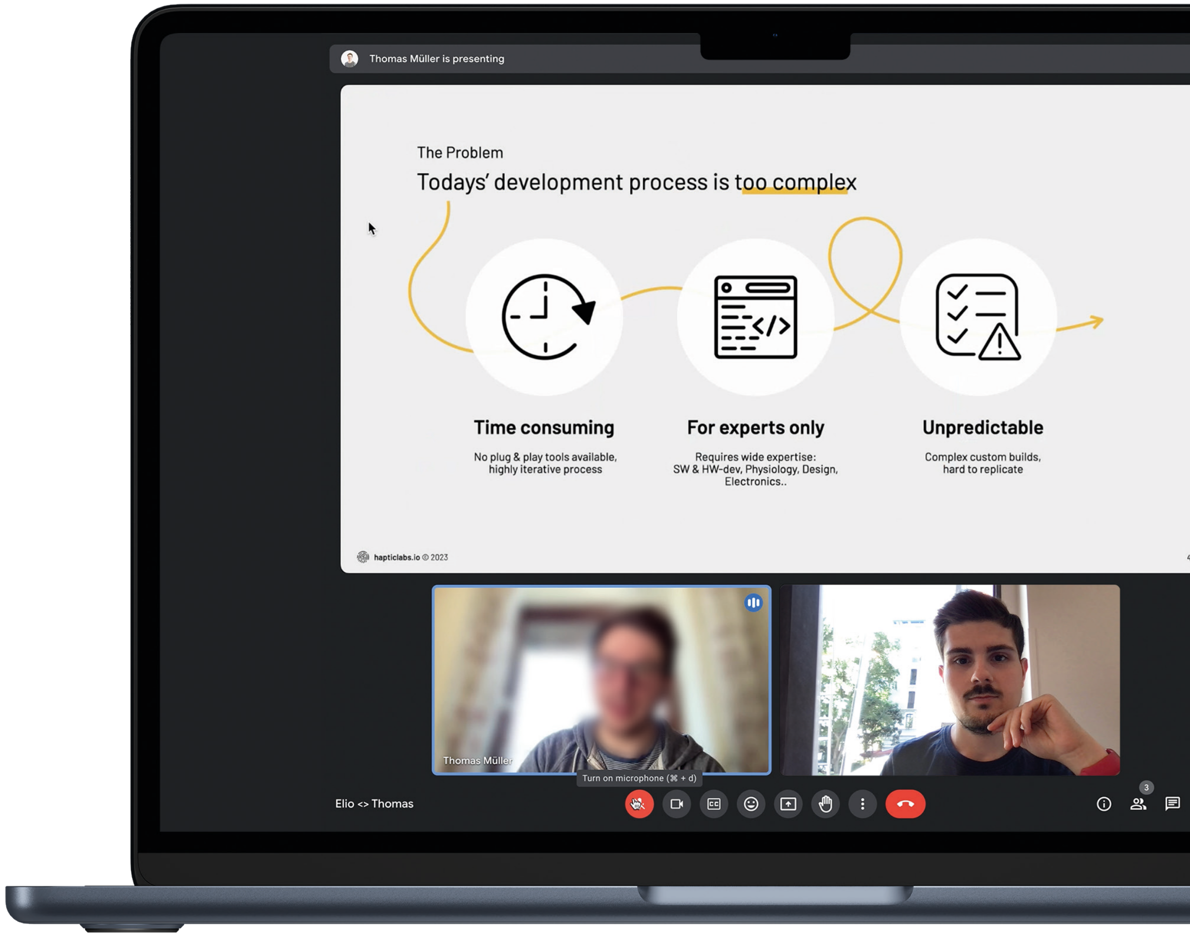
Thomas Müller, the founder of hapticlabs.io, embarked on his journey while working on his Master's thesis at Umeå University in Sweden. Like the focus of this thesis, his research aimed to explore ways to help designers integrate haptic dimensions into a broader range of products and interfaces. Specifically, he sought to map the haptic prototyping journey for designers by analysing their experiences and the available tools. As highlighted in the research portion of this thesis, he discovered that haptic prototyping can be complex, particularly for individuals who are not familiar with coding and electronics. This complexity represents a significant barrier, resulting in haptics being more commonly associated with engineering rather than design disciplines. Recognising the lack of intuitive prototyping tools, Thomas decided, as part of the project phase of his thesis, to envision and create an accessible platform for designers. The platform, comprised of a GUI interface called Studio and a plug-and-play hardware solution called Satellite, allows designers to create and iterate haptic feedback.

Throughout his journey, he also emphasised the **extensive knowledge and theory surrounding haptics, which often requires designers to invest significant time in finding reliable sources and educating themselves on the topic**. This challenge is compounded by the limited time and resources designers typically have available within their everyday working structures.

One opportunity identified by Thomas to inspire designers and showcase the power of haptic interfaces is the provision of real examples and case studies. Sharing such resources with individuals who have fewer resources and less knowledge would demonstrate how haptic solutions can be integrated and enhance user experiences when interacting with products.

Furthermore, during our discussion, it became apparent that, despite - and probably because of - the growing interest and investments in haptic interfaces, individual companies such as Apple, Immersion, and Sony are attempting to establish their own standards and dominate the market. This approach is counterproductive to the goal of achieving a universal and open-source standard that can improve accessibility and democratise haptics.

After the interview, Thomas offered to support this thesis research and project by providing me with the hapticlabs.io prototyping platform (Studio + Satellite). This assistance proved invaluable during the hardware analysis phase. Thanks to this collaboration, I was able to efficiently test various actuators and boards, gaining firsthand insights into their properties, which are summarised in Chapter 4.



The Problem

Todays' development process is too complex

Time consuming

No plug & play tools available, highly iterative process

For experts only

Requires wide expertise: SW & HW-dev, Physiology, Design, Electronics..

Unpredictable

Complex custom builds, hard to replicate

hapticlabs.io © 2023

fig. 77 | Meeting with hapticlabs.io's founder

Part III

Project & Testing

Support haptic interaction design

During the general research on haptics in Part I, we have discovered how important is for humans the role of the tactile channel when interacting with objects **(Jones, 2018)**, and how research and development efforts, starting from the 18th century **(Parisi, 2018)**, have started to experiment with its properties in order to communicate information with machines and interactive devices. With the advent of computers and touchscreen based interfaces, however, the sense of touch has lost more and more importance **(Parisi, 2018)**.

In the last few decades, due to new interaction challenges, the sense of touch seems to be rediscovered, especially in the fields of games and VR technologies. The tactile layer gives a tangible, direct and natural dimension to the interaction **(Ishii & Ullmer, 1997)**.

Given the complexity and the large breadth of topics underneath the world of haptics, to create something really impactful, in Part II I decided to narrow down my research efforts to **Dynamic vibrotactile stimuli** as a bi-directional Human Computer interface for sensory augmentation.

Among all the haptic stimuli, vibrations are by far those who got more attention in the consumer market because of their technical simplicity - compared to other haptic technologies, eg. force or surface haptics - and effectiveness in sensory augmentation.

As seen in the Part II, vibrations properties an their potential are already well defined; by modulating the basic building blocks - frequency, amplitude and duration - unique stimuli can be created and, when combined into patterns and linked to a metaphor, they become a way to communicate meaningful information to the user **(Baker, 2019)**, offloading the visual and auditory channels, or supporting them.

At the end of Part II, with a more detailed knowledge on haptics and design, from a focus on dynamic vibrotactile interfaces, we can now answer to all the research questions initially defined and that were left from the general research in Part I.

Despite the limited number of consumer products including quality dynamic vibrations, in these few cases, users have always had positive opinions and feelings regarding the overall experience enriched by the tactile channel (eg. PS5 DualSense). Moreover, reading and listening words from experts in the industry, fortified the thought that this type of communication method was destined to take hold on a larger scale. For this reason I was quite unsure about why then such applications are so limited and most of the times proposed by just few companies (PlayStation and Apple on the forefront).

By talking with experts in the field and people in my network on interactive products and interfaces, but also by trying in first person what is the current experience of a designer who wants to experiment with vibrotactile communication with users; what emerged is that the barrier is not the availability of knowledge or of tools to prototype and create haptic interactions as one might think, but instead what's lacking is a common awareness from the design community of the potential, guidelines, best practices, technologies and methods to prototype, test and evaluate this new kind of interaction modality.

Given this, as the final step of my research thesis, I would like to make a meaningful contribution to the haptic industry and HCI practice, by leveraging the theoretical and practical knowledge I collected and elaborated over the past months. **My objective is to enhance and support designers' experiences with haptics, ultimately bridging the gap between individuals and this field and fostering the development of more tangible, direct, and intuitive interfaces**.

Part III is dedicated to the project phase. Chapter 6 will cover the concept and the goal of the intervention, together with a detailed overview on the modalities and artefacts. In chapter 7, the test conducted to evaluate the effectiveness of the project, together with the results will be presented. Chapter 8 focuses on the conclusions, final reflections and potential future directions.

Haptikós Design Toolkit

06

Starting from the research, which highlighted the presence of a large availability of theoretical knowledge and the importance of the tactile channel to create tangible interfaces, I reflected on the possible solutions that could help designers to familiarise with the topic of haptics and start to experiment with vibrotactile communication. Given the current state of haptics in the design discipline the natural question that arises is:

> *" How may we support designers throughout the entire design process in order to help them envision and deliver more tangible and direct interfaces, through dynamic vibrotactile interactions? "*
>
> **— HMW question**

Reflecting on this HMW question I generated the concept of the intervention.

6.1

Haptikós

Haptikós is a design toolkit that provides designers with the basic knowledge about haptics, and guides them through a ideation, prototyping, testing and evaluation process (typical of the UCD approach) by means of design tools, activities and reflections.

Its ultimate goal is to bring designers and people interested in haptics closer to the topic and to encourage them to create meaningful interactions and dynamic Human-Computer interfaces through vibrotactile technologies.

The toolkit achieves its objective by using an applied learning approach used also by other institutions while researching into haptic design (eg. Apple with HIG). This approach combines essential theoretical knowledge, presented in a consumable way, with an hands-on discovery and design phase. The discovery and design phase is facilitated by real examples, generative and reflection activities, prototyping, and testing.

Name & Logotype

The name of the toolkit, Haptikós, originates from the ancient Greek term that gave rise to the word "haptic", denoting the ability "to grasp or perceive". **(Jones, 2018)** Just as the original term implies, the toolkit aims to serve as the primary reference and source for designers experimenting into the field of bi-directional haptic interfaces.
The name also acts as main logotype.

fig. 78 | Type of haptic technologies employed by participants

The App icon

The app icon, represents the shape of a stylised three dimensional vibration waveform. It is intended to be used in all digital stores and when referring to it.

fig. 79 | Haptikós App Icon construction lines

6.2
Case studies

To shape the toolkit in the best possible way, I wanted to understand how similar products created by reputable entities look like. It is for this reason that I've searched for some case studies of design toolkits already tested and proven on a large scale. In this sub-chapter a selection of relevant applications will be presented, each of which has been analysed on the base of four aspects:

- **Goal**;
- What **stage** of the design process do they support;
- **Approach** (guidelines, activities, etc.);
- **Artefacts**.

Microsoft

Inclusive Design

The Microsoft Inclusive Design toolkit aims to provide designers, engineers, developers, and managers with a guide for creating inclusive products that embrace human diversity. **(Microsoft Inclusive Design, n.d.)**

Stage

The toolkit is intended to work within an existing design process as a complementary instrument, helping makers to design products with customer's inclusivity in mind in all the project phases.

Approach

The Inclusive Toolkit has a notionistic and generative approach aimed at introducing designers to Inclusive Design and encouraging them to reflect and discuss during the design process with a critical mindset. The first part of the toolkit is dedicated to theory, including definitions, principles, and guidelines, and explains why it is important to design with inclusivity in mind. The second part of the toolkit is dedicated to activities that stimulate reflection, challenge beliefs, and generate ideas.

Artefacts

The home of the toolkit is the Microsoft Inclusive Design **website**. From here designers can read about it, stay updated and download all the material. A short and concise **booklet** contains all the theoretical knowledge, while **activity cards** support the designer by stimulating discussions and reflections during all the design phases: from the initial research by discovering problems and user needs, to concept generation, prototyping and evaluation.

fig. 80
Inclusive Design Toolkit
Microsoft, 2015

D.School

I Love Algorithms

The goal of the "I Love Algorithms" toolkit is to enable anyone to learn about the different Machine Learning algorithms and their functions, while also encouraging people to envision and prototype new solutions concepts in a fun and non-technical way. **(I Love Algorithms, n.d.)**

Stage

The toolkit is not intended to be used within an actual design process. Instead, it is an activity designed to inspire makers to envision possible solutions powered by Machine Learning in combination with datasets. The activity also encourages critical thinking about the possible implications of such solutions.

Approach

The toolkit uses a gamification approach where, similarly to a board game, users are encouraged to play together in order to learn, envision algorithm/dataset combinations and generate reflections about the possible implications.

Artefacts

The toolkit can be downloaded on its own website and includes two types of cards: game cards with ML algorithms and types of dataset, and notional cards, through which people can learn about each different algorithms through a simplified explanation, an illustration and an example; and some boards through that allow players to combine algorithms with datasets to create new products, services and reflect on their possible implications.

fig. 81
I Love Algorithms Toolkit
Stanford D.School, 2019

Accenture

AI meets Design

The toolkit aims to assist designers in turning AI technologies into user experiences. It provides guidance on how to apply design thinking when generating AI-powered concepts.

Stage

This toolkit covers most phases of the design process, including research, ideation, prototyping, testing, and evaluation. The creator notes that it is also possible to use only certain elements of the toolkit to better fit each design process.

Approach

"AI meets Design" has a step-by-step approach. It starts with a quick theoretical overview of AI technologies and then goes through all the IDEO's design phases. **(Design Kit, n.d.)**

The tool doesn't actively suggests the involvement of more designers, nor has team's activities.

Artefacts

It provides a short crash course on AI technologies inside the main digital booklet and for what regards the activities, it features generative cards for concept ideation and multiple printable worksheets and templates to bring the idea forward and evaluate it.

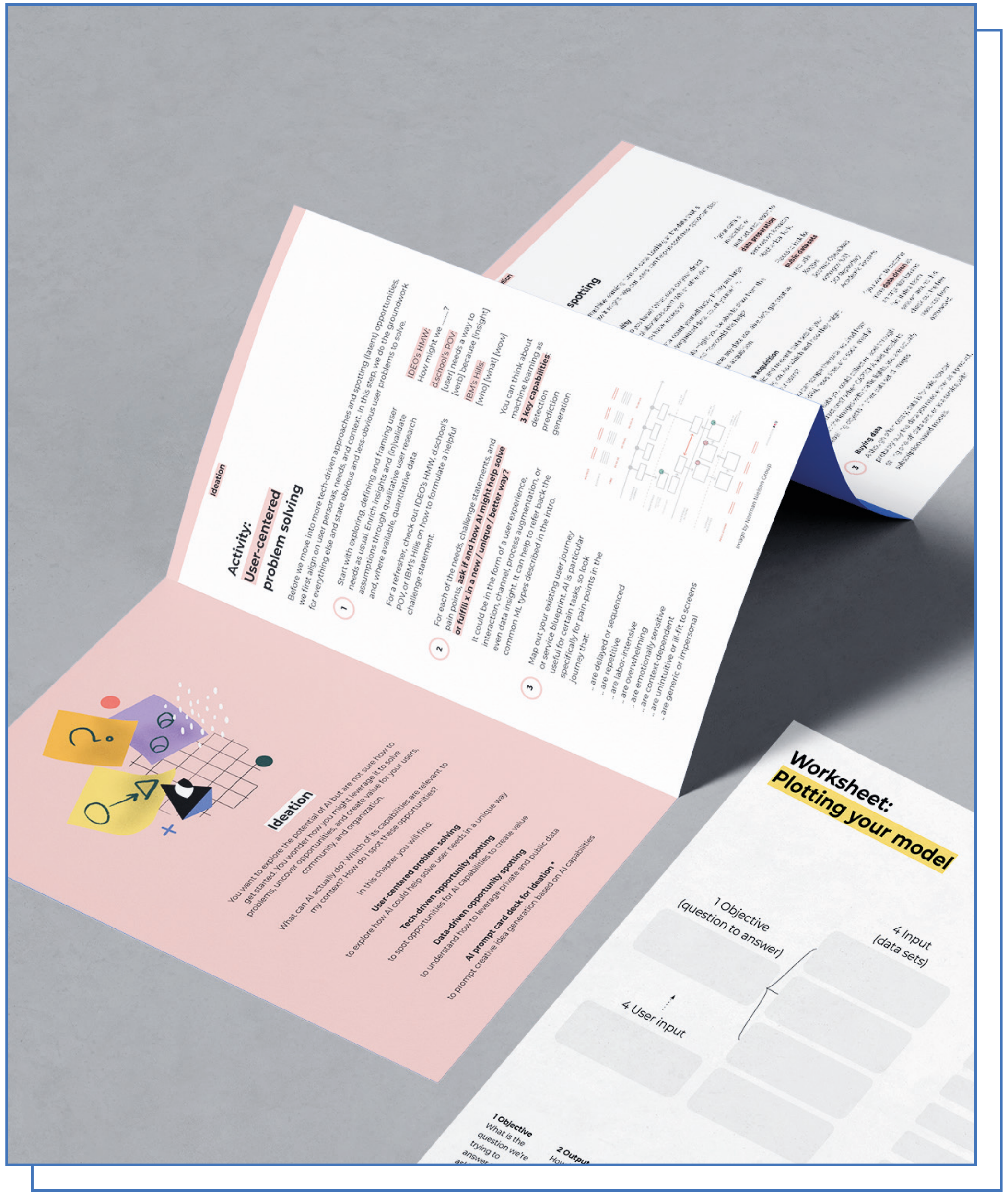


fig. 82
AI meets Design
Accenture, 2019

6.3

The Toolkit

To bring designers and makers closer to the topic of haptics and dynamic vibrotactile interfaces, the toolkit has been shaped with the intent of being suitable to people with all level of technical expertise, so that both beginners and pro users could experience and take advantage of its content in the same manner. With this requirement clear in mind I moved forward curating it in all its facets.

By following the toolkit in its completeness, teams and individuals can learn the foundations of haptic design and perception, vibrations properties and develop a functioning dynamic vibrotactile interface for sensory augmentation prototype.
The core of the toolkit is the booklet, which facilitates the discovery of tactile interactions and guides makers throughout all the phases of the User Centred Design process. To better convey theoretical information and let people understand their value, Haptikós includes hands-on activities during all its modules, and their development can be summarised as follow: learn, test, envision, prototype and evaluate. The modules are subdivided in seven chapters, each of which has its own topic and goal:

1. Haptic HCI

2. Human haptic perception

3. Vibrotactile communication

4. Haptic metaphors

5. Vibrotactile technologies

6. Haptic playground

7. Evaluate the interaction

The chapters draw heavy inspiration from the research advancements made during the development of this thesis, which proved to be fundamental in enhancing my understanding of the topic. Given the substantial volume of information gathered and the purpose of the toolkit, only the most essential and relevant information and insights have been included. These chosen pieces of information have been thoughtfully refined to ensure they are easily understandable and actionable, aligning with the objectives of the toolkit.

In addition to the booklet, the toolkit is composed by the Haptikós app developed during the research phase, and that is used to test vibration properties and patterns; and two activities: "Generating Metaphors" template and "Select the Hardware" template and cards.

A detailed overview of the chapters with the relative activities will be presented in the next pages.

fig. 83
Haptikós Toolkit
Booklet, Template, Cards and App

Haptics ≠ vibrations

Despite the common thought, the word haptics refers in its generic form "to the sense of touch, in particular relating to the perception and manipulation of objects."*

Vibrotactile stimuli are just part of the broad variety of haptic sensations people can feel. Haptic perception involves two fundamental and distinct, but correlated senses: **kinaesthesia**, related to body movement, and **tactile**, related to skin contact.

Vibrations are cutaneous haptics perceivable through direct contact between the skin and the source device.

15

* Oxford Dictionary

In this phase collaboration and discussion is fundamental. Discuss about everyday problems and opportunities.

13:10

Haptikós

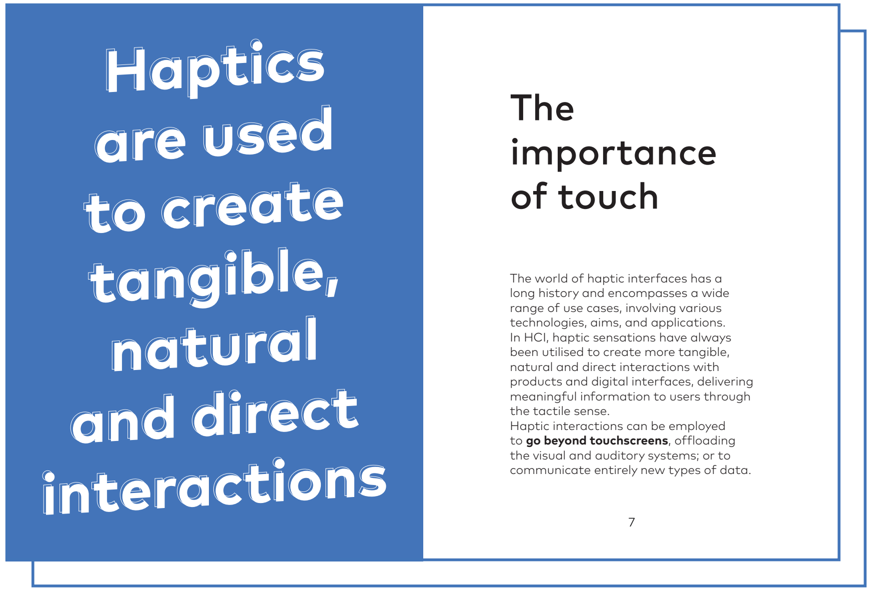
Create personalised vibrations and test native iOS patterns.

Chapter 1

Haptic HCI

Goal: introduction to the field of haptics

Divided in three parts, it presents the importance of the tactile channel in the field of HCI; commercial case studies to make people understand where haptics are involved; and finally, the three sensory purposes of haptics in HCI: substitution, augmentation and reproduction. **(Macpherson, 2018)**



Haptics are used to create tangible, natural and direct interactions

The importance of touch

The world of haptic interfaces has a long history and encompasses a wide range of use cases, involving various technologies, aims, and applications.
In HCI, haptic sensations have always been utilised to create more tangible, natural and direct interactions with products and digital interfaces, delivering meaningful information to users through the tactile sense.
Haptic interactions can be employed to **go beyond touchscreens**, offloading the visual and auditory systems; or to communicate entirely new types of data.

7

fig. 84 | Toolkit Booklet, Chapter 1 - The importance of touch

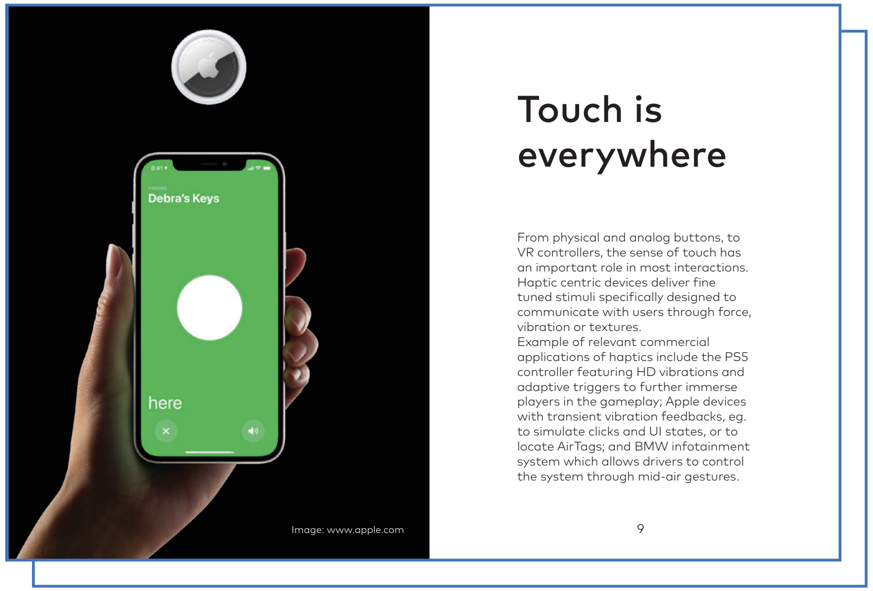


Image: www.apple.com

Touch is everywhere

From physical and analog buttons, to VR controllers, the sense of touch has an important role in most interactions.
Haptic centric devices deliver fine tuned stimuli specifically designed to communicate with users through force, vibration or textures.
Example of relevant commercial applications of haptics include the PS5 controller featuring HD vibrations and adaptive triggers to further immerse players in the gameplay; Apple devices with transient vibration feedbacks, eg. to simulate clicks and UI states, or to locate AirTags; and BMW infotainment system which allows drivers to control the system through mid-air gestures.

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fig. 85 | Toolkit Booklet, Chapter 1 - Touch is everywhere

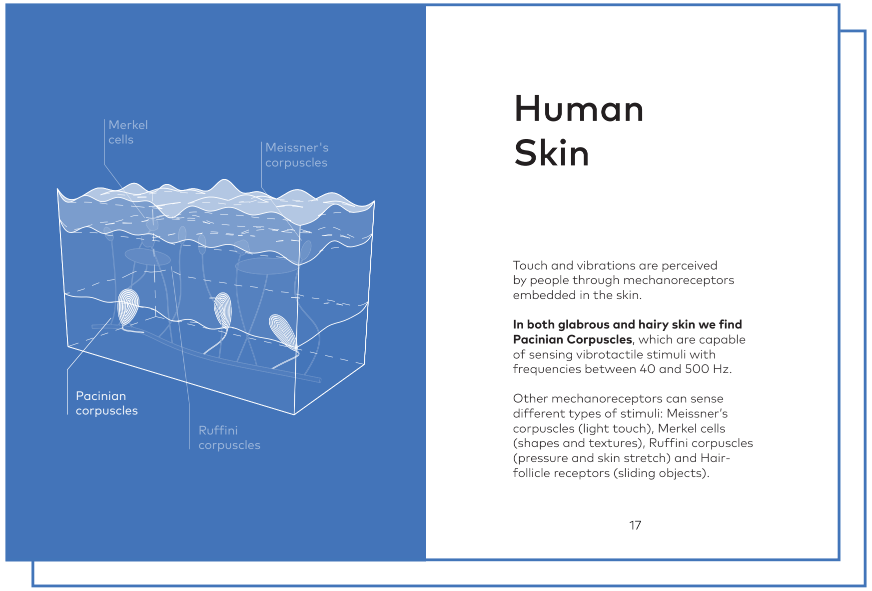
Chapter 2

Human haptic perception

Goal: understand how humans perceive haptic stimuli

With the importance of tactile interactions in mind, the second chapter goes deeper into haptic perception, by explaining the division into kinaesthetic and tactile, and the different types of haptic sensations (vibrations, gestures, force, etc.). The objective is to effectively convey to people that the term "haptics," commonly misinterpreted as referring solely to vibrations, actually encompasses a wide range of sensory experiences. **(Jones, 2018)**

The chapter, also includes how our skin senses haptic stimulations by means of mechanoreceptors and more specifically vibrations; finally, an overview on the body's spatial acuity is presented.



Human Skin

Touch and vibrations are perceived by people through mechanoreceptors embedded in the skin.

In both glabrous and hairy skin we find Pacinian Corpuscles, which are capable of sensing vibrotactile stimuli with frequencies between 40 and 500 Hz.

Other mechanoreceptors can sense different types of stimuli: Meissner's corpuscles (light touch), Merkel cells (shapes and textures), Ruffini corpuscles (pressure and skin stretch) and Hair-follicle receptors (sliding objects).

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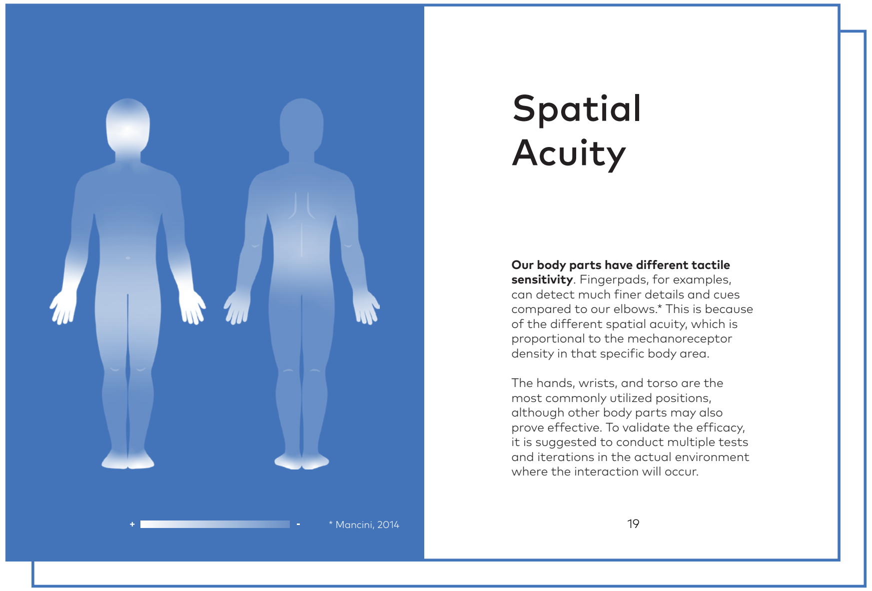
fig. 86 | Toolkit Booklet, Chapter 2 - Human Skin



Spatial Acuity

Our body parts have different tactile sensitivity. Fingerpads, for examples, can detect much finer details and cues compared to our elbows.* This is because of the different spatial acuity, which is proportional to the mechanoreceptor density in that specific body area.

The hands, wrists, and torso are the most commonly utilized positions, although other body parts may also prove effective. To validate the efficacy, it is suggested to conduct multiple tests and iterations in the actual environment where the interaction will occur.

* Mancini, 2014

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fig. 87 | Toolkit Booklet, Chapter 2 - Spatial Acuity

Chapter 3

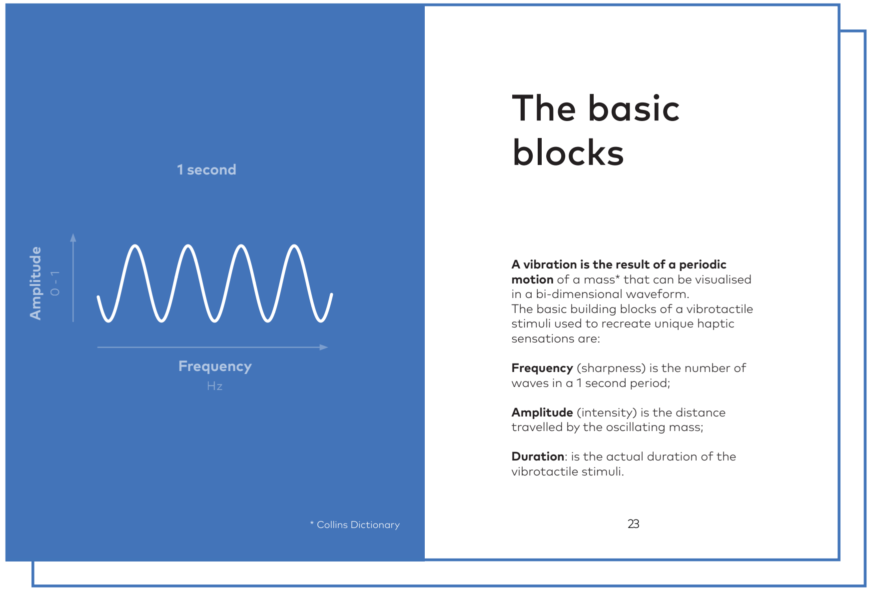
Vibrotactile communication

Goal: discover vibration properties and their role

In chapter three, users are introduced to vibrations and their basic building blocks (frequency, amplitude and duration), as well as to the difference between transient and continuous feedbacks. **(Apple Developer, n.d.)**

To make them better understand these concepts, a first testing activity is planned. Designers are invited to test the effect of vibration properties by downloading the Haptikós app for iPhone and use the "Custom" feature. Then they should reflect on how modulating each building block changes the perception of the stimuli.

The last part of the chapter is dedicated to haptic patterns and to the testing through the "iOS Patterns" feature on the Haptikós app.



The basic blocks

A vibration is the result of a periodic motion of a mass* that can be visualised in a bi-dimensional waveform.
The basic building blocks of a vibrotactile stimuli used to recreate unique haptic sensations are:

Frequency (sharpness) is the number of waves in a 1 second period;

Amplitude (intensity) is the distance travelled by the oscillating mass;

Duration: is the actual duration of the vibrotactile stimuli.

* Collins Dictionary

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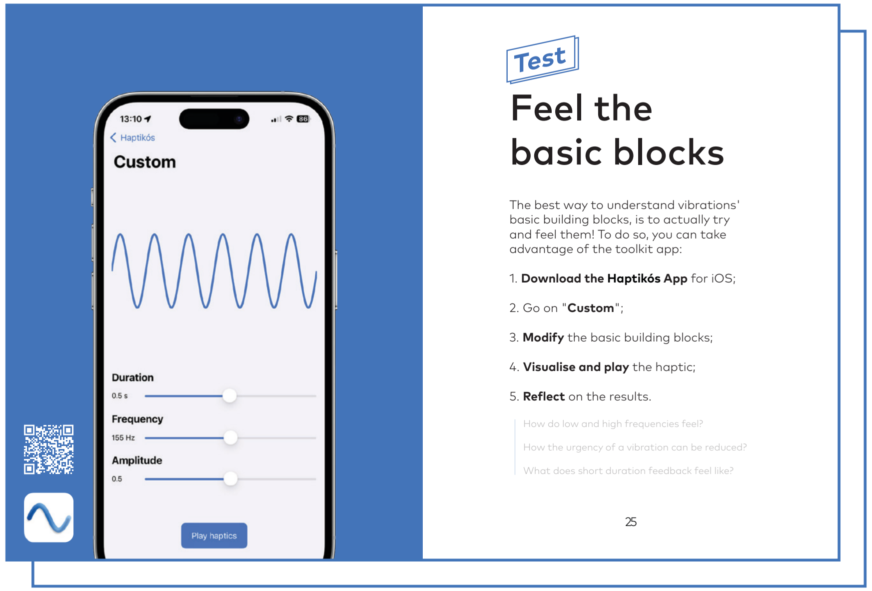
fig. 88 | Toolkit Booklet, Chapter 3 - The basic blocks



Test

Feel the basic blocks

The best way to understand vibrations' basic building blocks, is to actually try and feel them! To do so, you can take advantage of the toolkit app:

1. **Download the Haptikós App** for iOS;
2. Go on "**Custom**";
3. **Modify** the basic building blocks;
4. **Visualise and play** the haptic;
5. **Reflect** on the results.

How do low and high frequencies feel?
How the urgency of a vibration can be reduced?
What does short duration feedback feel like?

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fig. 89 | Toolkit Booklet, Chapter 3 - Feel the basic blocks

Chapter 4

Vibrotactile communication

Goal: introduce the concept of metaphors, select a design idea and generate the metaphor

With chapter four, users start their design journey that will lead to the actual creation of the prototype at the end of the toolkit.

To make a device communicate with users through vibrations, a metaphor able to convey meaning to the interaction is needed. To create this, the concept of metaphors **(Baker, 2019)** is presented, as well as multisensory perception principles **(Apple Developer, n.d.)**.

At this point of the process, users have a basic understanding of haptics, vibration properties and how they can be used as a bidirectional communication form in HCI.

An activity aimed at generating design opportunities and problems and at developing an haptic metaphor has been designed.

The concept of metaphors

When vibrations are utilised for sensory augmentation and so, to deliver information that are not perceived by the haptic sense, **metaphors can be used to communicate digital information and events** through physical representation perceivable by the sense of touch.*

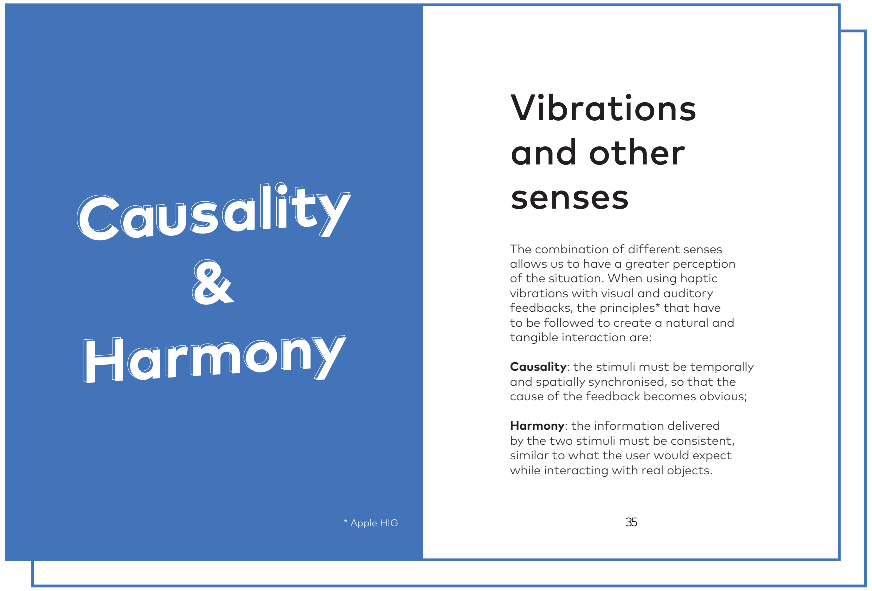
In "Astro's Playroom"*, the PS5 controller makes the user feel the tension of cords by modulating the vibration's frequency.

While locating an Apple AirTag indeed, the intensity of transient stimuli is gradually modulated to communicate the distance with the user's device.

* Backer, 2019

33

fig. 90 | Toolkit Booklet, Chapter 4 - The concept of metaphors



Causality & Harmony

Vibrations and other senses

The combination of different senses allows us to have a greater perception of the situation. When using haptic vibrations with visual and auditory feedbacks, the principles* that have to be followed to create a natural and tangible interaction are:

Causality: the stimuli must be temporally and spatially synchronised, so that the cause of the feedback becomes obvious;

Harmony: the information delivered by the two stimuli must be consistent, similar to what the user would expect while interacting with real objects.

* Apple HIG

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fig. 91 | Toolkit Booklet, Chapter 4 - Vibrations and other senses

The activity requires users to follow a template, which is divided in 4 consequent stages:

- **Problems/Opportunities**: through a brainstorming session, designers are encouraged to think about their daily routine, products and devices they use, and identify possible opportunities or problems that arise while interacting with them. Each case has to be noted on a post-it and placed in the respective area.
  At the end of this phase, designers must have selected 3/5 scenarios;

- **What data has to be communicated?**: for each case previously identified, in this session they must declare the type of information or data the product/interface has to communicate to users;

- **How should it be communicated?**: in the third stage, designers think about how the information should be communicated, with adjectives and without being technical (eg. when the system detects an high temperature, the feedback should be urgent and strong). Adjectives, as well as Onomatopoeia, allow people to better envision and communicate what the desired vibration actually feels, compared to mere values of frequency, amplitude and duration. **(MacLean, 2018)** At the end of this phase, also by looking at all previous ones, the team should discuss and select the most promising and feasible idea;

- **Haptic Metaphor**: the last section of the template is used to summarise the interaction idea into an easy to share single sentence metaphor. The sentence should be structured following the **when-do-as formula**, which gives also a clear guidance when users have to actually prototype the interaction (eg. when the system detects an high temperature, generate an urgent and strong feedback, as if someone was insistently calling you).

By the end of this activity the team must have identified the metaphor through which the initial problem will be solved or the opportunity fulfilled.

Activity

Generating metaphors

Welcome!
In this activity you are going to define a problem or opportunity you will solve with an haptic interface. At the end you will create the metaphor that allows the user to give meaning to the vibration stimuli.

INTRO
During the four phases of this template, try to come up with multiple ideas and to move forward with each.

STEP 1 - PROBLEMS/ OPPORTUNITIES
Think about your everyday life and the interfaces you use. Do you ever find any type of information difficult to read or hear? Is there any information that cannot be displayed in a specific scenario / environment? **Write each idea** on a post-it and place it in the first area.

STEP 2 - DATA
For each idea think about what is **the type of data that you need do communicate or receive** (eg. temperature, distance, etc.). Write it on a post-it and place it in the second area.

STEP 3 - COMMUNICATION
Once the data to communicate is clear, think about how that data should be communicated using adjectives. Discuss with the team and select the most promising idea/interface

STEP 4 - METAPHOR
As last step of this activity, clearly state your metaphor. Take the post-it created in the four steps and merge them using the when-do-as formula.

In this phase collaboration and discussion is fundamental.
Discuss about everyday problems and opportunities.

Problems / Opportunities
Use one post-it for each

People are not aware about the amount of water they use while showering

What data has to be communicated?
Use one post-it for each

I want to communicate the percentage of liters used during the shower

How should it be communicated?
Use one post-it for each, and use adjectives, sounds and similarities

When the liter are low, the feedback should be calm and gentle;
when the liter are high, the feedback should be urgent and crisp.

Haptic Metaphor
Use the when-do-as formula

When the liters are low, **play** a gentle and calm tap, **as** a water drop falling on your arm

Haptikós

fig. 92
Toolkit Activity Template - Generating metaphors

Chapter 5

Vibrotactile technologies

Goal: select the elements of the interaction and identify the logic

Before moving to the prototyping phase, designers must be aware of the technology behind vibration stimuli. In this chapter the elements of the interaction loop are presented (input, processing and output), together with an overview on the feedback part: vibrotactile actuators.

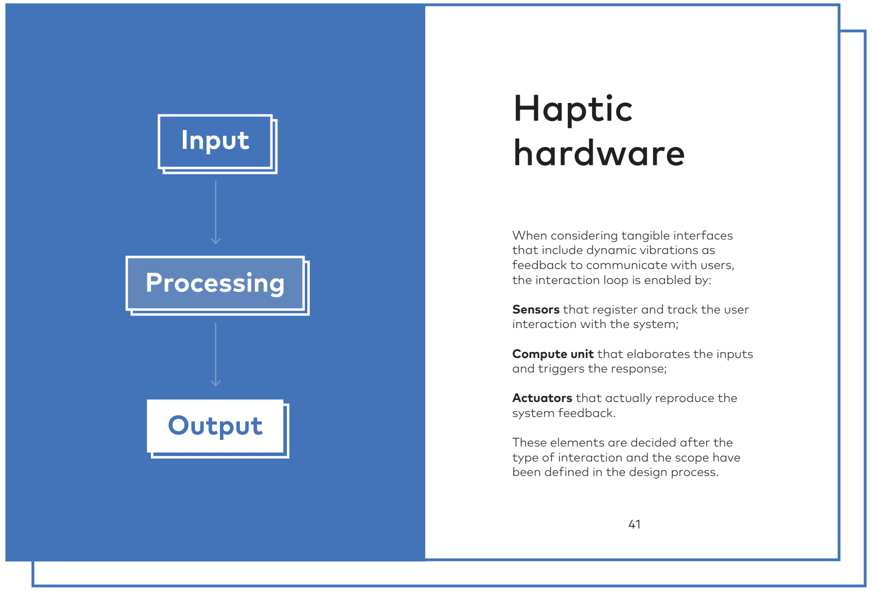
As last section of the chapter users have to identify:

- The sensor and the data it has to acquire;
- The actuator and the type of feedback it has to reproduce;
- The logic that translates the input values into haptic feedbacks.

This is made possible through an activity template and a deck of cards. The deck comprises two distinct types of cards: sensors and actuators. Each card features a wireframe illustration of the sensor or actuator, accompanied by a description. For sensors, the card also specifies the type of data it detects, while for actuators, the card outlines their respective advantages and disadvantages. As the range of sensors is extensive, not all of them have dedicated cards. To address this, the deck includes two special cards: a "Custom" card, which can be customised with details about a specific physical sensor, and a "Digital" card, which can be filled with data originating from digital sources such as software or APIs.

By looking at the metaphor defined in the last activity and reading sensors' and actuators' properties on the relative cards, users must select one sensor and one actuator and place their cards on the template. During this phase the team is invited to try and discuss about the pros and cons of the different possible combinations.

Afterwards they have to precisely note the type of data needed (eg.



Haptic hardware

When considering tangible interfaces that include dynamic vibrations as feedback to communicate with users, the interaction loop is enabled by:

Sensors that register and track the user interaction with the system;

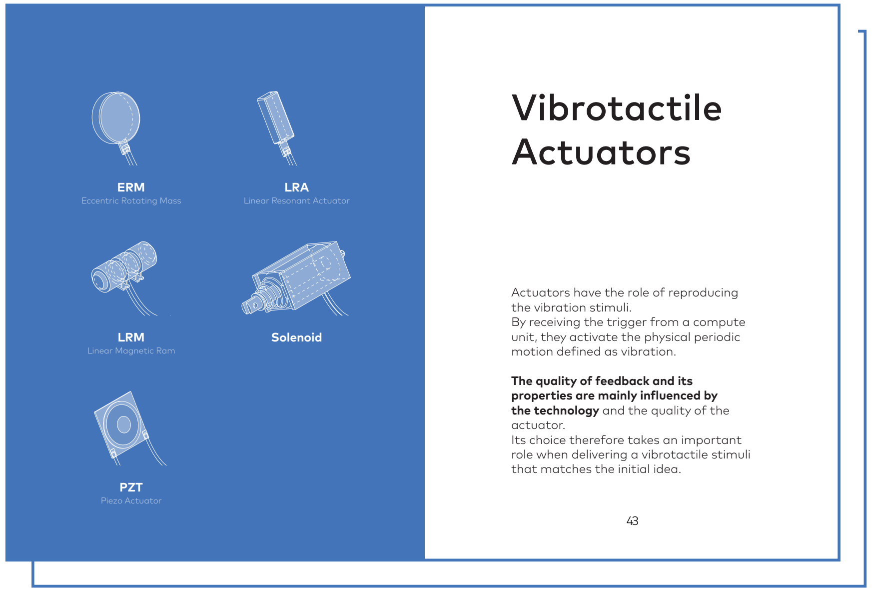
Compute unit that elaborates the inputs and triggers the response;

Actuators that actually reproduce the system feedback.

These elements are decided after the type of interaction and the scope have been defined in the design process.

41

fig. 93 | Toolkit Booklet, Chapter 5 - Haptic hardware



Vibrotactile Actuators

Actuators have the role of reproducing the vibration stimuli.
By receiving the trigger from a compute unit, they activate the physical periodic motion defined as vibration.

The quality of feedback and its properties are mainly influenced by the technology and the quality of the actuator.
Its choice therefore takes an important role when delivering a vibrotactile stimuli that matches the initial idea.

43

fig. 94 | Toolkit Booklet, Chapter 5 - Vibrotactile Actuators distance in cm every 500ms), the type of feedback to reproduce (eg. low frequency transient feedback when distance is high), and the logic that make the metaphor possible and enables the interaction (eg. when distance is equal to 100, pattern 1 has to be played, with an interval between stimuli of 3s) in the relative input fields.

At the end of this activity designers will have established the hardware and logic needed to create the functioning prototype.

Activity

Select the hardware

Welcome!
In this activity you are going to define the hardware, needed to fulfil your metaphor.

INTRO
You have been provided with two sets of cards, each of which represents two hardware categories:

1. Sensors;
2. Actuators.

Give them a look and try to understand the differences between actuators.

STEP 1 - SENSOR
By looking at the metaphor template, **define the type of data** you need in the interaction, and **select the most suitable sensor** to register it.
Then precisely **describe** the data in the relative input field.

STEP 2 - ACTUATOR
Once you have selected the sensor, **think about the type of feedback** you want to achieve, **the body position** and **the space available** for the actuator.
Compare this requirements with the actuator' properties and **select the most suitable one**.
Then precisely **describe** the type of feeling you want to achieve and where are you planning to place the actuator in the relative input field.

STEP 3 - THE LOGIC
Thanks to the processing unit, the concept idea can be translated into real-life action.
Write in the relative input field, **how real-time data gathered through the sensor are translated in haptic feedback** by the actuator.

Try multiple combinations and have a proactive discussion with your team about the pros and cons of each solution. ⚠

SENSOR

WHAT DATA DO YOU NEED?
(be as much specific as possible)

eg.
distance between the device and external objects in centimetres every 2 seconds.

SENSOR NOTES

PROCESSING UNIT

HOW SHOULD THE DATA BE TRANSLATED INTO HAPTICS?
(be as much technical as possible)

eg.
- distance = 100 -> interval = 3s
- distance = 10 -> interval = 100 ms

LOGIC NOTES

ACTUATOR

HOW SHOULD THE HAPTIC BE?
(be as much specific as possible, use adjectives, similarities and sounds)

eg.
- low frequency transient when the distance is high;
- high frequency transient when the distance is low

ACTUATOR NOTES

Haptikós

fig. 95
Toolkit Activity Template - Select the hardware

fig. 96
Toolkit Activity Cards
Sensors and Actuators

LRA Linear Resonant Actuat

LRAs are a popular choice for high precision stimuli, however they perform better at their resonant frequency. LRAs are used in high-end smartphones, wearables, Mac trackpad.

PROs "Click" effect, precise, small and multiple sizes

CONs More complex expensive compared to ERM

LMR Linear Magnetic Ram

Similar to LRAs, but the internal spring is missing. The movement is controlled by magnets and the mass can impact the chamber creating impact forces. Used in VR controllers and car's screens.

PROs "Click" effect, strong and very precise

CONs Medium size, expensive and power intensive

ERM Eccentric Rotating Mass

Frequency and amplitude of ERMs cannot be changed separately. The fastest the mass rotates, the stronger the feedback. They can be found in game controllers and old smartphones.

PROs Cheap, strong "rumble" feedback, different shapes

CONs No transient stimuli, low precision, power intensive

Gyroscope

It measures angular velocity or rotation. It is used to determine the orientation or movement of an object in three-dimensional space. By detecting changes in rotational motion.

DATA Rotation, motion

Force

Also known as a load cell, it is a device that measures the force or load applied to it. It converts the applied force into an electrical signal.

DATA Force, pressure

Chapter 6

Haptic playground

Goal: select the elements of the interaction and identify the logic

With chapter six makers are introduced to haptic prototyping, by presenting the boards available to manage the logic of the physical interaction, and the softwares through which they can program the sensing, logic and feedback design.

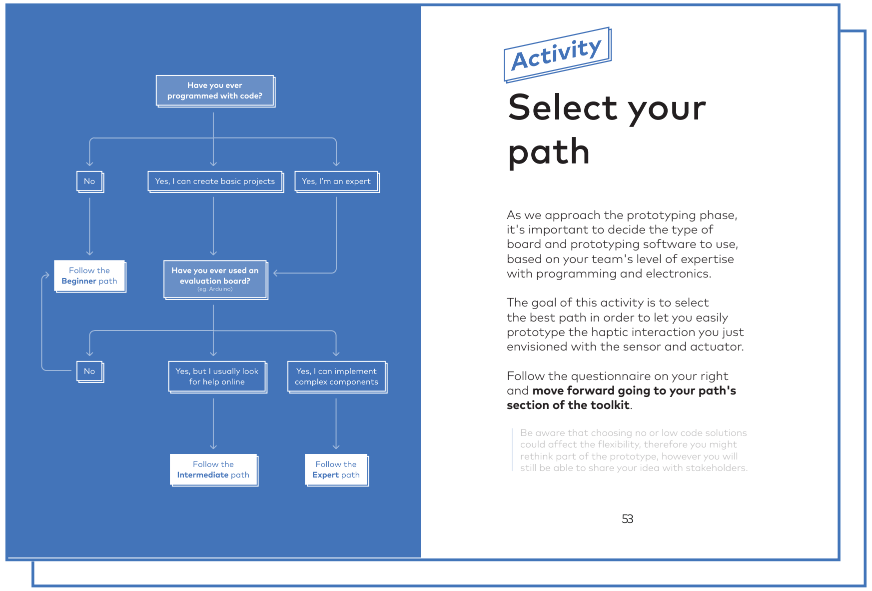
The toolkit offers three different paths for creating the final prototype, based on the designer's level of programming and electronics confidence: Beginner, Intermediate, and Expert. This approach was taken to involve designers with varying levels of expertise.

To help each user or team to identify the best path to follow, a multi-choice questionnaire to asses their technical knowledge is provided.

Each path has its own software and board suggestion, which range from no-code and off-the-shelf solutions, to code and custom ones.

Especially for the **Beginner** and **Intermediate** paths, the use of hapticlabs.io is suggested. This is due to the possibility of creating high quality feedback with a minimal effort and an intuitive UI. Also for **Expert** users this approach is proposed, since vibration design with "Code" tools could require extensive time, sometimes with worse outcomes.

The last part of this chapter is dedicated to the prototyping activity, which consists in transforming the initial haptic metaphor into the actual interface, by referring to the components and logic previously defined, and by using the hardware and software solutions according to the followed path.



Activity

Select your path

As we approach the prototyping phase, it's important to decide the type of board and prototyping software to use, based on your team's level of expertise with programming and electronics.

The goal of this activity is to select the best path in order to let you easily prototype the haptic interaction you just envisioned with the sensor and actuator.

Follow the questionnaire on your right and **move forward going to your path's section of the toolkit**.

Be aware that choosing no or low code solutions could affect the flexibility, therefore you might rethink part of the prototype, however you will still be able to share your idea with stakeholders.

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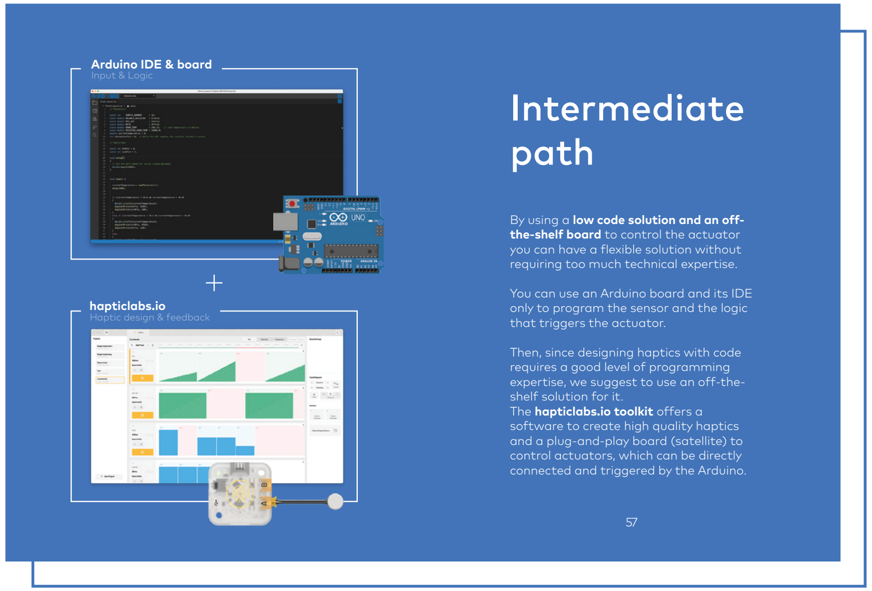
fig. 97 | Toolkit Booklet, Chapter 6 - Select your path



Intermediate path

By using a **low code solution and an off-the-shelf board** to control the actuator you can have a flexible solution without requiring too much technical expertise.

You can use an Arduino board and its IDE only to program the sensor and the logic that triggers the actuator.

Then, since designing haptics with code requires a good level of programming expertise, we suggest to use an off-the-shelf solution for it.
The **hapticlabs.io toolkit** offers a software to create high quality haptics and a plug-and-play board (satellite) to control actuators, which can be directly connected and triggered by the Arduino.

57

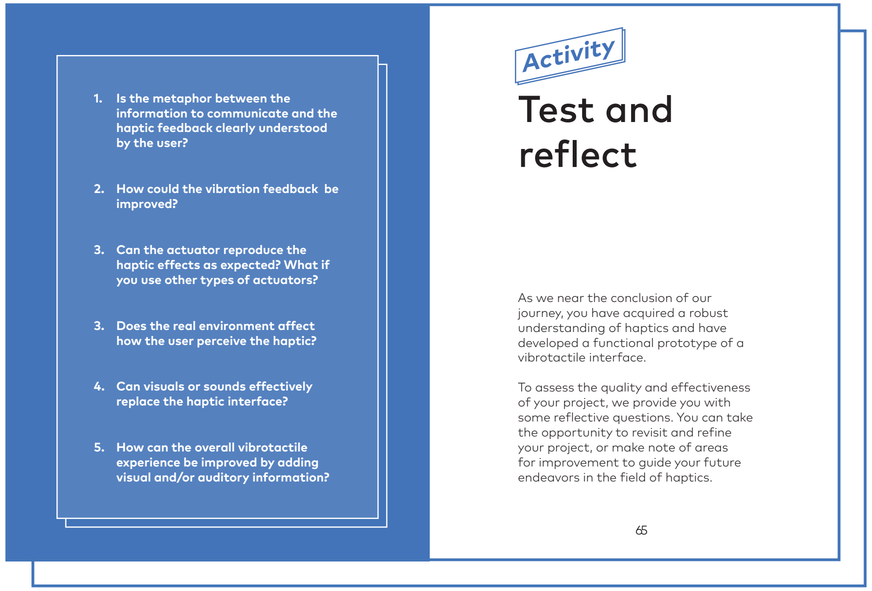
fig. 98 | Toolkit Booklet, Chapter 6 - Intermediate path

Chapter 7

Evaluate the interaction

Goal: reflect on the effectiveness of the interaction

The chapter serves as the concluding section of the toolkit. During this phase, the team or individual is encouraged to test the prototype and engage in a retrospective analysis of the initial problem or opportunity. Through a series of reflection questions, the team is prompted to assess whether they have successfully achieved their intended goals, identify areas for potential improvement, and explore strategies for enhancing future iterations.



1. Is the metaphor between the information to communicate and the haptic feedback clearly understood by the user?

2. How could the vibration feedback be improved?

3. Can the actuator reproduce the haptic effects as expected? What if you use other types of actuators?

3. Does the real environment affect how the user perceive the haptic?

4. Can visuals or sounds effectively replace the haptic interface?

5. How can the overall vibrotactile experience be improved by adding visual and/or auditory information?

Activity

Test and reflect

As we near the conclusion of our journey, you have acquired a robust understanding of haptics and have developed a functional prototype of a vibrotactile interface.

To assess the quality and effectiveness of your project, we provide you with some reflective questions. You can take the opportunity to revisit and refine your project, or make note of areas for improvement to guide your future endeavors in the field of haptics.

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fig. 99 | Toolkit Booklet, Chapter 7 - Test and reflect

6.3.1
Modalities and artefacts

The toolkit has been designed to be used in two main ways. Firstly, it can be used **within a workshop setting** where one or more groups of designers and makers work together. In this scenario, an expert facilitator would present the theoretical content, dictate the timings, and offer support for all the activities. Alternatively, it can be used **individually**, where single teams or individuals can refer to the book and use it as a guide throughout all the phases.

The two distinct approaches are similar to what the Design Sprint from Google **(The Design Sprint, n.d.)** and the Enterprise Design Thinking from IBM **(Enterprise Design Thinking, n.d.)** already offer.

In terms of artefacts, they have been created to accommodate all practical requirements. The booklet is available both in a printed and a digital version, while activity templates take into consideration all possible scenarios:

For **facilitated workshops and business settings**, the templates comes in a large scale as posters. This dimension allow teams to position them on a wall and have discussions around.

Smaller teams or individuals can use the same templates, available in an A4 format. This makes them easy to print, place on any surface, and carry away without losing any information due to the smaller dimensions.

Online teams or individuals can still work together on the toolkit by collaborating in real-time by using the FigJam files featuring the activity templates. It removes barriers also to remote and international teams.

6.3.2
Website

To make the toolkit easily accessible to a wider audience and promote its content, visitors can access all relevant information and download the artefacts from its website at **www.haptikos.design** .

The landing page includes a presentation of the toolkit, a section to download the booklet and templates, and contact information to request a facilitated workshop or further details.

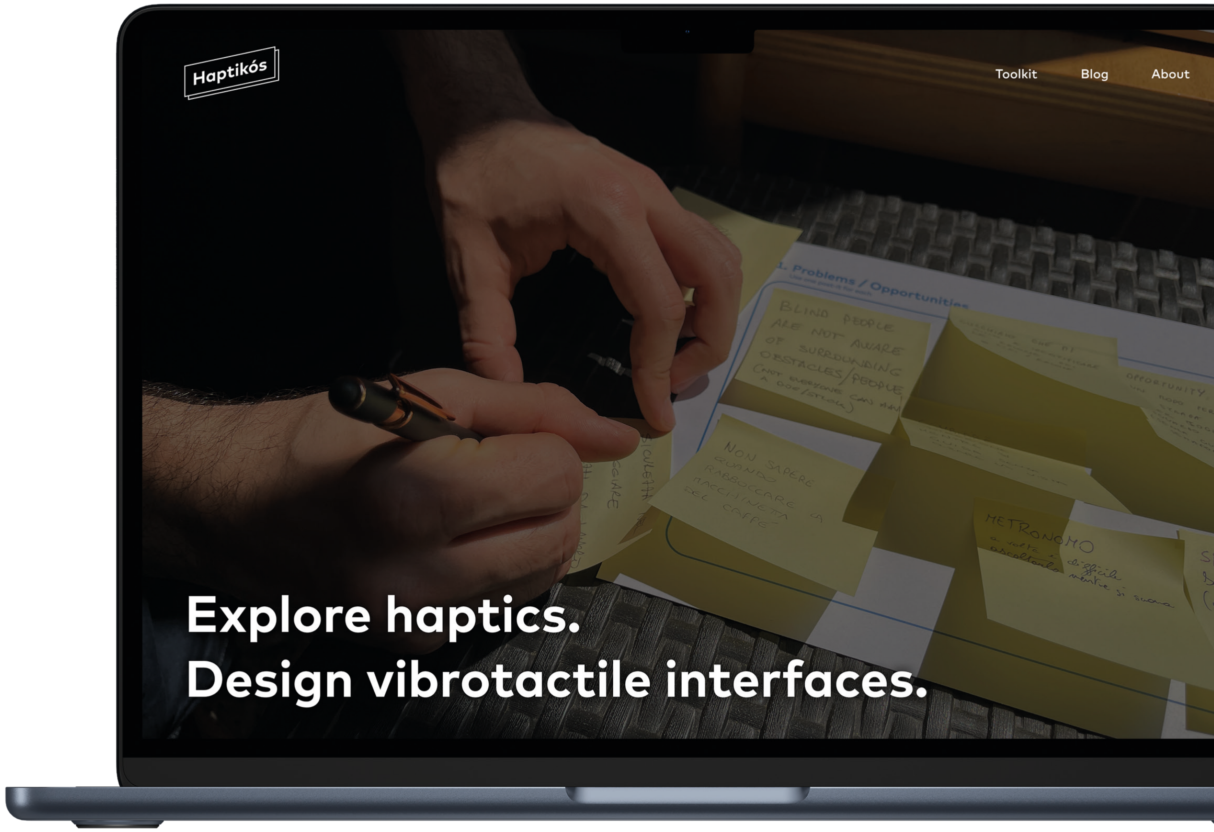

fig. 100 | Haptikós website

Toolkit evaluation

07

Despite the toolkit lays down its foundation from the results coming from the research, and took inspiration from reputable toolkits, in order to thoroughly assess its effectiveness in all aspects and as an integral part of the design process, I deemed it necessary to organise and conduct a series of testing activities.

Objective

To determine the appropriate types of tests, a clear understanding of their objectives was crucial. First and foremost, the tests needed to align with the central goal derived from the HMW question formulated at the outset of the project phase: "How may we support designers throughout the entire design process to enable them to envision and create more tangible and direct interfaces through dynamic vibrotactile interactions?" by providing the necessary knowledge to start ideating haptic HCI, and offer clear guidance during the prototyping phase of dynamic vibrotactile interfaces. Furthermore, the secondary objective was to evaluate the user experience in various scenarios, including workshop settings, individual use by a single team, and individual use by a single user.

Planning

Considering these requirements, I defined three distinct testing activities that would validate the idea and its interpretation while simulating all the scenarios the toolkit is expected to be utilised. These tests took place in a chronological order as follows:

1. **A facilitated workshop**: This test aimed to comprehensively evaluate the toolkit by using it in its entirety for the first time. The workshop provided an opportunity to gather initial feedback and insights.

2. **A supervised single-user test**: This test focused on assessing the usability of the toolkit for non-expert individuals. By closely observing and giving only small guidance when needed to a single user, I aimed to gain a deeper understanding of their understanding and interaction with the toolkit.

3. **An unsupervised team test**: This test aims to gauge the effectiveness of the toolkit without external support. By receiving feedback from the team's usage of the toolkit in an unsupervised manner, the goal is to evaluate its potential for independent use and collaboration.

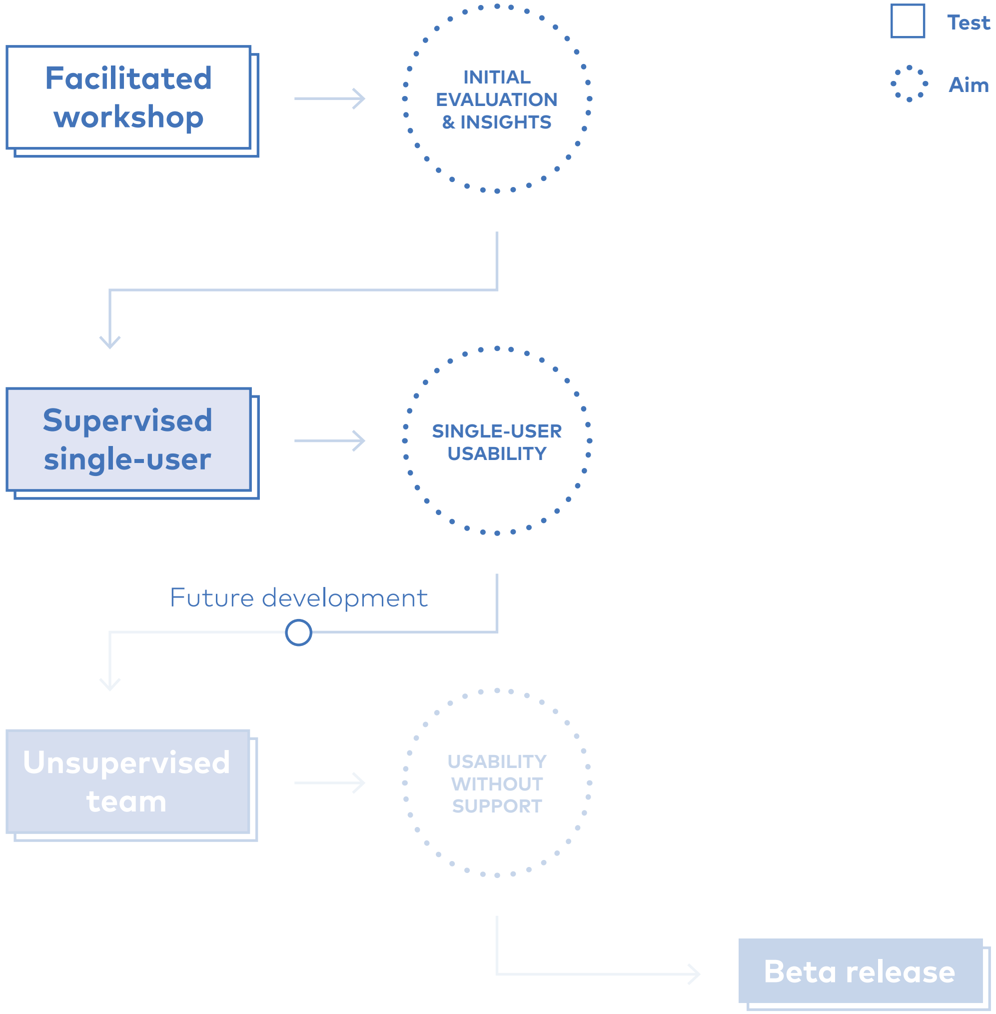

fig. 101 | Testing sessions roadmap

Execution

Due to time constraints, **only the first two scenarios have been tested**.

During the two tests, users were presented with the fundamental theoretical knowledge about haptics and vibrotactile communication. During the first "Generating metaphors" activity they generated design opportunities and problems, identified the need for clear metaphors to fulfill or resolve these issues, and, after discovering vibrotactile actuators, they compiled a list of necessary hardware components (sensors, actuators, logic) for prototyping.
Next, they were faced with the available tools and paths suitable for their programming and electronic proficiency. During the prototyping phase, all the participants used the hapticlabs.io platform for haptic design, in combination with Arduino for input sensing and logic programming.

The use of a plug-and-play board and a GUI software to manage the actuator revealed to be a winning approach, since it allowed users to stay engaged while prototyping, testing and iterating the idea.

Success evaluation

In order **to gather quantitative metrics on the toolkit's quality and success, a survey was distributed to all participants**, featuring similar questions to the first questionnaire described in chapter 5, aimed at understanding the interest in haptic technologies and their familiarity with them in the first part; questions regarding the toolkit material in the second, and questions targeted at evaluating their knowledge after consuming the toolkit.
The feedback obtained from each test played a crucial role in interpreting the insights and subsequently enhancing the materials for subsequent iterations. This iterative approach ensured that the toolkit evolved and improved based on the valuable input received throughout the testing process.

7.1

Facilitated workshop

Participants: 4 Designers + 1 facilitator
Duration: 5 hours (3h of prototyping session)

Set-up

- Presentation display;
- A desk;
- 4 iPhones with the Haptikós App;
- Templates in A4 format;
- A computer for Arduino and hapticlabs.io Studio;
- Arduino board and hapticlabs.io satellite.

The participants of the workshop are three recent graduate from the Master Degree of Digital and Interaction Design, at the moment all working in design companies; and one design student from the Master degree of Product Service System Design. Participants were chosen because of their familiarity with Interaction Design and interest in digital technologies.

The workshop comprehensively addressed all chapters within the toolkit. Rather than distributing booklets to all participants, I, as the facilitator, delivered the content through a presentation. Throughout the session, the designers actively engaged by asking insightful questions, seeking additional information, and offering illustrative examples.

The Haptikós app implementation in the first theoretical module was a success as the team experienced the vibration building blocks firsthand, enhancing their understanding of the theory.

Activities and prototyping

In the initial activity "Generating Metaphors", the team collectively identified eight distinct problems or opportunities across various product areas based on their personal experiences. After careful consideration, they selected the winning problem: the challenge of perceiving the temperature of food while eating, which often led to the risk of burning one's tongue with hot food or experiencing discomfort with cold food. Consequently, their objective was to develop a cutlery-integrated device capable of conveying uncomfortable food temperature through modulated vibrations. They aimed to capture a specific feeling associated with this device by utilising a meaningful metaphor.

Once the hardware properties were understood, the team proceeded to the "Select the Hardware" activity. They chose a temperature sensor to collect food temperature data, an LRA actuator due to its small dimensions that would fit into the cutlery, and its precise capability to deliver both transient and continuous stimuli. The logic required to translate the input data into appropriate feedback was also determined. The hardware selection process was straightforward since the requirements had been thoroughly defined during the initial activity.

To prototype the interaction, the team utilised the Arduino IDE and an Arduino Uno board, along with the hapticlabs.io platform to design and test the feedback. However, **their programming knowledge proved insufficient, necessitating my intervention to handle the input sensing and logic components**. Despite this challenge, they thoroughly enjoyed the feedback design aspect.

As a result of this experience, a multi-choice questionnaire was created and integrated into the final toolkit to assist in selecting the appropriate expertise path, addressing the issue encountered during the workshop.

fig. 102
Facilitated workshop
Presentation

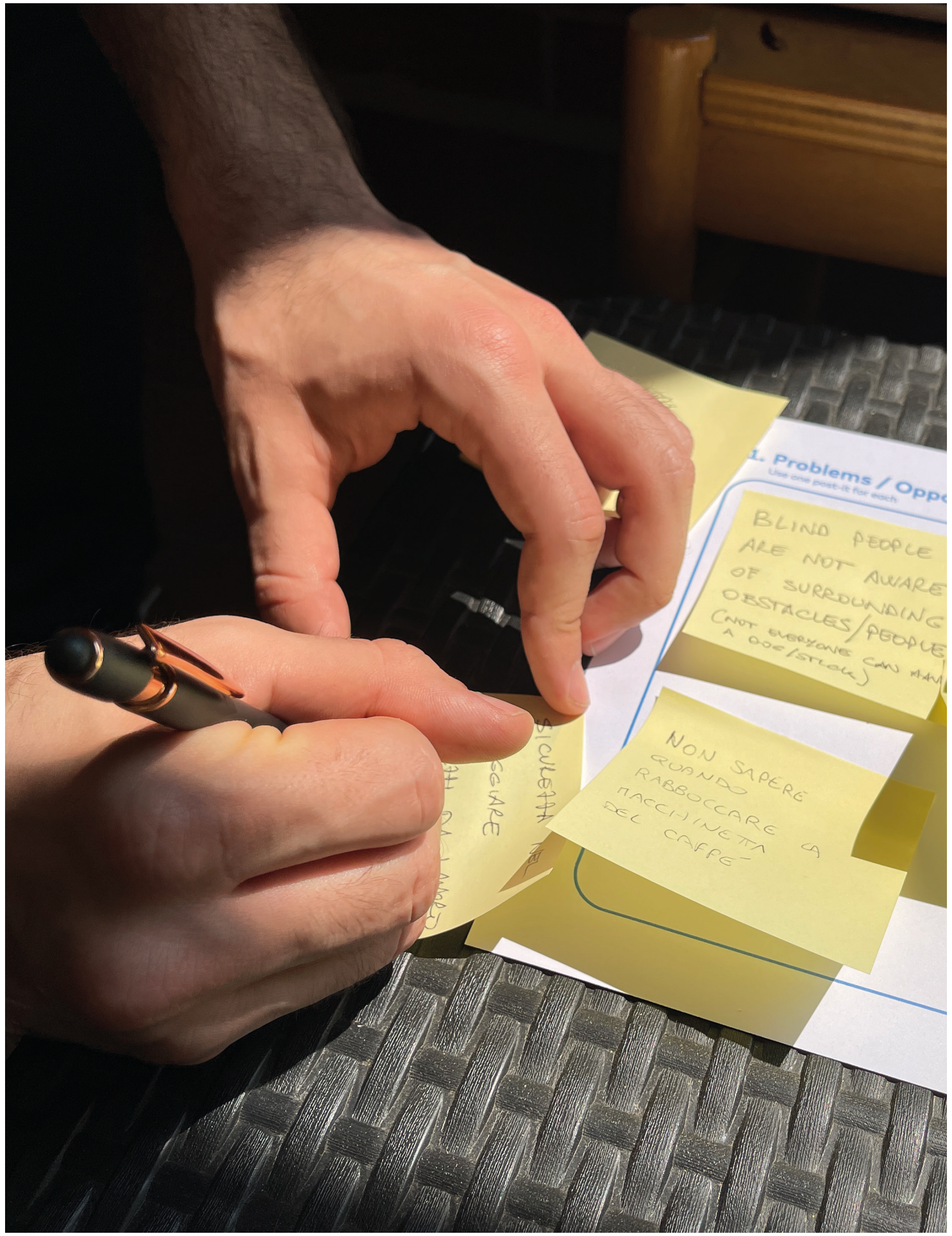

fig. 103 | Facilitated workshop - Generating metaphors activity

fig. 104 | Facilitated workshop - Prototyping session

Insights

The facilitated workshop format with the toolkit was overall successful. Having an expert figure always available for support proven to be a great value for the overall experience. When participants had further questions or doubts about specific topics, especially during the first theoretical phase, I, as facilitator, was able to answer and solve their queries. This would have been more time and effort intense, requiring them to check online, possibly founding sources with a low reliability or, as also seen during the research phase, contradictory material.

From the survey emerges that, before the workshop, all designers nurtured a high level of interest in haptic interfaces but had limited knowledge about them and their potential. Participants found every aspect of the toolkit to be clear and engaging, with particular appreciation towards the first phase and the Haptikós app. The prototyping part happened to be less successful due to the complexity of programming the input sensing and logic with Arduino, and therefore time-consuming.

A valuable insight from the final survey was that **one of the participants desired a repository of links for further readings on the various theoretical topics**. To address this, **the final toolkit now includes a QR code that directs users to the toolkit's website**; from here they can explore an always up to date section with additional resources and delve deeper into the content.

All designers reported feeling more confident in designing and recognising the value of haptic interfaces, and believed that the toolkit could bridge the gap between makers and the world of haptics. Despite their significant declared increase in knowledge after the workshop, from beginner to intermediate, they mentioned the fact that they would need more experience to consider themselves experts in the field of haptics. All designers, then, have stated that they would have referred to the toolkit again with colleagues for working purposes, or if they had to design a product with an haptic interface.

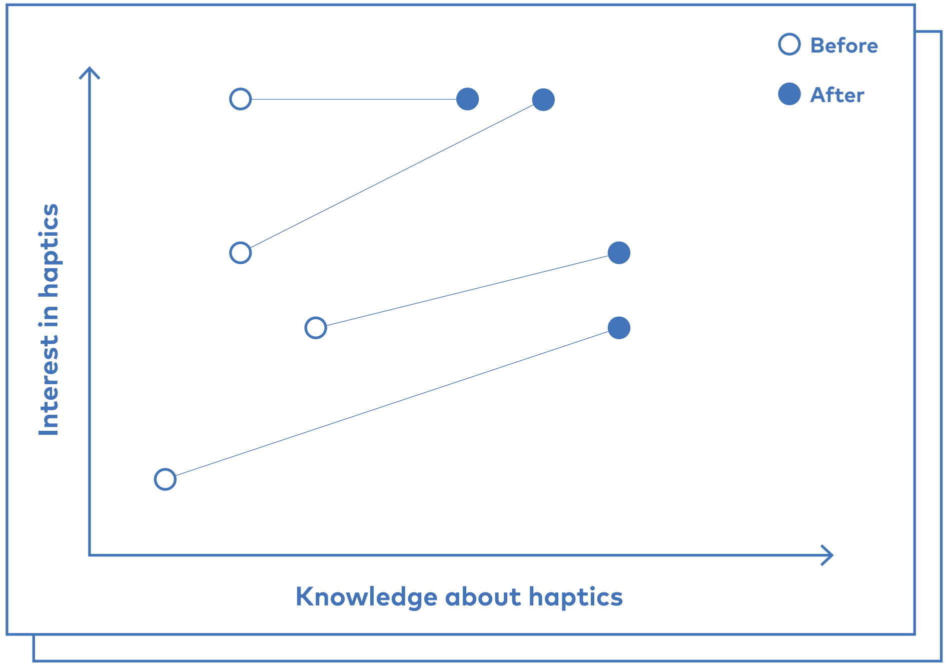

fig. 105 | Participants interest and knowledge before and after the test

7.2

Supervised single-user test

Participants: 1 Front-end developer
Duration: 2:30 hours (30min of prototyping session)

Set-up

- iPad with the toolkit booklet;
- A desk;
- 1 iPhone with the Haptikós App;
- Templates in A4 format;
- A computer for Blokdots and hapticlabs.io Studio;
- Arduino board and hapticlabs.io satellite.

The participant of this test is a front-end developer professional, interested in UI design. This profile was chosen because the toolkit is designed for al kinds of makers, that don't necessarily have a design background. The participant was provided with the toolkit booklet in its digital version on an iPad, and the activity templates in A4 format.

The entire activity was conducted on an individual basis, with the participant explicitly instructed to verbalise their thoughts and actions aloud while I took notes.

During the first theoretical part, **the tester has particularly paid attention to the iconographic elements in support to the text**, highlighting the importance of these.

Activities and prototyping

Compared to the team-based activities in the workshop, the participant dedicated more time to generating problem statements and opportunities, resulting in a total of three unique ones. Ultimately, due to his personal passion for plants and gardening, he decided to address a problem he personally experiences: the challenge of quickly assessing the soil humidity of multiple plants and determining when to water them. This issue served as the foundation for defining the haptic metaphor.

During the "Select the Hardware" activity, the participant easily tackled the sensor selection and logic components. However, **he encountered difficulty in choosing the appropriate actuator**. Unlike during the previous workshop, the participant didn't have the chance of trying haptic actuators during this phase, but only after in the prototyping session. Despite the provided images and descriptions of each actuator type, he struggled to make a decision independently. I had to step in and explain the pros and cons of each option and guide him towards a choice. As a result, **the final version of the cards now includes the pros and cons for each actuator to provide clearer guidance**.

Moving on to the prototyping phase, the participant opted for the intermediate path. Leveraging his programming skills, he efficiently developed the code to sense humidity and trigger corresponding feedback using Arduino. When faced with the haptic design aspect, he appreciated the user-friendly nature of the GUI software and the plug-and-play board. Overall, he expressed great satisfaction with the speed of iteration enabled by the prototyping tools, allowing him to experiment with different actuators he had previously been uncertain about during the hardware selection activity.

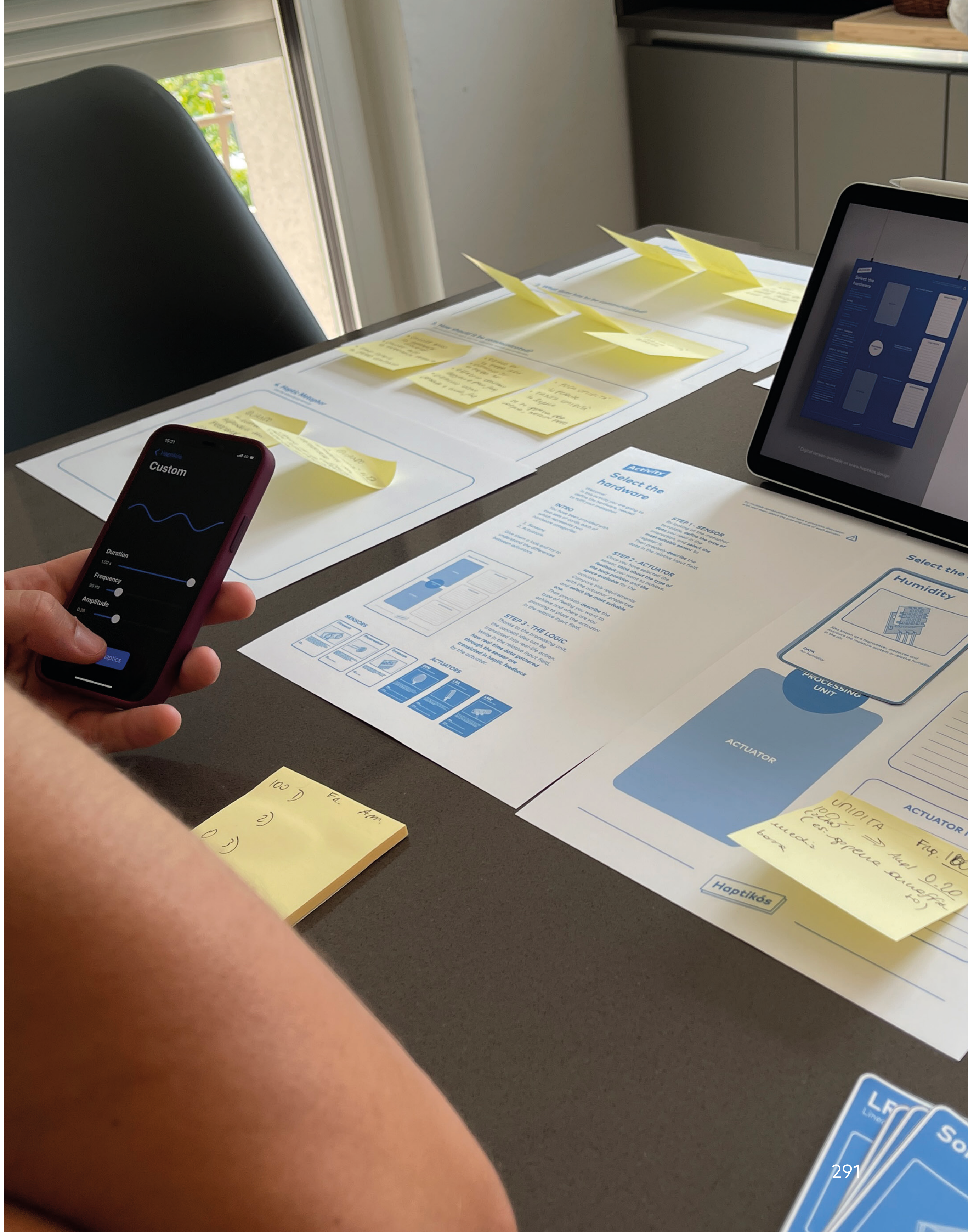

fig. 106
Single-user test
Select the hardware Activity

fig. 107 | Single-user test - Generating metaphors activity

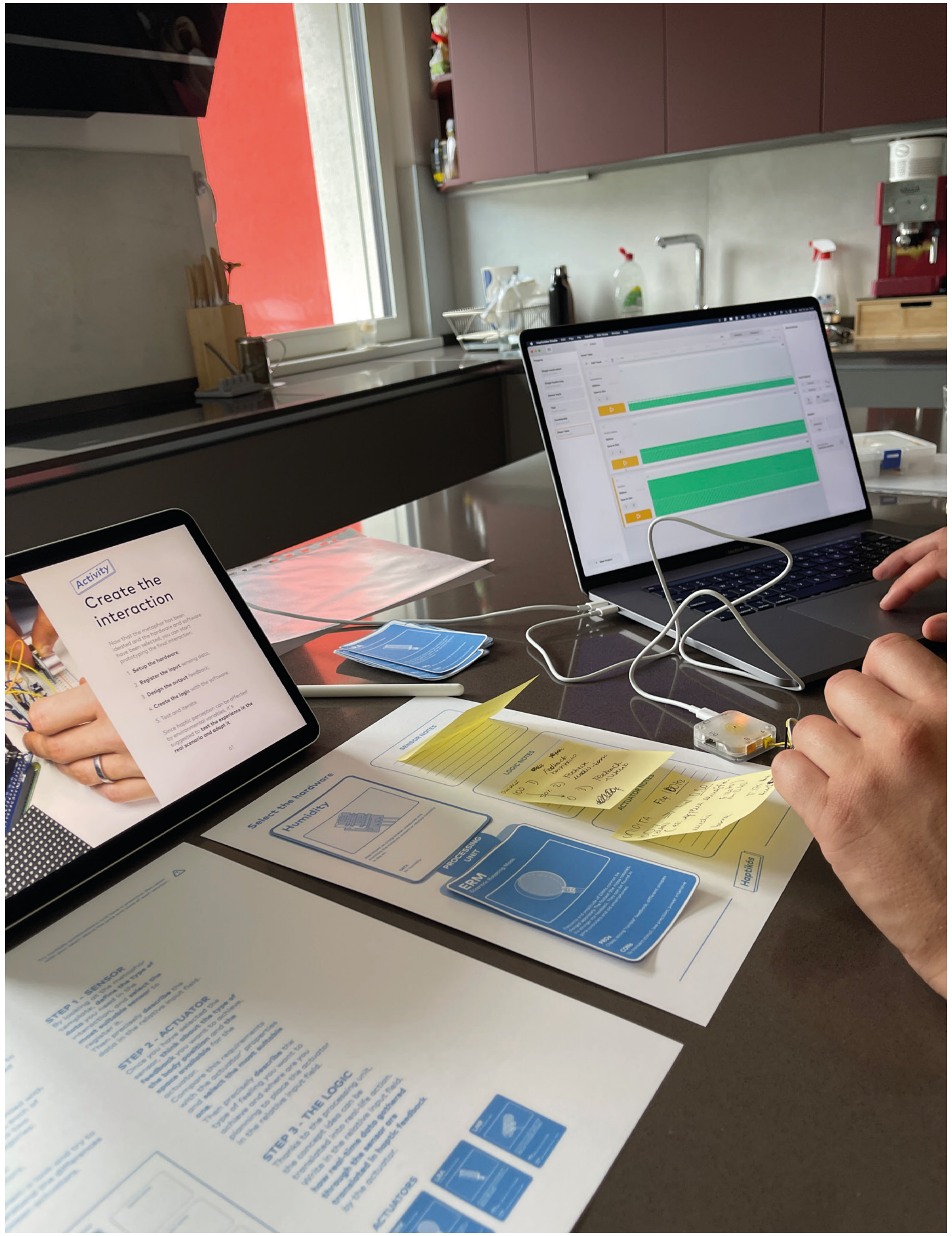

fig. 108 | Single-user test - Prototyping session

Insights

This test yielded two significant findings. Firstly, it demonstrated that **makers without a design background can still generate ideas and prototype haptic interfaces**, thereby increasing awareness among individuals working in various stages and roles of product development, such as front-end development. Secondly, it showed that **even individuals with little to no knowledge about haptics can successfully use the toolkit independently**. However, more tests without the presence of a supervisor would be necessary to further validate this.

In this particular case, the tester displayed an interest in haptic interfaces but had no prior knowledge. Overall, he thoroughly enjoyed all phases of the toolkit, and also in this case, with a particular appreciation for the initial theoretical part and the Haptikós app. Regarding the app, **the user suggests an improvement that would allow the creation and saving of multiple vibrations for easy comparison**. This enhancement would be especially useful during the "Select the Hardware" activity when precise descriptions of feedback types are required.
Although time constraints prevented the implementation of this feedback before the thesis delivery, it is acknowledged as extremely valuable and will be addressed in future iterations of the toolkit.
Upon completing the toolkit activities, the tester reported feeling more confident in designing haptic interfaces and transitioning from a beginner level to a high-intermediate level.

> *" I enjoyed the whole flow, considering that I was not familiar with haptic feedback at all.*
>
> *The application was essential to touch on and try out the different types of feedback. The part about actuators is a bit complex, solely because it is not taken for granted that users have specific skills.*
>
> *Overall, **the experience was excellent and satisfying, far exceeding the expectations** of a beginner."*
>
> **— Front-end developer, Individual tester**

7.3
Outcomes

7.3.1
Limits

Due to the **time constraints**, only two of the three scenarios have been tested, moreover, an expert person was always available in both cases, able to guide and solve tester's queries about the theory and the activities.

Another limitation was the **lack of background diversity among the testers**. If it's true that I've involved both designers and makers with a non-design background, during the first workshop all designers were students or recent graduates, with little experience in the job market and all working on similar products.

The third limitation regards **the hardware**. On one hand there's the limited selection of sensors, which influenced the idea selection and the prototyping phase; on the other there's the limit of hapticlabs.io platform, which at the moment, doesn't allow real time modulation of frequency and intensity, and to save more than two patterns on the board at the same time. This limitation forced designers to develop patterns and test only two at a time (eg. cold and extremely cold and hot and extremely hot for the workshop idea).

7.3.2
Positive insights

In both the tests, users appreciated the overall development of the toolkit, starting from the very basic theory, moving towards more engaging activities. Throughout the entire sessions, the Haptikós has been extremely helpful. In the first instance to try and get to know vibration basic building blocks, and to communicate them with other participants. Then to define the feedback properties to be integrated within the prototype, along with the values of these, which were then entered into hapticlabs.io Studio.
Moving to the templates, the use of post-its allowed for fast thinking and iteration. For what concerns the "Generating metaphors" activity, the intentional lack of specific guidelines in the problem/opportunity ideation section, led to a broad and diverse selection of ideas as well as an intense and fruitful discussion. The last part, dedicated to the selection of the metaphor, resulted not only useful, but also engaging for users, which had the chance of generating sometimes extrovert examples to describe the type of sensation they wanted to make the user feel, to communicate specific information.

The "Select the hardware" activity was noticeably faster compared to the previous one. This was because the necessary data had already been defined, making sensor selection an immediate process. Regarding actuator selection, the main objective of this activity was to generate a clear list of hardware that could be purchased without wasting money on unnecessary sensors or actuators. However, during the first workshop, participants had the opportunity to test all the actuators, which resulted in a rapid and informed decision-making process. In contrast, the second testing activity required additional guidance, leading to a slower selection process.

Lastly, during the prototyping phase, all participants expressed their appreciation for the no-code and plug-and-play prototyping platform offered by the toolkit. They were highly engaged and not only created the required haptic pattern for the prototype but also explored different types of vibrations and the varying effects produced by different actuators.

To conclude this section, all participants evaluated the toolkit as a positive experience that brought them closer to the field of haptics. Moreover, they affirmed that they would have been interested in repeating it again, maybe with other people, or with a real and work related opportunity or problem in mind, originated by a detailed research.

7.3.3

Weaknesses

Although the initial theoretical part of the toolkit received positive feedback, users expressed their desire for an improved section on the concept of metaphors. Despite the inclusion of two case studies, namely the "Astro's Playroom" game for the PS5 and the "Precision finding" feature of the Apple AirTag, users believed that the understanding of the concept could be further strengthened by incorporating additional practical examples that they can personally experience or observe. By introducing more hands-on demonstrations, the users believe that their comprehension of metaphors would be significantly enhanced. To address this, **a QR code directing users to a specific page of the toolkit's website has been implemented** and a possible solutions is explained in the section about "Further improvements".

Transitioning to the first activity, testers greatly appreciated the inclusion of pre-printed example post-its on the template, which proved to be highly beneficial. However, during the step that required defining how the data should be communicated to address the initial problem/opportunity using adjectives (without referencing vibration properties), users in both test sessions encountered difficulties in selecting suitable adjectives. As a result, they often resorted to using repetitive adjectives or onomatopoeic sounds, lacking variety and precision in their descriptions.

During the "Select the hardware" activity, as previously mentioned, users who lacked access to physical actuators experienced a lack of confidence in their selection process (a possible solutions is discussed in the section about "Further improvements"). Additionally, in the first workshop, where both sensor and actuator cards were visually identical with only an image and description, users expressed the need for further differentiation. To address this issue, actuator cards have been modified to include a pros and cons section and are now distinguished by a blue color. On the other hand, sensor cards have retained their white color but now include a list of the data they can sense. During the second workshop, this change proved to be successful in effectively distinguishing between the two types of hardware and meeting user needs.

In conclusion, it is worth mentioning again that users in the first test found it difficult to translate the metaphor into an actual functioning prototype. This has been solved with the path selection questionnaire section in the toolkit.

7.3.4

Further Improvements

As seen, despite the appreciation and the positive outcomes of the two tests, there have been some flaws that should be addressed to improve the experience of using the toolkit and its effectiveness, before being proposed to a larger audience.

First and foremost, since the toolkit is designed to be used individually, without the presence of an expert, it is crucial that all phases are clear and that users can easily comprehend the theoretical content and navigate the templates successfully. To ensure this, it is important to address the uncertainties that arise during the explanation of "The concept of Metaphors." Users have expressed a need for more case studies that demonstrate the use of metaphors to convey information through vibrations. However, it is worth noting that, as observed during background research, applications of vibrotactile communication for sensory augmentation are limited. To overcome this limitation, one possible solution, whose need was also shared through the discussions with the hapticlabs.io team, is to internally develop and create case studies or “demonstrators” specifically designed to effectively communicate the concept of metaphors.

Next, to demonstrate the properties of actuators and enable users to select the most suitable option without the need to purchase and test each one individually, two potential solutions have been conceived.

The first solution involves creating, for each haptic actuator, an accessible list of case studies that integrate these, so that users can explore and experience their properties by themselves. These case studies would offer practical scenarios and hands-on demonstrations, allowing users to see how each actuator behaves and performs in various contexts.

The second solution entails producing informative videos that present and showcase the different actuators. These videos would highlight the unique features and functionalities of each actuator, providing users with visual demonstrations and explanations of their properties.

7.3.5

Conclusions

Overall, the series of testing activities conducted to evaluate the haptic interface design toolkit have provided valuable insights and outcomes. The facilitated workshop and the supervised single-user test demonstrated the effectiveness and usability of the toolkit in supporting designers throughout the design process. The workshop, however resulted more impactful in terms of experience for all users, due to a greater involvement of each participant and more proactive nature, where discussion and testing became natural.

While the first modules have been proved successful, the impact of the prototyping phase is highly correlated to the user’s programming and electronics knowledge and skills, which are variables that can be challenging to address directly within the toolkit. However, the Haptikós addresses this challenge by suggesting a path with specific tools to assist users with varying levels of expertise. In other areas where the need for further improvement have been identified, some possible solutions have been proposed.

Despite all, outcomes of both tests showed that users reported feeling more confident in designing haptic interfaces and acknowledged the toolkit as a valuable resource. The feedback received from the participants played a crucial role in refining and improving the toolkit’s materials for subsequent iterations.

In conclusion, although the need of further tests in different settings, the results of the initial testing activities validate the effectiveness and usability of the Haptikós toolkit.
It has proven to be a valuable tool in supporting designers throughout the design process, enabling them to ideate and prototype tangible and direct interfaces through dynamic vibrotactile interactions, therefore centering its initial purpose.

Future directions

With the advancement of technologies and the continuous change of people's lifestyles and needs, new challenges for makers working with interactive products and interfaces will arise in the near future. It is for this reason that I believe designers should be open to going beyond two-dimensional screens and be ready to explore new sensory modalities that are different from vision and sound, two senses already oversaturated in everyday applications.

To mention recent trends, for example, with spatial computing, new opportunities to interact with digital elements open the door for exploration in this field from a sensory perceptual level. Since the environment can be digitally enhanced in its entirety, users can perceive information through all their senses.

In the automotive field, indeed, where driver's distraction is crucial, removing information from the visual channel and thinking of new interaction modalities and metaphors to transfer them to the tactile one could bring numerous advantages from a safety perspective.

These are just two of the areas where haptics and the sense of touch seem intuitively to be the next sense that technology will overtake. Despite Haptikós' goal being far from the unique source of information for designers, it adapts to those applications and can, for sure, be one of the bridges that brings designers closer to the exploration of tactile interactions by stimulating their ideas and supporting them throughout their journey in the world of touch.

Since a lack of education and awareness emerged from the research as the main reason why the majority of today's products do not include this type of interface, I think it's important to start as early as university to introduce students to haptics and teach them how to exploit its potential. What young designers hear and experience during their university years marks them throughout their careers. It is for this reason that I believe Haptikós should be proposed to educational institutions in the form of facilitated workshops so that students can be guided by an expert, have active discussions with peers, and test all the hardware available on the market provided by the workshop organizer. The session could last one week, where students begin to learn about the theory and test vibration properties on day one, generate metaphors and select the appropriate hardware on day two, and finally develop the prototype on days three and four, with a final presentation on day five.

The idea of testing Haptikós as a workshop in an academic setting arose during the final development stage of the project. It should have happened with a sample of thirty Master's students within a workshop sponsored by a company. Unfortunately, due to logistic barriers, this opportunity has faded away. Nevertheless, I believe that now that the booklet and the templates have been completed in their entirety, a new workshop can be organized for the next academic year.

The results would help further improve the material and evaluate its effectiveness.

The last point is about a possible collaboration with hapticlabs.io. The platform offers a very intuitive and quick way to prototype and iterate with vibrotactile feedback and has proven to be a fundamental resource during the applied research of the thesis development and the two tests. Since the very first time I met the founder, he confirmed the value and expressed great interest in something that could help educate on and connect designers with the field of haptics. In view of the assumptions made earlier, a possible form of collaboration could be that they provide their prototyping platform to be used during the workshops, where they can gain greater exposure in the academic and design community. Moreover, the toolkit pages regarding haptic hardware and software could feature their platform and suggest it to people downloading the toolkit on the Haptikós website.

Lastly, since the tests revealed that more case studies would be useful to understand the concept of metaphor, we could envision and build the previously discussed "demonstrators."

Conclusions

The one I embarked 9 months ago turned out to be an interesting and fruitful journey that helped me to discover a new trait of HCI I wasn't aware of. By researching and experimenting with haptics, and more in particular with vibrations, I became more conscious on the potential benefits they can bring in products and interfaces, and more expert from the prototyping perspective. Interfaces featuring this kind of solutions become more tangible and therefore natural, removing the barrier between people and the digital world, while bringing them closer to it, and sometimes creating a magical surprising effect given by directness of the interaction. By means of metaphors, vibrations become meaningful and digital information can be transferred through the haptic sense, augmenting people's abilities.

If at the beginning I thought that the main reason why haptics are not so popular in today's products is because of the lack of prototyping solutions and the earliness of technologies, by digging deeper into the history of haptics and its role in HCI, I slowly understood that numerous efforts have been spent in this area in terms of R&D, but the biggest limit - and challenge - is actually the acknowledgment from the design community of touch as a media of communication with users. In the last decade some major players (eg. Apple, Sony) have been taken advantage of it, by setting their own standards and guidelines, thus emerging from the competition. It is therefore important, in my opinion, that also we as creatives, makers, designers, and individuals who have power in the process of shaping new products and interfaces; start to exploit this sensory modality and contribute through the definition of new haptic design guidelines, best practices, tools and case studies.

After the tests, the Haptikós toolkit proved to be successful in bridging the gap between the world of haptics and makers, allowing them to grasp the basic knowledge necessary to start envisioning and developing concept powered by dynamic vibrotactile interactions able to fulfill new opportunities, or change the way we interact with objects and interfaces.
From what I could see from the research and my exploration in the field, haptic design and technologies are set to grow, bringing touch back into new products and experiences. While there is much work to be done, the future for tangible interfaces looks promising.

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List of figures

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Ed infine a te... sei talmente importante che mi viene difficile descriverlo in poche parole su questa pagina. Grazie per la tua compagnia durante questi anni, per aver condiviso e contribuito ai miei successi e per esserci stata in tutti i momenti più importanti.
Questo è solo l'inizio, promesso.

A tutti voi, grazie.

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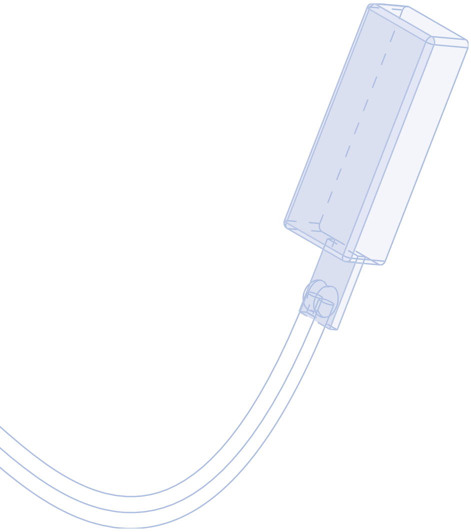
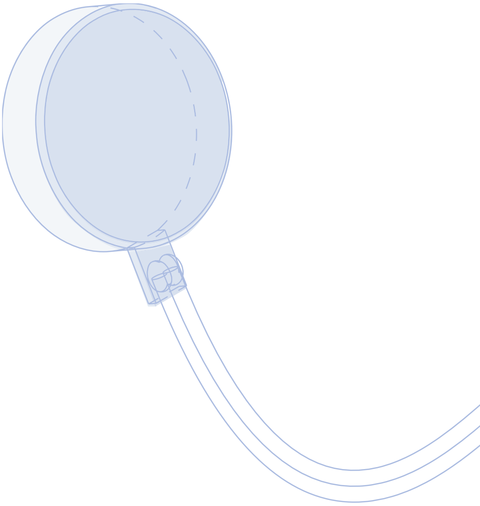
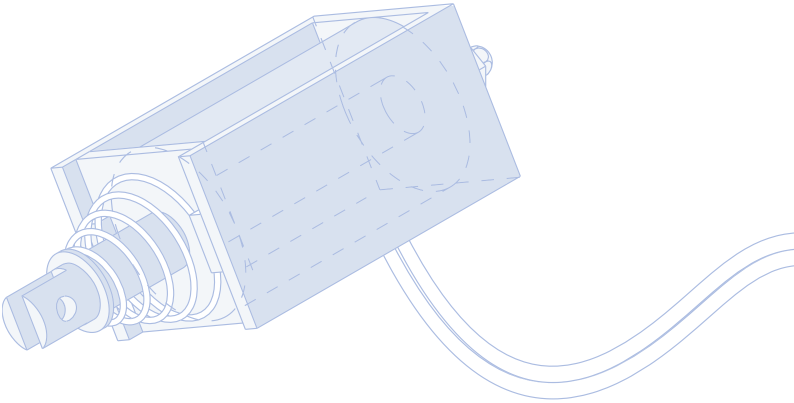
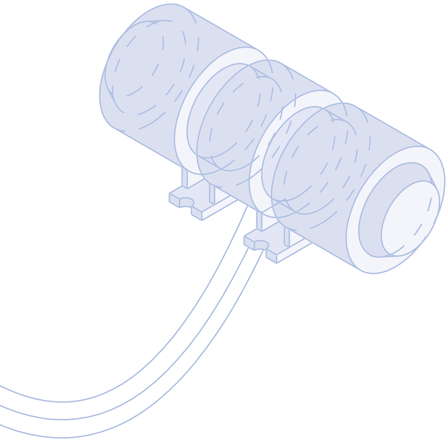
This is just the beginning, I promise.

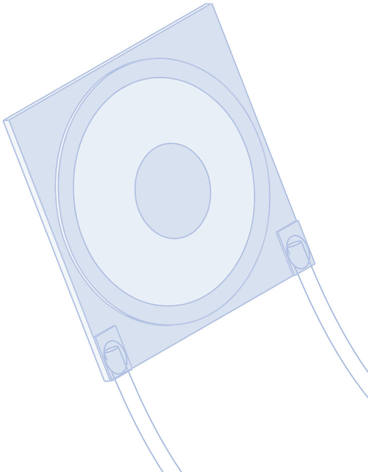
To all of you, thank you.











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