Designing with **Haptic Feedback**

MFA Thesis in Advanced Product Design

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Thomas Müller
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Designing with Haptic Feedback

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Without you, this project could never have happened.

Abstract
What this project is about

Most interactions with physical objects are based on three senses: Sight, hearing and touch. Although we highly rely on visual communication nowadays, haptic feedback is not only involved in every single interaction, but plays a significant role in how we perceive our surroundings.

One major reason why there are only few applications available incorporating active haptic technology is the complex design process, which requires a profound understanding of electronics, coding, physiology and psychology. Unfortunately there is currently little support and guidance available to get you started and help you during the process.

In this thesis I explored the opportunities of haptic feedback and how we can ease access to the field for designers.
The outcome is called hapticlabs.io and consists of two parts:

A prototyping kit which allows you to design, evaluate, and integrate haptic feedback without requiring any expertise in coding or electronics.

A knowledge base which provides condensed and easy to understand background information, opportunity areas showcasing capabilities, as well as a collection of design principles guiding you through the process.

Hapticlabs.io provides an ecosystem to democratise haptic design. It simplifies the process of modulating the feedback, creating functional prototypes and taking full potential of the capabilities.

Introduction

Haptic feedback
What, why and how?

Personal motivation

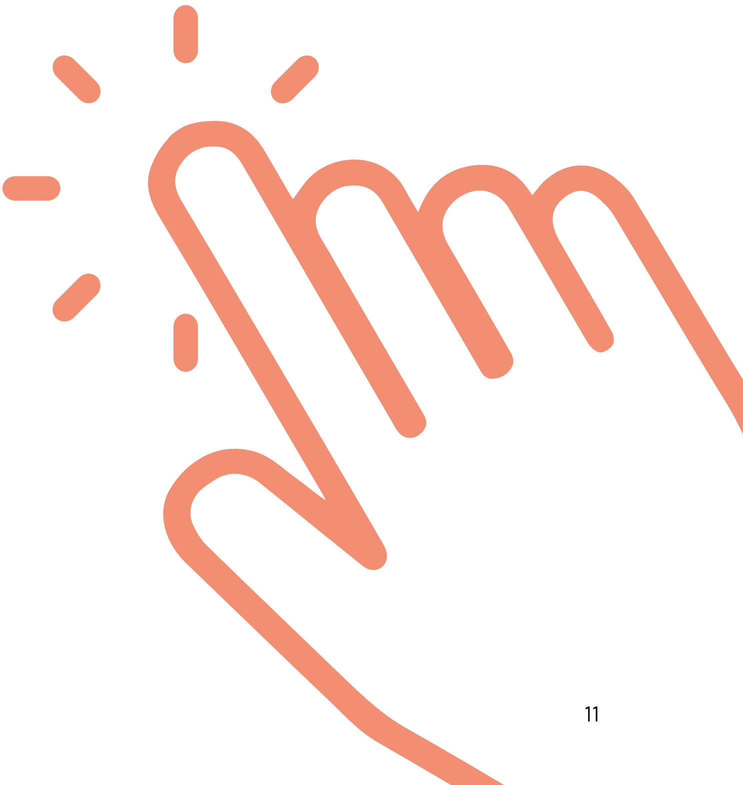
Looking back on my previous working experience and education, I realised almost all projects involved haptics in some way, but it was barely defined any further. This also came true when talking to a lot of colleagues and professionals in the field.
My aspiration was, therefore, to not only use this thesis to make myself be able to work with haptics in detail, but also to provide guidance and inspiration to others interested in the topic.

Not being a classic industrial design topic, it also allowed me to push myself out of the comfort zone, while staying close to the physical object. This aligned well with my personal ambitions and also reflected the current trend in design overall.

Methods

This thesis took a more experimental approach compared to the usual graduation projects in APD. Prototyping was an essential part of discovering possibilities and new applications. I began the project by creating and think through at least one new application of haptic feedback each day for the first month. This approach allowed me not only to discover advantages and challenges, but to develop solutions based on hands-on explorations across various areas.

The report not only has the goal of illustrating the design process, but also to be a compendium of information and learnings in the field of haptic feedback in general.



Scope
Why it's more important than ever

Smart devices

„In future, every electronic product of Bosch will be web-enabled.“ [1]

Smart products are flooding our lives with displays and incorporating connected technology is not anymore a trend, but has already taken place. Applications range from consumer electronics such as smart watches and cameras to professional applications such as power tools and surgical tools. The world of screens is trying hard to enhance glass covered devices and VR-applications with a human touch, while at the same time we are using the same standardised push-buttons and interfaces in the products we use. Through new haptic technology we have the opportunity to create tailored tangible interactions - not only in smart devices.

How can we utilise haptics to enhance everyday objects? What if every interaction and every button press can be tailored to its action?

Feeling it

What is the most natural and desirable - even invisible - way for human being to interact with technology?“ (Rose, 2015, p. 29)

A few years ago our interaction with physical products relied on form, the used material and visuals such as graphics. While the amount of information increased, digital interfaces took over to deal with the complexity. To be able to interact with the new technology we had to learn a new language of swiping, sliding and tapping. As human beings we are extremely capable of sensing haptics: Everyone knows how to act on a shoulder tap and recognises the smallest fly running on our skin.

Can we use haptic feedback as a universal language to communicate information? How can we use haptics to resume to a more analogue and human interaction?

Cold technology

We live in a world where interactions are based on flat, emotionless screens which are sold like warm cookies. While the discussion about the smartphone pinky (the pinky finger transforms due to supporting the weight of the smartphone) is debatable, the amount of influence on our minds and bodies is not. We pack more and more functionality in small devices which makes our daily lives more and more complex.

How can we declutter our daily lives and return to a point where we are enchanted by the products we use?

Muted interactions

„[...] we often don't want to see and hear more than we already do; rather, we want better filters so we see and hear less or just exactly what we want.“ (Rose, 2015, p. 40)

Using electronic devices, we are faced with screaming interactions, including sounds, flashes and buzzing haptics. While this usually is just an annoying part we have to deal with, there are situations where information clutter leads to distraction impairing our concentration. While driving a car at top speed, getting notified about the next oil change in bright red or an alarm from your in-box might not be the best solution.

What if we can communicate without interfering with the user?
How can we seamlessly include feedback into devices?

Enchanted products

„Its a [...] fusion between analogue and digital while preserving all the familiar characteristics.“ (Rose, 2015, p. 70)

While a few years back we found the idea of smart products exciting and were charmed by the thought of a fridge telling us about how to improve our lives, nowadays most of us are annoyed by the plain sight of displays and electronics in objects. Most of this frustration is due to an inadequate and complex setup process, but is also based on our wish for seamless and simple interactions. Speech-enabled systems moved into our apartments, and while one can argue against them in a lot of aspects, there is one thing they do exceptionally well: They integrate seamlessly, and if I don't want to use it, it won't bother me.

What if products can stay analogue but inherit technology without showing off?
How can we introduce technology to enchant products and crate exciting experiences?

Collaboration
Who was involved

In order to gain close-up insights from the professional environment, I had the chance to spent two months at Intuity Media Lab GmbH, which is a design driven consultancy based in Stuttgart, Germany combining "Strategy, creativity, design, science and technology in one place" [3] Their work and projects covers a variety of areas ranging from digital experiences to healthcare products and AI applications. Combined with a highly cross-disciplinary and user-centred approach as well as valuing the physical prototyping process, Intuity was the perfect match for this thesis. During my stay I took part in a client project including haptic feedback, while I still had the freedom to explore the field on my own. The collaboration allowed me to gain insights from the clients' as well as the consultancies' perspective and helped to kickstart this project.

» We combine strategy, creativity, design, science and technology in one place. «

Approach
Framing the process

Early on, it became apparent that not only will the topic demand a deep theoretical understanding but an extensive exploration, which highly depends on a tangible experience of haptic feedback.

By collaborating with Intuity, talking to users and companies in the field and reserving time to allow for physical prototyping, I made sure that the final outcome will not be the result of a theoretical study, but is based on findings and experiences from an applied exploration.

The research of this thesis was conducted through four approaches:

Theoretical research

Background research to achieve a basic understanding of physiological, psychological and technical aspects.

Collaboration partner

Hands-on experience while working on a client project at Intuity Media Lab.

User insights

Interviews with professionals in the industry on approaches and challenges.

Applied research

Exploration of haptic feedback through a variety of case studies.

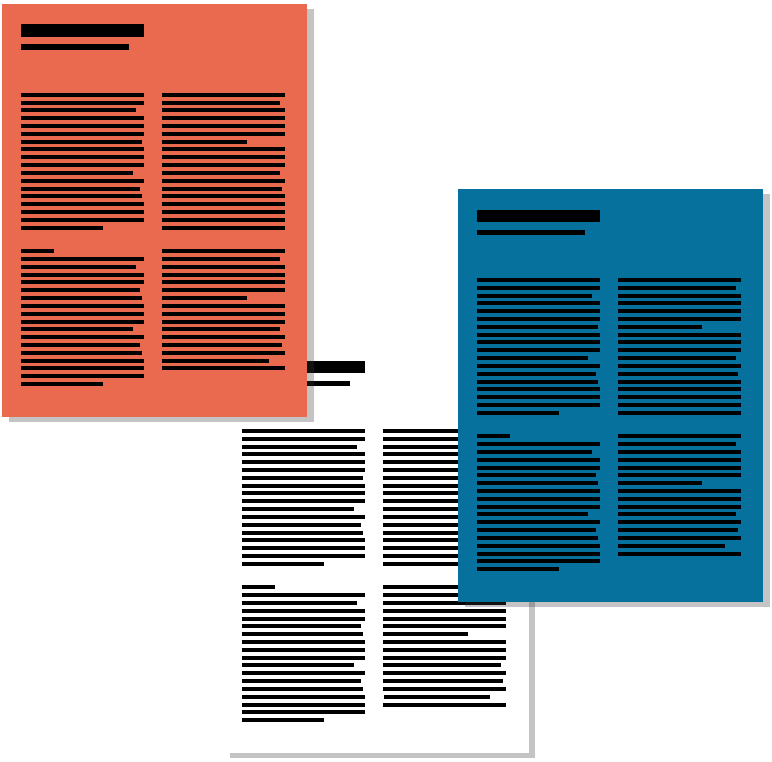
Theoretical research

Theoretical research
Where to begin?

Haptic feedback not being part of the current design practice, is certainly not due to a lack of information and materials. One can easily get overwhelmed by the vast amount of literature and research studies available. Throughout this thesis, I tried my best to acquire background information on all necessary topics and at the same time condense and translate the content into a format which is easy to understand and digest.

The following pages illustrate part of the basic knowledge of how haptic feedback is perceived and created.

This is by no means a complete summary, but a simplified overview to be able to start designing for and with haptic feedback.



Sensory system
How we perceive our environment

Each interaction with a physical object is a multisensory experience, and in the vast majority of cases, three modalities are involved:

Sight - Visual feedback
Hearing - Auditory feedback
Touch - Haptic feedback

The information input of these is not distributed equally, and we are most often guided by visual feedback through displays, text or graphics.

While you can close your eyes or put on noise-cancelling headphones, you can not turn-off the haptic perception. During our daily lives, we are usually oblivious to it and only recognise its absence when our sensory system is somehow impaired: Closing a zipper with cold hands, searching for a light switch in the dark or when a limb falls asleep (paresthesia).

Amount of information
consciously perceived.

Haptic perception
Physiological background

Simply put, haptic feedback can be divided into tactile and kinaesthetic perception. [4]
Imagine holding a cup of hot coffee:

You can feel the rough ceramic material, a vibration if somebody is giving you a refill and you also know how much force you need to put into the grip to prevent the cup from "slipping" through your fingers.

You can feel the warmth inside with the help of thermoreceptors, and if the temperature is above 40°C [5], nociceptors come into play signalling pain.

All of this information is part of the tactile perception based on receptors in your skin.

Kinaesthetic perception gives you feedback about the weight and the size of the cup, as well as the position and movement in relation to the body. This feedback is received through receptors inside your muscles, joints as well as in the skin.

To recognize these mentioned attributes of a cup we make use of feedback from:

18	Joints
79	Muscles
19.000	Skin receptors

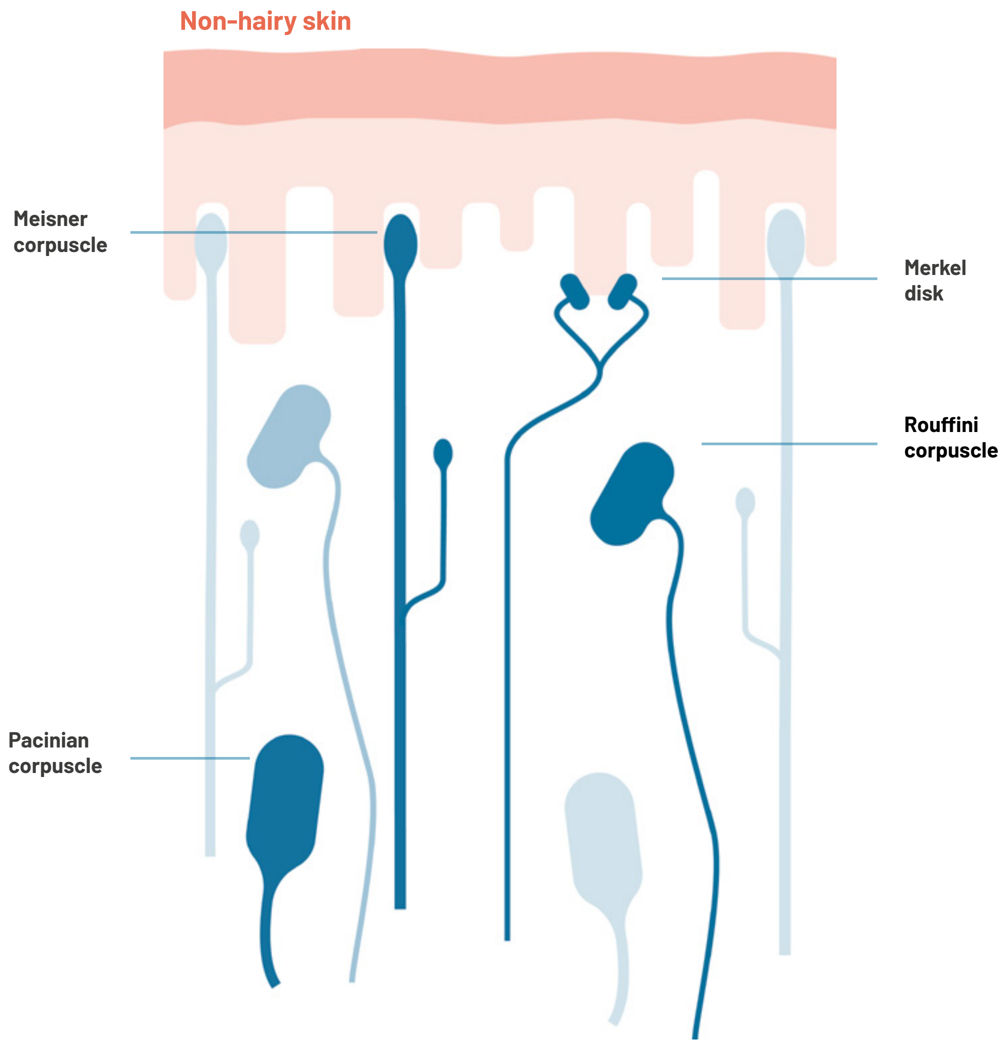
Tactile feedback

Texture
Slip
Vibration

Temperature
Pain

Kinaesthetic feedback

Weight
Size
Position

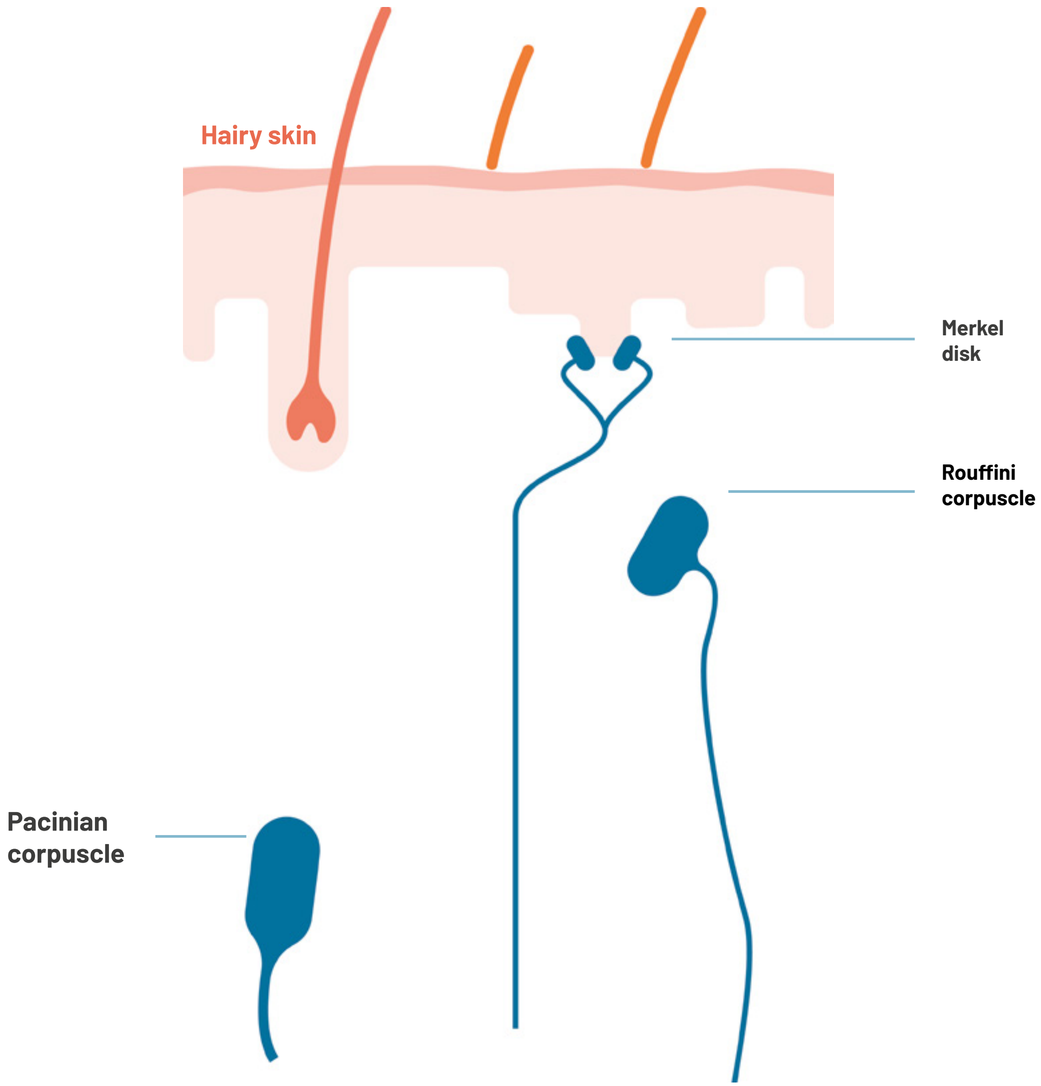


Cutaneous Mechanoreceptors

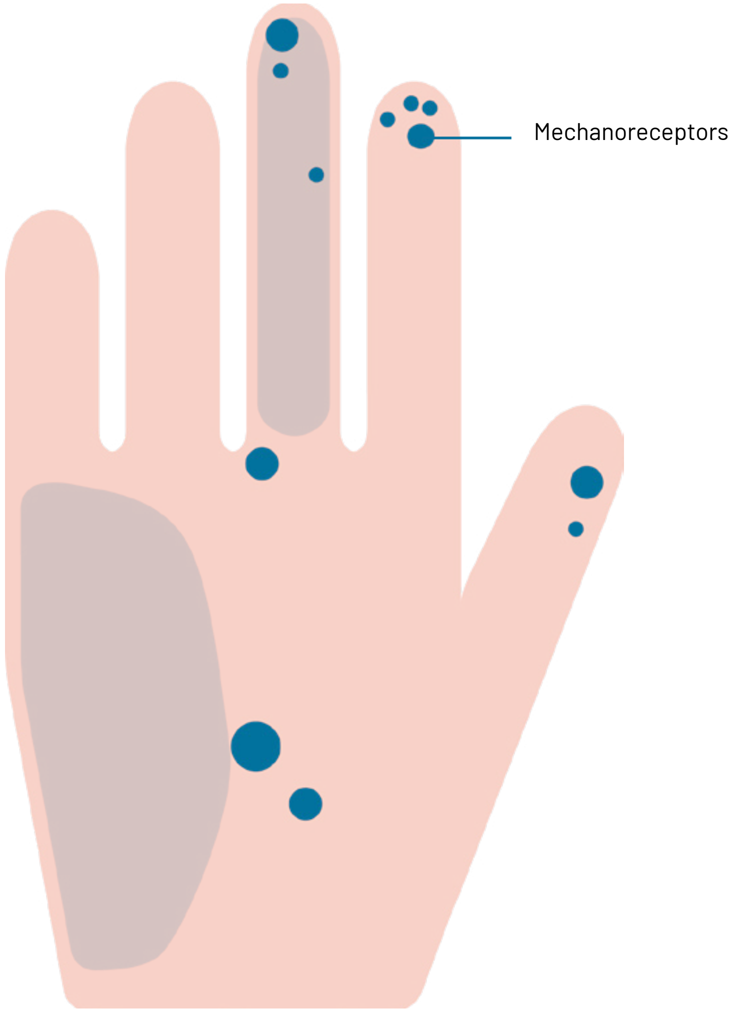
There are four types of receptors in our skin (cutaneous) through which we experience tactile feedback. They differ not only in their reaction to stimuli but also in depth, density, the field of reception and adaptation rate. The latter describes how fast a receptor stops firing and adapts to signals when exposed to a constant stimulus. [18]

Adaptation rate

The adaptation rate can be illustrated through a simple experiment: If you move a finger over the edge of a paper placed on your desk, you can clearly feel the displacement. If you however pause and let your finger rest right at the edge for several seconds, the receptors adapt to the stimulus, and the feeling will subside until it disappears.



	Adaptation rate	Receptive field	Density [Fibres/ cm³]	Stimulus	Perceptual function
Merkel	Slow	3-4 mm	100	Indentation	Form and texture
Meissner	Rapid	3-4 mm	150	Motion	Grip control - detect slipping objects
Rouffini	Slow	> 10 mm	20	Stretch	Shape of hand, object motion
Pacinian	Rapid	> 20 mm	20	Vibration	Vibration when grasping objects



Coarse area
Rouffini & Pacinian receptors

Defined area
Merkel & Meisner receptors

Palm sensitivity

Our haptic sense mainly relies on input from our hands. While the skin area only covers about 1,5% of our body, our hands feature about 40% of the skin receptors. The area at the base of the thumb and the skin on the back of the hand are also most sensitive to changes in temperature.

Receptors vs. limb sizes

The amount of receptors is not dependant on the size of the limbs, but almost equal in every human body. As a result, smaller hands have a higher skin sensitivity than larger due to a more dense arrangement. [6]

We are most sensitive to vibrations between 200 and 300 Hz. [24]

The skin response to vibrations ranging from about 0.4 Hz to 1000 Hz.

The skin can distinctively separate two pulses spaced 10ms apart.

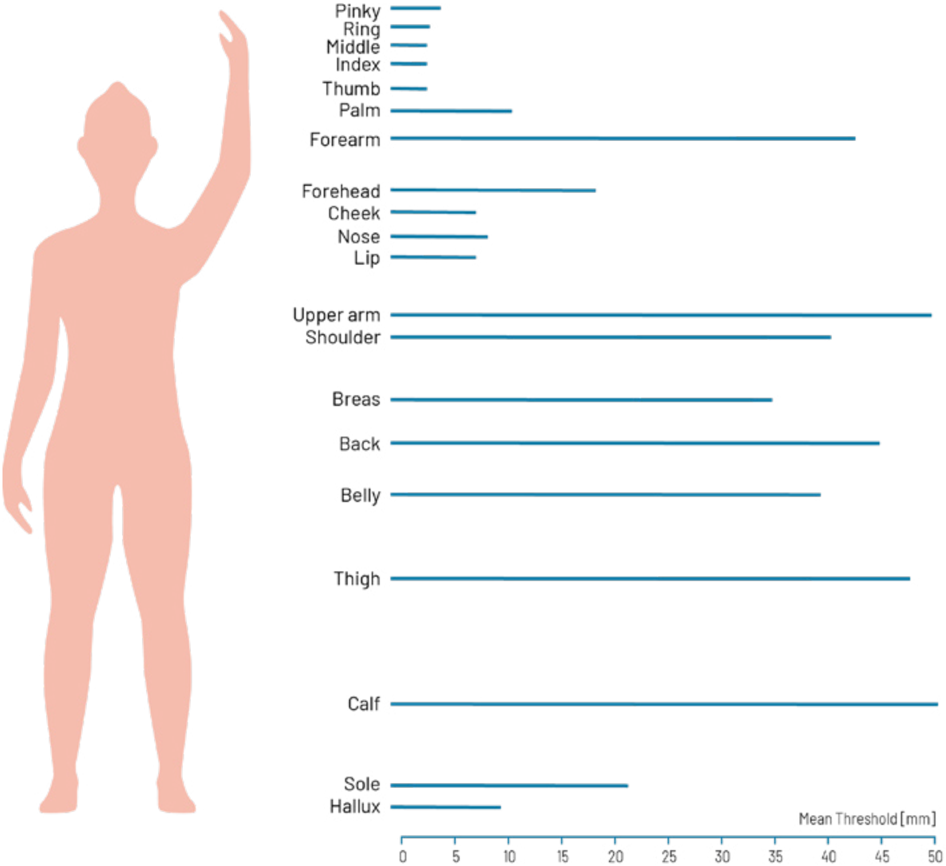
Latency between a sound and a vibration should be lower than 12 ms to maintain the illusion they are related. [15]

Physiological aspects

The sensibility for tactile feedback is not spread evenly across our body, which is due to the varying number of receptors in the skin (mechanoreceptors) [6]

» At a location with high sensitivity a vibration can be of lower intensity to get the same perception of intensity. « [8]

The illustration shows the result of a test where two points on the skin are stimulated with varying distance (two-point threshold).
Almost all physical stimuli are being recognized as stretch or compression of our skin which is translated into a sense of depth. Examples are moving your fingertip across a rough surface, reading Braille or being touched by someone else. [6]



The result of a two-point discrimination test illustrating the skin sensitivity

Kinaesthetic feedback

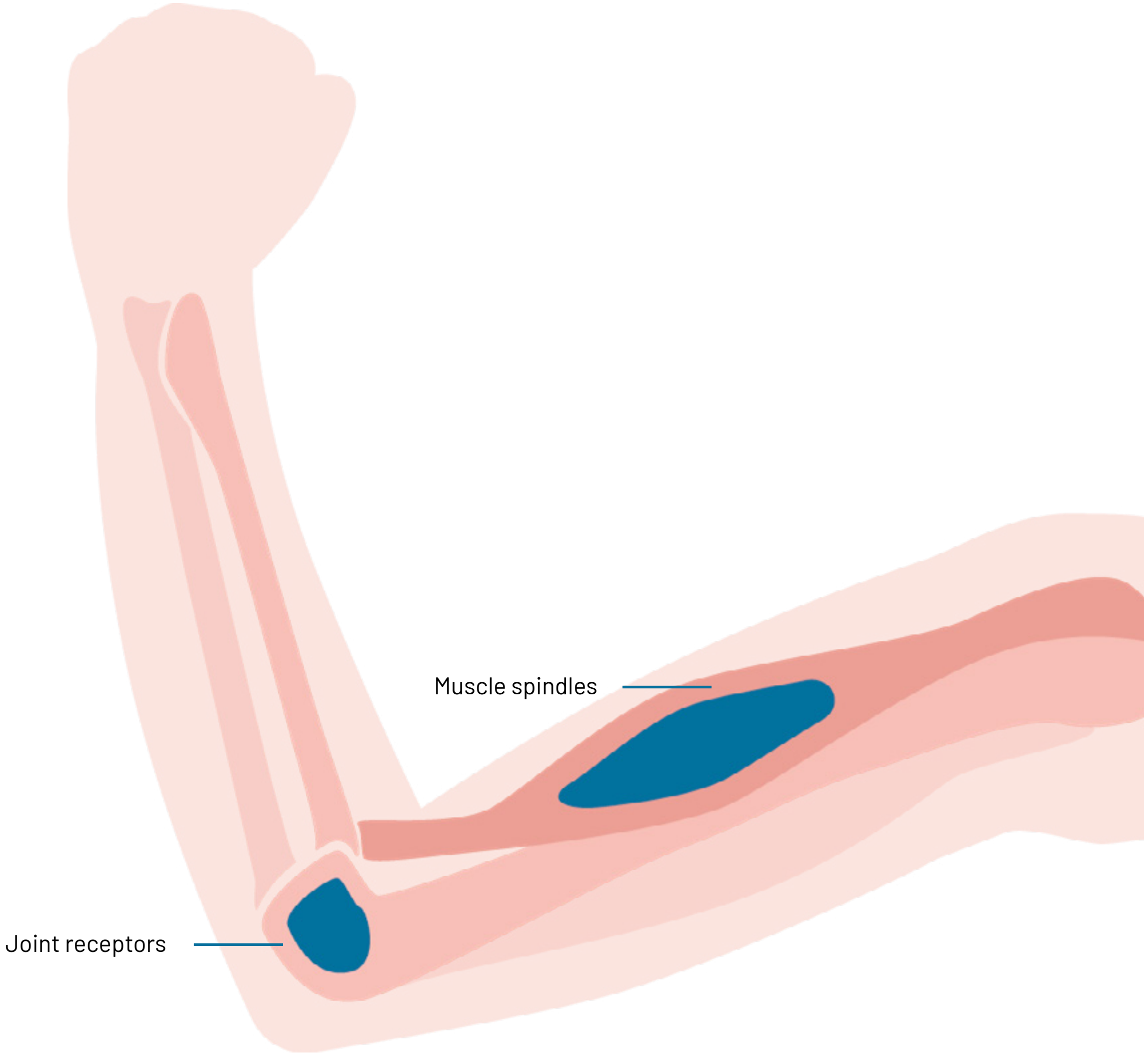
Information about our bodies position, movement and forces it is exposed to coming from receptors in our muscles and joints is called kinaesthetic feedback. Typical examples are turning a knob or lifting an object.

A lot of haptic feedback involves both tactile and kinaesthetic stimuli. When turning the volume knob on a stereo, you will receive tactile feedback from the grid (coarse or fine) and the skin stretch of you fingers knuckles, as well as kinaesthetic feedback from your forearm and hand about the angle you turned it.

Resolution

The resolution of our kinaesthetic reception is not equally spread as well - A small change in the angle of the upper arm, is easier to recognise compared to a slight bending of the finger.

When it comes to sensing weight and forces, we are capable of recognising a change or difference if it differs by at least 6% (differential threshold). Two apples with a weight of 250g and 235g will be identified as not equally heavy. [6]


Muscle spindles
Joint receptors

Terminology
Finding common ground

One can easily get confused by deviating definitions of the term 'haptic'. This is due to the fact that there are two different perspectives on the topic: One based on behavioural psychology and a second one on perception physiology and functional groups. The latter one is more commonly used in technical fields and therefore, the basis of this thesis. [7]
In the following pages, I set myself out to create an overview of different areas and definitions of haptic feedback while trying to stay as close to a common ground in literature as possible.

be we can use
tic feedback?

Why don't you just
call it vibration?

Active exploration

Passive haptics

Active vs. passive exploration

In comparison to all the other senses, haptic perception is bidirectional. In order to receive information from our environment we have to actively explore and/ or manipulate it. You have to lift an object to determine its weight or squeeze a strawberry to determine its ripeness. [6]

Passive exploration

Active haptics

Active vs. passive haptics

Active haptic feedback is based on electro-mechanic components inside of devices. [6] The most common applications are gaming controllers simulating virtual environments or your smart-phone buzzing. Instead of actively exploring an object, the haptic feedback is felt through passive exploration/ body contact.

Passive haptics

Natural haptics

Natural occurring haptics

Physical properties of a material and object

Object haptics

Tangible object feedback

Physical button

Surface haptics

Receiving tactile feed-back through passive exploration

Gaming controller

Virtual/ syntheti

Simulate nat object hapt

iPhone hor button

Overview

Currently, the main focus of the industry lies on making screen interactions and virtual environments more tangible. At the same time, material science makes big leaps in altering physical properties of objects such as the rigidity or surface structures. Active haptic feedback only recently became more popular in consumer electronics and everyday objects besides smartphone applications. The list is showing different application areas and at the same time illustrates the difficulty in finding common terms and definitions.

Active haptics

c haptics	Advanced haptics	Surface haptics	VR/ Artificial haptics
ural/ ics	Simulate physical attributes	Tangible screen information	Make 3D space tan-gible
			
me	Altering the object rigidity	In-car interfaces with a customizable surface roughness	VR / Game controller

Tactile displays

Technical applications can be divided into two fields: Tactile and haptic displays.

Tactile displays simulate tactile feedback to the user which can happen in three kinds of input delivered to the skin: Vibra-tion, static pressure in which the skin is indented, and lateral or tangential skin stretch. [6]

Haptic displays

Haptic displays simulate kinaesthetic feedback (= force feedback) and can be divided into resistive (limiting the users' movement) or active feedback (support-ing/ guiding the users' movement). Exam-ples are motorized slider or dials such as the BMW iDrive. Haptic displays are more complex compared to tactile displays and require powerful actuators as well as a closed-loop controlling system.

Applications of active haptics

Where is it used?

Logitech Spotlight

Presentation device

Programmed haptic notification after a timer has ended. It allows for a subtle notification only felt by the presenter.

Teenage Engineering OP-Z

Synthesizer

A low-frequency vibration mimics sub-woofer vibrations, as well as a silent metronome for the artist to feel even during live performances.

Apple iPhone

Smartphone

The mechanic button is replaced by a capacitive area connected to a haptic actuator. This allows for tailored feedback based on the context.

Razor Nari Ultimate

Gaming headphones

Information from the game is translated into stereo vibrations, creating a more immersed experience. [9]

Valve Steam Controller

Game controller

Virtual environments are simulated through haptic actuators inside the controller.

Oculus Rift Touch

VR Controller

Virtual environments are simulated through haptic actuators inside the controller.
VR companies are pushing the boundaries when it comes to simulating virtual materials as well as kinaesthetic feedback.

Focus

In contrary to the development in technology, I decided to focus on enhancing physical products, by incorporating active haptic feedback in analogue objects (sensory addition) or replacing modalities such as visual information (sensory substitution).

~~How might we make screen interactions more tangible?~~

~~How might we make virtual space more tangible?~~

How might we utilise haptic feedback to enhance physical product interactions?

... and preserve an analogue and human interaction?

Branding
More than just a feeling

Generic feedback:
None/ reaching a physical stop

Improved feedback:
Obvious "click"

Sam
diffe

Functional v
exper

Besides using haptic feedback to guide the user, for example, if an action was successful, designing its character can profoundly influence the user and branding experience. Shown above are products of the same category with a different kind of haptic characteristic.
Sharpie is known to pay close attention to the feedback produced when closing the lid. A distinct "click" in this case can emphasise a more professional and high-end character.
The dials on the SIGMA fp camera are very mushy, and the feedback feels undefined. On the Leica Q2, the controls have a very mechanical, precise and distinct character which certainly fits the branding and price level.

e but
erent

s. emotional
ience

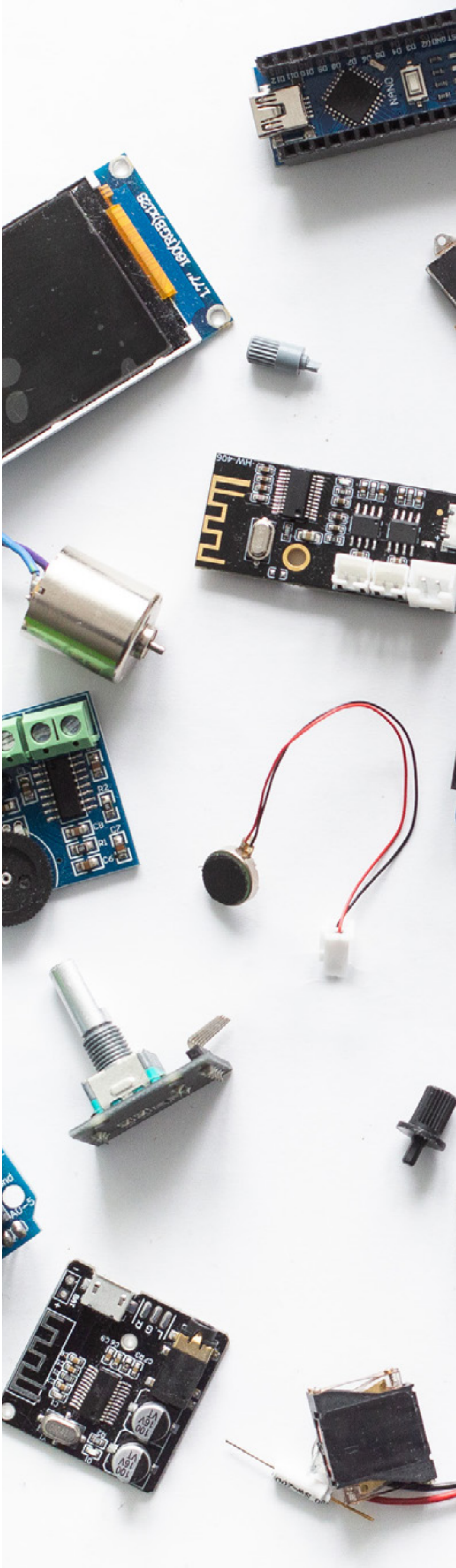
SIGMA feedback:
Soft, undefined

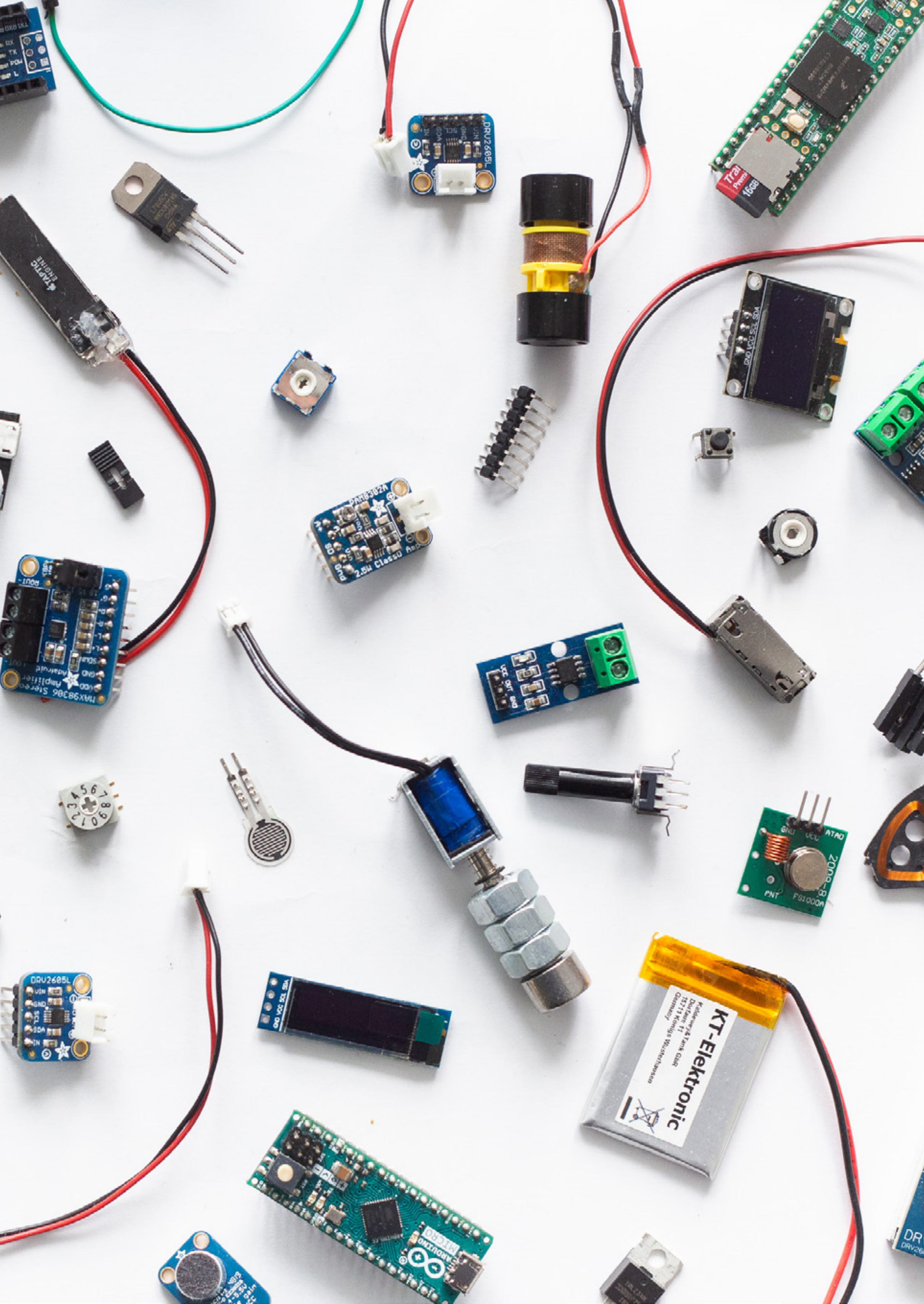
Leica feedback:
Mechanical, distinct

Haptic technology
Make it come alive

After I had a look at how we perceive haptics, it was about time to discover how it actually feels and which technology is used in the field. It was surprisingly difficult to identify what is available on the market as well as how the solutions differentiate from each other.

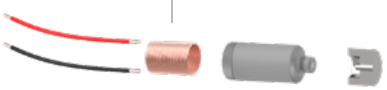
Especially in the field of VR, new and experimental technologies arise almost every week. Making use of ultrasonic waves, piezoelectric actuators, shape-shifting materials or pneumatics just to name a few is highly promising. I put my focus on electro-magnetic actuators for the following reasons:
They are easy(ier) to use, cheaper and widely available, already tested in products on the market and their capabilities are still far from exceeded.

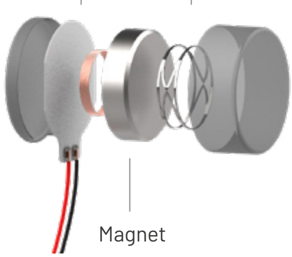



DRV2605L
DRV2605L
2.5W ClassD Amp
KT-Elektronic

Haptic actuators
What lies underneath

At the time of this thesis, these types of electro-magnetic actuators were common:



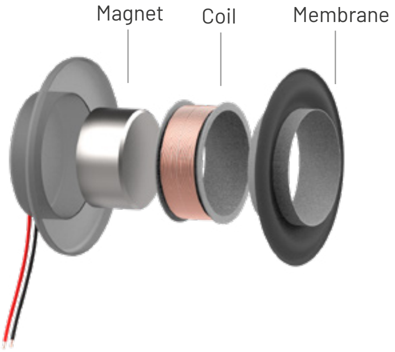


ERM - Eccentric rotating mass

The oldest method to produce haptic feedback is based on a motor with a small weight placed eccentrically on the shaft. The force is produced in two axes perpendicular to the shaft of the motor. They used to be found in all smartphones producing the characteristic vibrations. The amplitude (strength) is determined by the frequency (speed) of the motor. ERMs are DC powered.

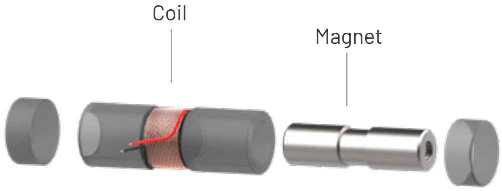
LRA - Linear resonance actuators

Inside LRAs a voice coil pushes a magnet against a spring. By applying AC voltage, this oscillating movement results in vibrotactile feedback in a single axis. The feedback from an LRA is more directed and clean compared to ERMs which is why they took over most of the market.
An LRA is tuned to a specific frequency based on the internal spring [resonance frequency]. This allows controlling the vibration amplitude, without affecting the frequency to a certain degree. [14]



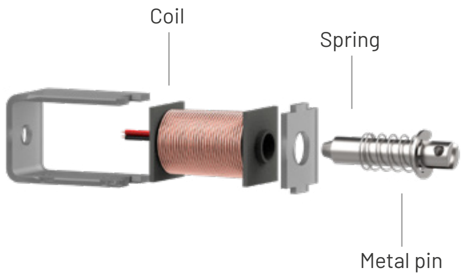
Surface transducer

By removing the membrane of a speaker, you end up with the bare voice coil. Attached to a surface, they transduce an input signal into auditory or in this case tactile feedback. They are very similar to LRAs and also require AC voltage.



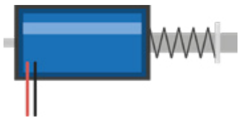
Accelerated ram

A mix between an LRA and a solenoid are accelerated rams or linear transducers. They are larger in size and produce single impulses and vibrations by accelerating and stopping an internal mass though an electromagnetic field in two directions. In the case of the Tac-Hammer (Nanoport) one side features a mechanical stop for a clicking sensation, while the opposite features a magnetic stop for soft feedback. They are mostly driven by AC Voltage.

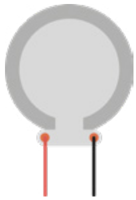


Solenoids

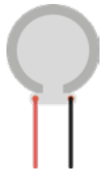
A close relative to the LRA is the solenoid. In comparison it is not optimised for an oscillating motion but accelerates an internal mass until it reaches a mechanical stop. A spring is pushing the mass back to its origin. Solenoids are DC powered and depending on the size, produce a very high impact force.



Generic
Solenoid



TEAX25C05-8 2W
Surface exciter

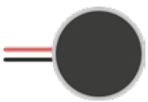


TEAX25C05-8 1W
Surface exciter

Tactile labs Haptuator BMXC
LRA

Tactile labs TL-002-14R Haptuator
LRA

Nanoport Tac-Hammer
Accelerated Ram



Generic
LRA

Alps Haptic Reactor
LRA

Apple taptic engine
LRA/ Accelerated Ram

Lofelt L5 Actuator
LRA

Generic
ERM

	ERM	LRA	Ram	Transducer	Solenoid
Response time (ms)	20-50	05-10	05-10	05-10	05-10ms
Audible noise	High	Moderate	None-High*	None-High*	Moderate - high*
Price	Low	Low	Moderate	Moderate	Low

[13] *Depending on impact material

Choice of component

For my exploration, I started out by ordering ready-made actuators from electronic stores and replacement parts such as the taptic engine from an iPhone or the LRA out of a Nintendo Wii controller. Through my collaboration partner I was able to also test more advanced actuators such as the Haptuator which come at a very high price tag of 200€ each. In addition, I used various electronics such as solenoids, motors, and servo motors to create my own actuators which worked surprisingly well. Constant hands-on prototyping is unavoidable when designing with haptic feedback. Obviously one has to feel the feedback in order to be able to define it, but in addition also the characteristics highly depend on the material and object it is applied to.

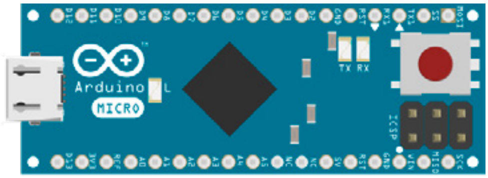
Evaluation

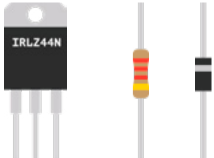
When evaluation haptic feedback, it can be helpful to in the first step, block out any other input such as visual or audible information. Also triggering the feedback should be done by a different person or through a capacitive button to avoid a mix-up of sensory input.

Prototyping haptics
How to make it move

Especially with little experience in the field of electronics, prototyping with haptic actuators can be quite intimidating. Although I have worked with a lot of electronics before, getting an overview and deciding for the right hardware was a challenge.
Throughout this thesis, I have used different approaches:

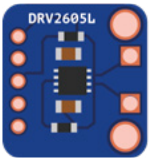
- Rudimental circuits based on an Arduino and a mosfet or h-bridge
- Dedicated haptic drivers, e.g. provided by Adafruit and TDK
- Ready-made control systems such as the TDK Evaluation module
- An audio-based amplifier circuit based on the Teensy microcontroller and an audio amplifier

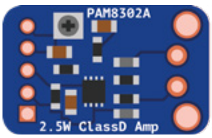




Arduino Micro

Microcontroller



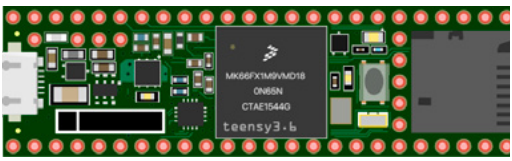


Adafruit DRV2605L

Haptic Driver

Adafruit PAM8302A

Audio Amp



Teensy 3.6

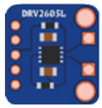
Microcontroller

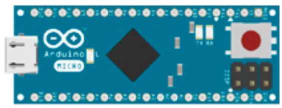
Haptic driver DRV2605

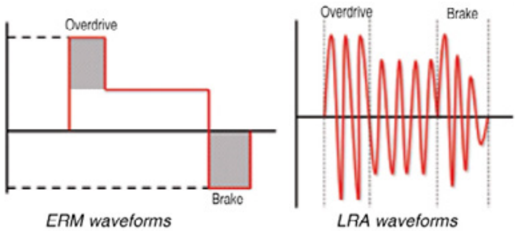
The most popular approach is to make use of the TDK DRV2605 which is a motors driver optimised for haptic actuators. It comes with a library [provided by Immersion, shown to the right] including 123 presets.

A big advantage comes when dealing with ERMs and LRAs. Due to their construction, especially ERMs, take time to spin up and down. This latency makes it difficult to create very crisp haptic sensations. The TDK driver overcomes this is by applying overdrive [driving the actuator with a higher voltage in the beginning] and braking it [reverse direction at the end].
It can also identify the actuators resonance frequency in which it consumes the lowest power and has the highest force output. [19]

The downside is that it involves utilising code [example shown bellow] and soldering of electronics [microcontroller, power, driver and cable connections]. The amount of presets is also quite overwhelming and the descriptions can be misleading. Defining patterns or adjusting one of the presets is very limited and can be a tedious task, especially for beginners.







Effect ID#	Waveform Name	Effect ID#	Waveform Name	Effect ID#	Waveform Name
1	Strong click – 100%	42	Long double sharp click medium 2 – 80%	83	Transition ramp up long smooth 2 – 0 to 100%
2	Strong click – 60%	43	Long double sharp click medium 3 – 60%	84	Transition ramp up medium smooth 1 – 0 to 100%
3	Strong click – 30%	44	Long double sharp tick 1 – 100%	85	Transition ramp up medium smooth 2 – 0 to 100%
4	Sharp click – 100%	45	Long double sharp tick 2 – 80%	86	Transition ramp up short smooth 1 – 0 to 100%
5	Sharp click – 60%	46	Long double sharp tick 3 – 60%	87	Transition ramp up short smooth 2 – 0 to 100%
6	Sharp click – 30%	47	Buzz 1 – 100%	88	Transition ramp up long sharp 1 – 0 to 100%
7	Soft bump – 100%	48	Buzz 2 – 80%	89	Transition ramp up long sharp 2 – 0 to 100%
8	Soft bump – 60%	49	Buzz 3 – 60%	90	Transition ramp up medium sharp 1 – 0 to 100%
9	Soft bump – 30%	50	Buzz 4 – 40%	91	Transition ramp up medium sharp 2 – 0 to 100%
10	Double click – 100%	51	Buzz 5 – 20%	92	Transition ramp up short sharp 1 – 0 to 100%
11	Double click – 60%	52	Pulsing strong 1 – 100%	93	Transition ramp up short sharp 2 – 0 to 100%
12	Triple click – 100%	53	Pulsing strong 2 – 60%	94	Transition ramp down long smooth 1 – 50 to 0%
13	Soft fuzz – 60%	54	Pulsing medium 1 – 100%	95	Transition ramp down long smooth 2 – 50 to 0%
14	Strong buzz – 100%	55	Pulsing medium 2 – 60%	96	Transition ramp down medium smooth 1 – 50 to 0%
15	750-ms alert 100%	56	Pulsing sharp 1 – 100%	97	Transition ramp down medium smooth 2 – 50 to 0%
16	1000-ms alert 100%	57	Pulsing sharp 2 – 60%	98	Transition ramp down short smooth 1 – 50 to 0%
17	Strong click 1 – 100%	58	Transition click 1 – 100%	99	Transition ramp down short smooth 2 – 50 to 0%
18	Strong click 2 – 80%	59	Transition click 2 – 80%	100	Transition ramp down long sharp 1 – 50 to 0%
19	Strong click 3 – 60%	60	Transition click 3 – 60%	101	Transition ramp down long sharp 2 – 50 to 0%
20	Strong click 4 – 30%	61	Transition click 4 – 40%	102	Transition ramp down medium sharp 1 – 50 to 0%
21	Medium click 1 – 100%	62	Transition click 5 – 20%	103	Transition ramp down medium sharp 2 – 50 to 0%
22	Medium click 2 – 80%	63	Transition click 6 – 10%	104	Transition ramp down short sharp 1 – 50 to 0%
23	Medium click 3 – 60%	64	Transition hum 1 – 100%	105	Transition ramp down short sharp 2 – 50 to 0%
24	Sharp tick 1 – 100%	65	Transition hum 2 – 80%	106	Transition ramp up long smooth 1 – 0 to 50%
25	Sharp tick 2 – 80%	66	Transition hum 3 – 60%	107	Transition ramp up long smooth 2 – 0 to 50%
26	Sharp tick 3 – 60%	67	Transition hum 4 – 40%	108	Transition ramp up medium smooth 1 – 0 to 50%
27	Short double click strong 1 – 100%	68	Transition hum 5 – 20%	109	Transition ramp up medium smooth 2 – 0 to 50%
28	Short double click strong 2 – 80%	69	Transition hum 6 – 10%	110	Transition ramp up short smooth 1 – 0 to 50%
29	Short double click strong 3 – 60%	70	Transition ramp down long smooth 1 – 100 to 0%	111	Transition ramp up short smooth 2 – 0 to 50%
30	Short double click strong 4 – 30%	71	Transition ramp down long smooth 2 – 100 to 0%	112	Transition ramp up long sharp 1 – 0 to 50%
31	Short double click medium 1 – 100%	72	Transition ramp down medium smooth 1 – 100 to 0%	113	Transition ramp up long sharp 2 – 0 to 50%
32	Short double click medium 2 – 80%	73	Transition ramp down medium smooth 2 – 100 to 0%	114	Transition ramp up medium sharp 1 – 0 to 50%
33	Short double click medium 3 – 60%	74	Transition ramp down short smooth 1 – 100 to 0%	115	Transition ramp up medium sharp 2 – 0 to 50%
34	Short double sharp tick 1 – 100%	75	Transition ramp down short smooth 2 – 100 to 0%	116	Transition ramp up short sharp 1 – 0 to 50%
35	Short double sharp tick 2 – 80%	76	Transition ramp down long sharp 1 – 100 to 0%	117	Transition ramp up short sharp 2 – 0 to 50%
36	Short double sharp tick 3 – 60%	77	Transition ramp down long sharp 2 – 100 to 0%	118	Long buzz for programmatic stopping – 100%
37	Long double sharp click strong 1 – 100%	78	Transition ramp down medium sharp 1 – 100 to 0%	119	Smooth hum 1 (No kick or brake pulse) – 50%
38	Long double sharp click strong 2 – 80%	79	Transition ramp down medium sharp 2 – 100 to 0%	120	Smooth hum 2 (No kick or brake pulse) – 40%
39	Long double sharp click strong 3 – 60%	80	Transition ramp down short sharp 1 – 100 to 0%	121	Smooth hum 3 (No kick or brake pulse) – 30%
40	Long double sharp click strong 4 – 30%	81	Transition ramp down short sharp 2 – 100 to 0%	122	Smooth hum 4 (No kick or brake pulse) – 20%
41	Long double sharp click medium 1 – 100%	82	Transition ramp up long smooth 1 – 0 to 100%	123	Smooth hum 5 (No kick or brake pulse) – 10%

Effects library of the DRV2605

complex | Arduino 1.8.11

nplex

```
nclude <Wire.h>
nclude "Adafruit_DRV2605.h"

afruit_DRV2605 drv;

d setup() {
erial.begin(9600);
erial.println("DRV test");
rv.begin();

/ I2C trigger by sending 'go' command
rv.setMode(DRV2605_MODE_INTTRIG); // default, internal trigger when sending GO command

rv.selectLibrary(1);
rv.setWaveform(0, 84);  // ramp up medium 1, see datasheet part 11.2
rv.setWaveform(1, 1);  // strong click 100%, see datasheet part 11.2
rv.setWaveform(2, 0);  // end of waveforms


d loop() {
 drv.go();
 delay(1000);
```

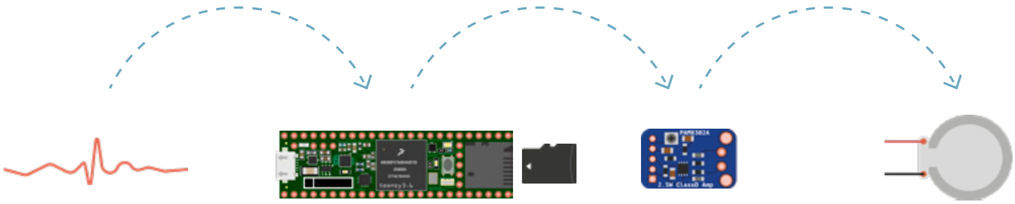
Sound and haptics
Opportunity and challenge

There is no haptic feedback without sound - if there is no sound, you just can not hear it. At least when it comes to real-world experiences, we are not used to experiencing haptic feedback isolated, it is most often accompanied by auditory or visual feedback.

Due to the mechanical build of the electromagnetic actuators, the auditory feedback is always produced at the same time which can be annoying, especially when it is used to be integrated seamlessly without disrupting the user's focus.
While this is a challenge in most times, it can also be used as a possibility to modulate the feedback.
If a sound is played at the same time as the haptic feedback is produced, our brain will connect and process them as a single piece of information. Through this you can add more sharpness to a soft vibration or make artificial feedback become more natural.

This not only allows you to shape the feedback, but can also directly applied to drive haptic actuators.

Basically, one can record sound, for example from a light switch and feed this file/ soundwave to an actuator through an audio amp. The haptic feedback will feel surprisingly similar to the real-world experience, even without the actual displacement of the switch.
This principle allows for a quite straight forward prototyping and exploration process, based on simple components and recorded or generated sound files.
The Teensy board is perfect for any audio application and is exceptionally easy to handle due to the visual programming environment, where one can add effects through a node-based editor.
https://www.pjrc.com/teensy/gui/



Generated/ recorded
Soundwave

Teensy 3.6
Microcontrol-
ler

Adafruit PAM8302A
Audio Amp

Haptic actu-
ator

User interviews
Qualitative analysis

During the research, I reached out to designers in the industry in order to identify the importance, work methods and approaches when it comes to haptic feedback such as the ones highlighted. As a summary one particularly interesting aspect of each interview is shown on the following pages.

How do you prototype haptic feedback?

Which challenges are you facing?

Where do you see opportunities in utilising haptic feedback?

Why is it not used more often?

Inhouse, Philips Experience Design

Interaction Designer

» Haptic feedback is rarely used to it's full potential, but will become increasingly important as more products are becoming more complex «

Consultancy, The Techno Creatives

Interaction Strategist

» Haptic feedback is a vast field, understanding the basic principles of human perception is a must to create meaningful solutions «

Consultancy, Above

Creative technologist

» Through digital haptic feedback, one can create feedback tailored to each interaction «

Inhouse, Logitech

Interaction Designer

» It's hard to sell [active feedback] due to component size, cost and complexity «

Inhouse, Philips Medical

Interaction Designer

» There is usually no time to explore possibilities, especially in consumer products «
» Designers are normally not trained to sketch with haptics «

Inhouse, BMW

Strategic Designer

» Haptics always have both a functional and an emotional value. There is a difference between feeling pleasant and being pleasant «

Inhouse, BSH

Product Designer

» Sometimes one would rather have no haptics than bad haptics «

Inhouse, Google

Interaction Designer

» Working with haptics is a speciality. Often one can only evaluate it in the final product, when it's too late to take actions «

Consultancy, Intuity

Creative technologist

» Once familiar with the technical aspects, the challenge is in utilizing it to create new applications and better interactions «

Expert interviews
Providing haptic experiences

In addition I was able to talk to several experts in the field ranging from in-house designers to manufacturers and consultants.

Lofelt is a Berlin-based company who developed its own haptic actuator focusing on audio devices (such as the Teenage Engineering OP-Z and Razor Nari).

Nanoport is a US company developing haptic actuators such as the tac-hammer.

Inhouse, Apple

Interaction Designer

» Haptics are incredibly powerful, but also incredibly hard to grasp «

» Haptic feedback becomes especially powerful in a multi-modal experience «

Development, Lofelt

Sales representative

» Unfortunately, there is no common approach or standard in the industry when it comes to programming and driving haptics «

Development, NANOPORT

Haptic Engineer

» Powering an actuator is easy, but taking full control and fine-tuning takes time and experience «

Inhouse, Logitech

Haptic engineer

» Every interaction, object, feedback and actuator is different and needs to be tailored to its application «

Research synthesis
Challenges and pain points

Looking back on the interviews, a lot of the feedback matched with my experience so far: There are little to no guidelines available, and the complexity makes it hard to get started and work with it in professional life.
A big motivation for the project was that every designer was excited to talk about the topic and how it could become more prominent in the design of physical objects proofing that there is a need for an easy to use solution.

When it comes to prototyping, almost everyone relied on hardware and electronics that are commonly available such as Arduinos or similar. While one company also created a custom solution, none of them were using a ready-made toolkits. The difficulty of acquiring coding skills even for simple prototypes was a challenge for many industrial designers in particular.

Perception
Awareness

Although we are constantly using our sense of touch, we are barely aware of its functionality. When processing haptic feedback, we rely on an unconscious library of how objects and interactions are supposed to feel.

Inspiration
Application

Due to the little number of applications, most designers and companies are unaware of the possibilities and opportunities haptic feedback can offer.

Learning
Guidance

While there is a vast amount of theoretical knowledge available, there is no quick and straightforward way to get started.

Learning
Education

Haptic feedback is currently not part of most traditional design education, and most knowledge has to be acquired while working on real-world projects.

Learning
Resources

Working with haptic feedback relies a lot on trial and error. Incorporating it in a professional environment requires a significant investment in time and effort to acquire the needed knowledge and skills.

Design
Tailored

Every feedback needs to be tailored to its application, and there can be no general solution.

Learning
Complexity

To better understand haptic feedback, one needs to have a basic understanding across multiple areas such as physiology, psychology and technology.

Design
Context sensitive

Haptic feedback needs to be designed based on its context such as the objects' material, target group, environment and body application area.

Research synthesis
Advantages

Using haptic feedback comes with a lot of advantages and benefits. Some of the most important ones are listed on this page.

Information
Invisible

No visual and only limited auditory information is involved which results in less disruptive interactions in both social and critical environments.

Communication
Private

Information can be precisely targeted at the person interacting with the object.

Sense
Always on

In contrast to sight and hearing, one can not turn off the haptic perception.

Reaction
Immediate

Especially through a multi-modal communication, information is perceived with less effort.

Interpretation
Obvious

Notifications such as a single impulse do not require interpretation but can be acted on in a reflex

Applied research

Applied research
Entering the workshop

After what I felt was a good enough foundation of theoretical background knowledge, I started incorporating hand-on prototyping to my daily work.

In the beginning, I focused on following the manufacturer's instructions on how to use their haptic actuators but was eventually able to utilise them in the fashion I felt was best for the project.

In the following chapter, an excerpt of the exploration is shown featuring both projects with a client focus during my stay at Intuity, as well as general explorative studies.

For each of the studies, I collected my takeaways and learning, which were later-on the basis of a knowledge base.

Due to the confidentiality agreement, certain aspects of projects can not be shown, but instead are illustrated in other ways.


STIHL

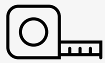
Object exploration
Identifying opportunities

I began by collecting and studying objects in my environment. What if I add haptic feedback to the lamp, the mouse or the chair?
Which opportunities could come up? Which challenges? And which properties do I need to account for and pay attention to?

Over the course of four weeks, I explored one application per day which was a great way to discover a variety of different objects and challenges.

Some of the objects were later on translated into physical prototypes. Unfortunately due to the COVID-19 pandemic, I could not carry out all the physical investigations I would have wanted to, due to the lack of access to a workshop.

#19
Tape measurement



Body interaction	Hand-held
Contact level	Active contact + passive contact
Object material	Plastic/ rubber
Advantages	Large grip area
Challenges	Small volume, no power source in current product
Current Information	Visual feedback on the measured length
Functional Opportunities	Indicate degree steps (fixed/ based on speed)
Feedback opportunities	Impulses/ vibrations, add/ remove friction
Functionality	Indication of certain distances through haptics
Advantage	No visual reading needed, faster measurements
Technology	LRA or small size ram
Feedback (character)	Technical, mechanic, crisp, sharp
Importance	Low
Complexity	Low
Learning	Easy

Example study

01 Working desk

02 Digital camera

03 Computer mouse

04 Navigation-system

06 Scale

07 Chainsaw

08 Screwdriver

09 Hand mixer

11 Work helmet

12 Doormat

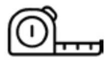
13 Multimeter

14 Chair

16 Coffee machine

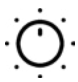
17 Key

18 Spirit level



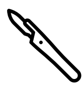
19 Tape measurement

05 ECG



15 Oven knob

10 Door handle



20 Surgical tool

Usage vs. Contact
When to apply haptic feedback?

Applications

One of the reasons why haptic feedback is most common in smartphones is the fact that even when not in use, we can still feel the vibration in our pockets.

The approach of dividing applications between duration of use and contact has been used before. [12] I enhanced it by introducing four primary groups:

Group A / B:
Objects in these groups are in continuous contact with the user while being in use.

Group C:
Objects in this group are in continuous contact with the user, even when not in use.

Group D:
Objects in this group are only in contact with the user during a short amount of time.

Opportunities

Integrating haptic feedback in each of these groups can make sense, but the amount and kind of information, as well as the kind of haptic feedback, differs. Some of the possibilities are listed below:

Active contact (A+B):
During active usage only

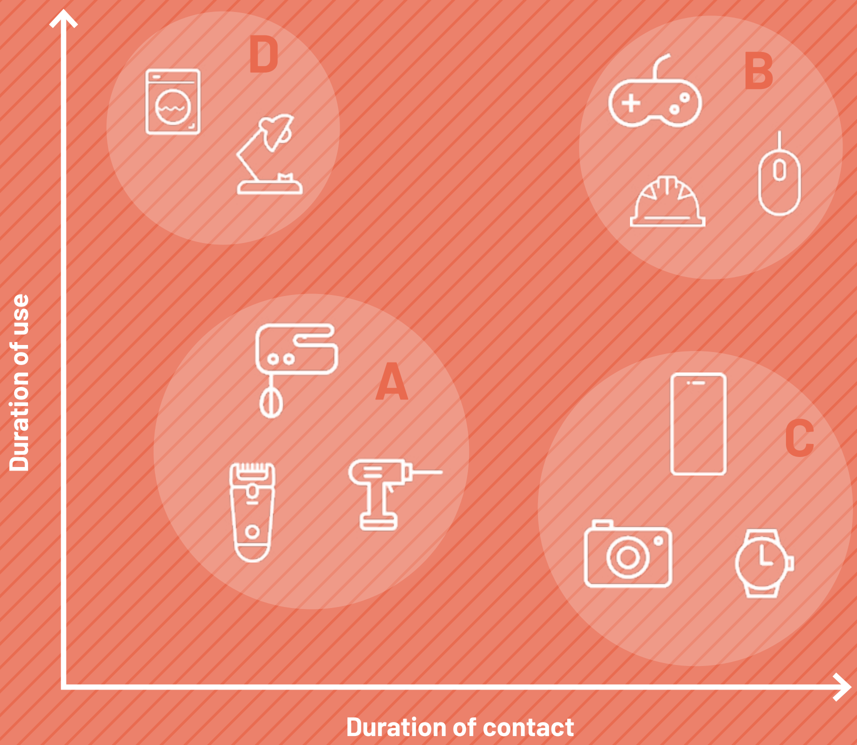
Interfaces (buttons/ dials)
Functional feedback (on/ off/ confirmation)
Notification (low battery/ used for x min)
Guidance (move up/ less force)

Continuous contact (C):
During active and passive usage

Same as for Active contact

Occasional contact (D):
During passive usage only

Interfaces (buttons/ dials)
Direct manipulation of the object (adjust height/ open lid)


D
B
A
C
Duration of use
Duration of contact

Shoulder tab
Translating human interactions

During the stay at my collaboration partner Intuity Media Lab, I had the chance to take part in a client project focusing on haptic feedback right from the start. This not only allowed me to experience the work process, challenges and approaches, but also to combine theoretical knowledge with a direct application.

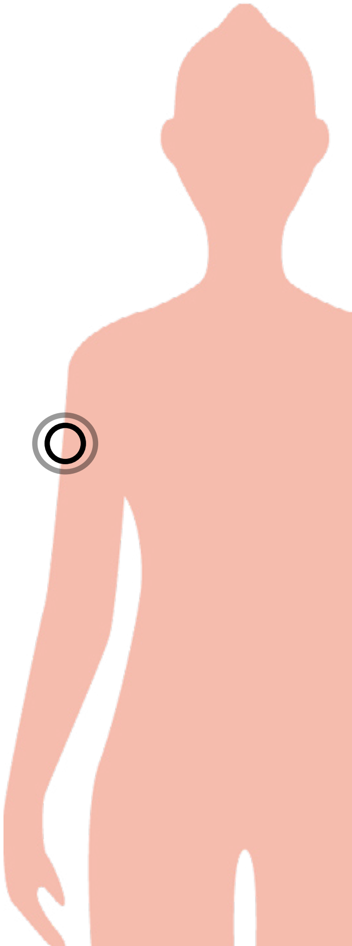
The objective of the project was to create a communication channel for simple, predefined messages between at least two individuals through haptic feedback in a wearable device placed on the shoulder. Three factors made this especially challenging:

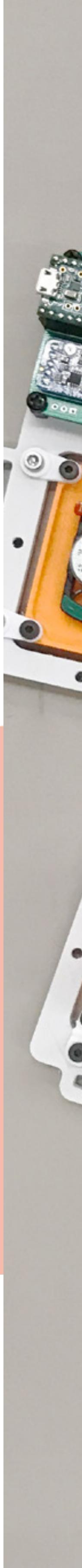
› Identifying a suitable haptic actuator

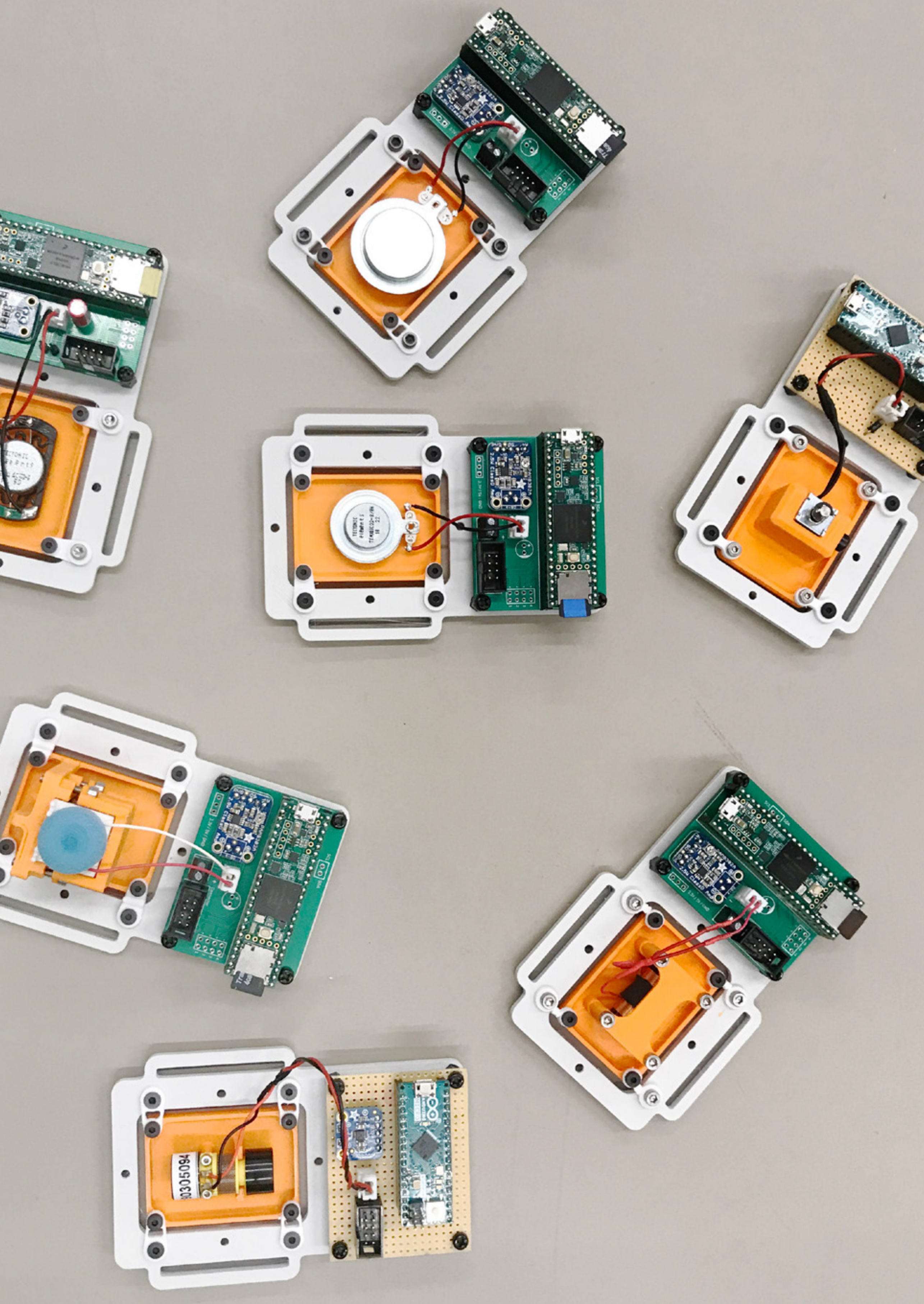
› Providing obvious feedback through the users' clothes

› Provide intuitive feedback while the individual is working with active equipment

The work process was divided into four stages: Identifying and testing components, define which information should and can be communicated, how to modulate the feedback to express a certain message and how to implement the feedback into a physical shape.







The actuators were driven by a Teensy-board utilising an audio source to design the haptic feedback. On the right-hand side, an excerpt of my exploration is shown. One take-away was that the visual representation of the soundwave made it much easier to talk about and evaluate the feedback. In this project, I had the responsibility to design the feedback and support building the prototype.

Takeaways:

› High frequencies were barely recognised through the clothing.

→ The frequency needs to be low in order to reach through material

› The feedback greatly differed depending on the clothing layer.

› The suspension and attachment of the actuator influenced the characteristic of the feedback.

› Adjusting the amount of pressure in which the actuator is put onto the arm is essential.

→ Prototype early and often to identify the right solution

› The skin sensitivity on the upper arm is relatively low.

› Even smaller and less powerful actuators have produced an easy to identify sensation.

› Keeping the feedback as simple as possible helps in processing it.

› A signal which is to loud for the actuator (overdrive) results in a distorted feel.

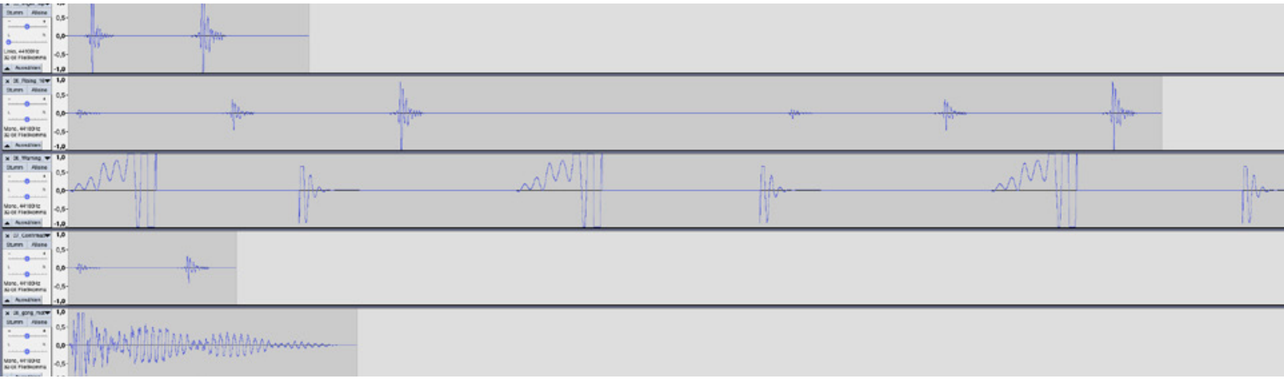
→ The most powerful actuator can produce unsuitable feedback when driven by the wrong signal

Information: Notification
Importance: Medium
Modulation: Soft impulse, 0,3s gap
Repetition: 3 impulses, increasing intensity, repeated

Information: Confirmation
Importance: Low
Modulation: Soft impulse
Repetition: 2 impulses, increasing intensity

Information: Grab attention
Importance: Low
Modulation: Soft impulse
Repetition: 2 impulses, 0,2s gap (shoulder tap)

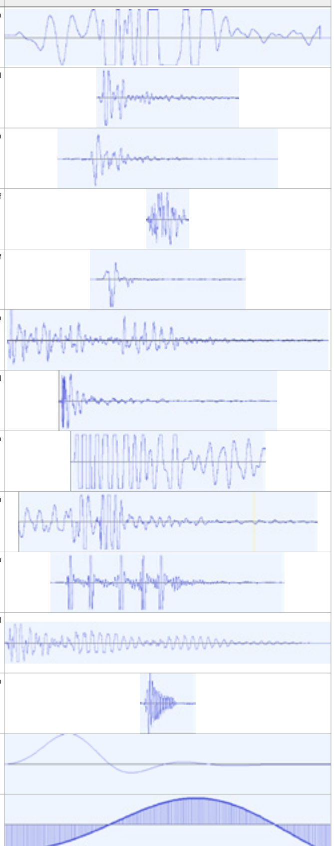
Information: Warning
Importance: High
Modulation: Ramping + Sharp impulses
Repetition: 2 impulses, repeated until confirmation



Feedback definition and resulting waveforms

Exploration of sound

Button	File	Dauer (s)	Peak frequenz (Hz)	Beschreibung
1	2	0,45	40	Erdbeben
2	6	0,18	150	Weich, Nachhall
3	4	0,28	100	Weich
4	3	0,05	124	Scharf
1	7	0,2	70	Dumpf
2	8	0,4	90	Detonation
3	9	0,28	120	Basketball
4	10	0,25	80	Sawtooth
1	11	0,38	120	Detonation
2	12	0,3	250	Rau
3	13	0,6	70	Metall, hall
4	14	0,07	330	Tropfen
1	2	0,05		
2	5	0,01		



Helmet application
Creating awareness

In a second project, I was exploring how haptic feedback could be included in a hardshell helmet, used in an outdoor environment. The goal and the exact message was not defined from the beginning, which created a challenging but also exciting scope to work with.

I ended up with three prototypes, each making use of a different actuator technology to indicate a directional feedback [left/ right].

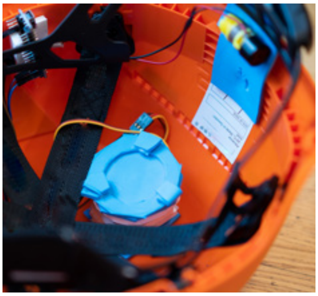
Prototype one was using two relatively large surface transducers which were placed on each side of the head. A modular framework inside the helmet allowed to explore different placements.

Prototype two used an array of small LRA actuators which were triggered in series, thus simulating a vibration that moves from side to side on your forehead. The analogy of a windshield wiper effect came close to describe the sensation.

For **prototype three**, I took a different approach using a servo motor to twist the skin on top of the head by moving it clockwise and afterwards counter-clockwise.
I also tried an accelerated ram to create linear movement on the back of the head. The force, however, was too weak to be recognised.

Prototype one
Single actuators

Prototype two
Vibration strap



Prototype three
Skin stretch

The head as input channel for tactile displays is especially demanding:

Human interaction

As humans, we are not used to touch, vibrations or impulses on the head. There is only a small window of sensations which are perceived as being pleasant or neutral.

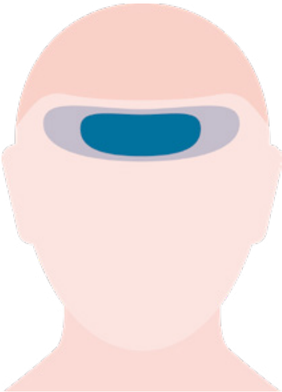
We connect a lot of these sensations with unpleasant experiences such as a visit to the dentist [high pitch vibration] or a bug crawling through the hair [slow/ low pitch vibration or movement].

Physiology

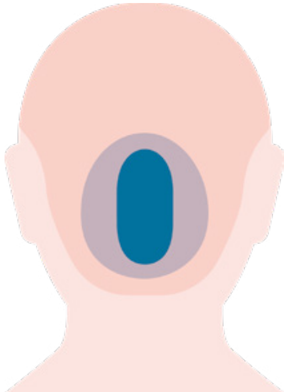
The large part of our head is covered in hairy skin which features fewer receptors. The layer of hair also has a dampening effect which requires a more localised/ isolated feedback. The sensitivity of 7,5mm two-point threshold is almost half compared to 3,9 mm in non-hairy skin areas. [22]

Sensitivity

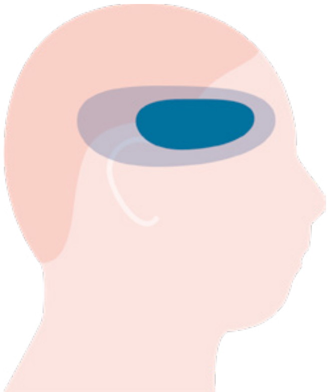
The head is extremely sensitive for over-stimulation, which results in distraction/ annoyance or worst case headaches. Especially the temple-area is prone to this. Due to the little amount of tissue, also vibrations get easily distributed and amplified by the skull. When placing feedback close to our ears, one needs to be particularly careful about the auditory feedback.
While vibrotactile feedback is most common, skin indentation or stretch can be used to create a more pleasant sensation.



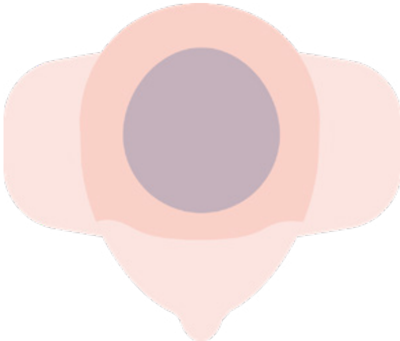
Frontal



Back/ Occipital



Side/ Temporal



Central/ Parietal

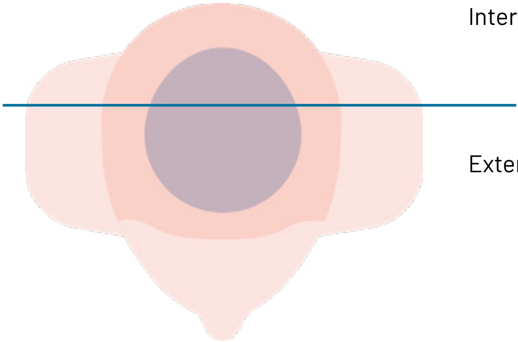
Non-hairy skin

Hairy skin

High sensitivity

Medium sensitivity

Takeaways:



› Especially in the upper part of the head one needs to place the actuators far apart to sense the feedback of two individual actuators.

→ Keep actuators at least 15 mm apart to allow them to be easily identified as separate impulses. [22]

› Adding too many actuators does not help increase the solution, but instead makes is rather more mushy and harder to interpret.

→ Use low-density arrays (four to five tactors). [22]

› Actuators placed in the frontal area of the head similar to the eyes or ears are easier to process, compared to when placed in the back of the head. Input from the front is perceived more conscious/ external, from the back is more subconscious/ internal.

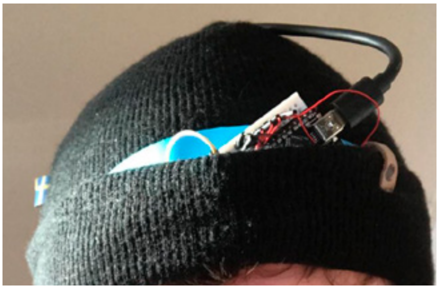
→ It is easier to process Feedback applied to the frontal part.

› The head is very sensitive to high frequencies.

→ Especially frequencies above 150Hz become uncomfortable. [22]

→ The pleasantness however is equal across the head. [22]

› Keeping the feedback as simple as possible helps in processing it.



Low-fi prototype

Prototype connected to the PC

Stand alone prototype with milled plastic frame

Servo motor covered by a 3D printed rubber attachment

Vibration motors covered by textile

Tape measurement
Indicating physical units

Highlighting physical units is an especially exciting application. One can utilise it to either enhance or substitute other modalities and create a more accessible and faster to process feedback.

In case of the tape measurement, a haptic clicking sensation was presented every single cm or 10 cm, adjustable by a press on the rotary encoder. This feedback allowed the user to speed up the measurement process in case only a rough estimation is needed rather than a precise reading.

Two Apple taptic engines were used due to their ability to create a very realistic "click" feeling, similar to mechanical feedback.

Takeaways:

› Haptic feedback is distributed across the whole device, thus the position of the actuator did not matter.

→ In small devices with tightly fitted parts, the position of the actuator might not matter.

› Mechanic noise/ vibrations make subtle feedback tricky to feel.

→ Haptic feedback needs to have a higher intensity than surrounding mechanical noise.

› The small volume does not allow for the electronics to be embedded.

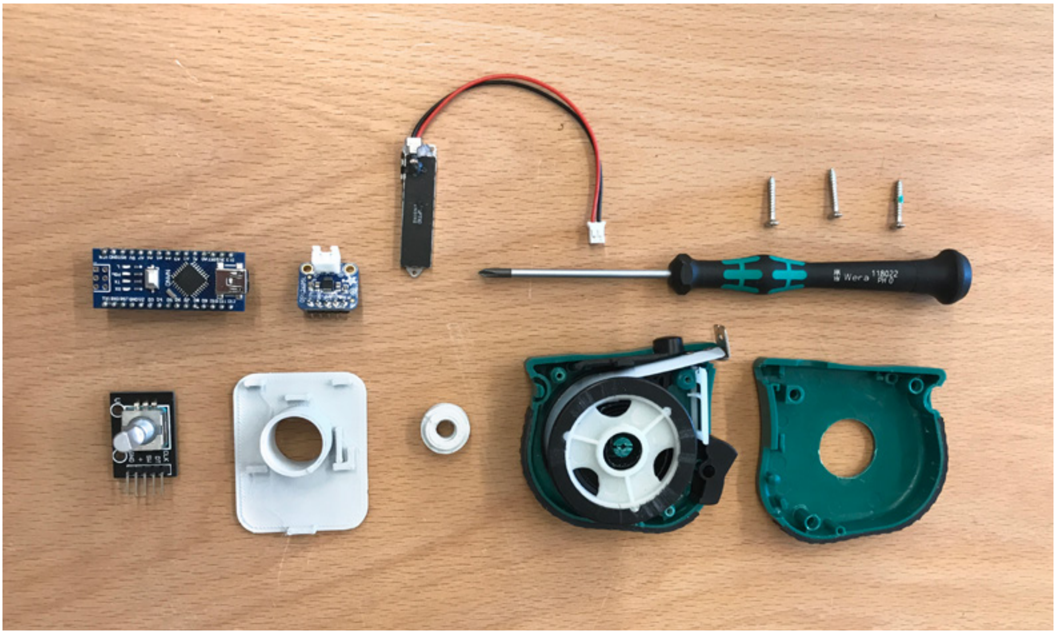
› Mapping haptic feedback precisely to the real measurement is challenging but necessary to create an immersive experience.

→ The feedback needs to be mapped precisely to the real-world application to create a believable and enchanting experience.

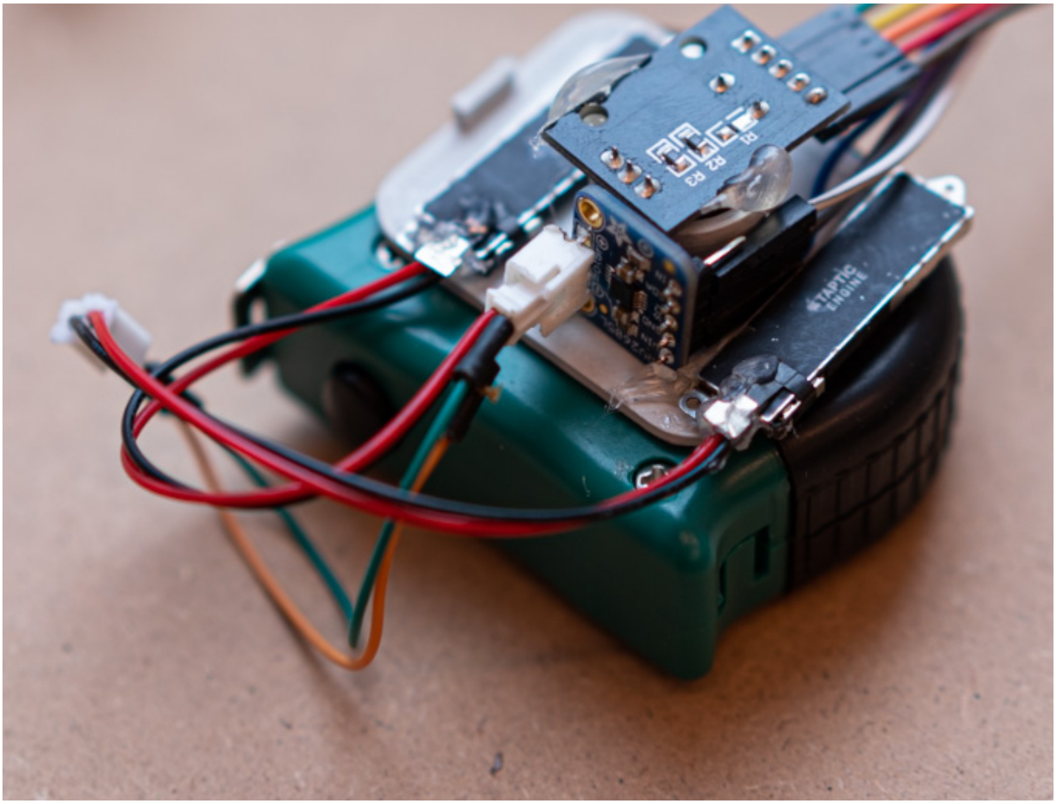
› The feedback was quite low, and in combination with the actuator characteristic, it was perceived as being mechanical/ natural.

› The cable connection had a serious impact on the user evaluation.

› Creating a small technical package which was also standalone was not feasible in the time frame and for this level of prototyping.



Components used for the feedback [Arduino nano, Adafruit DRV2605, rotary encoder, Apple taptic engine] and a printed attachment



Smallest possible package with ready-made components

Spirit level
Angle indication

Similar to the measuring tape, a spirit level was enhanced with haptic feedback highlighting when a certain angle is reached [45/ 90°].

A Nanoport Tac-Hammer was used which can achieve a strong clicking characteristic as well as a distinct clicking sound.

The functionality could easily be extended by being able to set a custom angle or adding feedback for every change in angle.

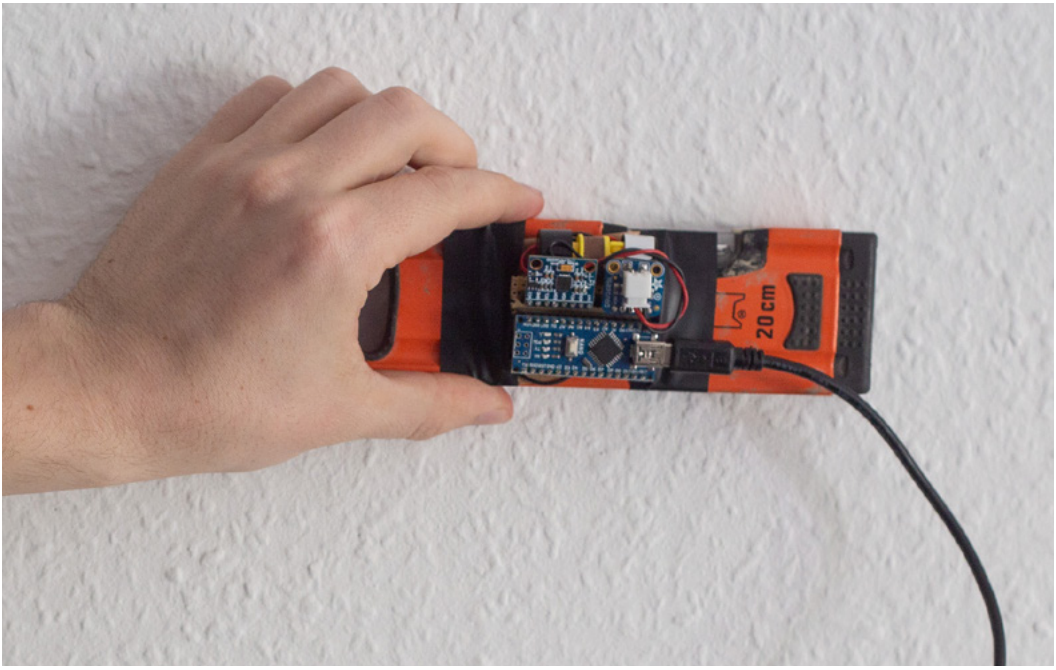
Takeaways:

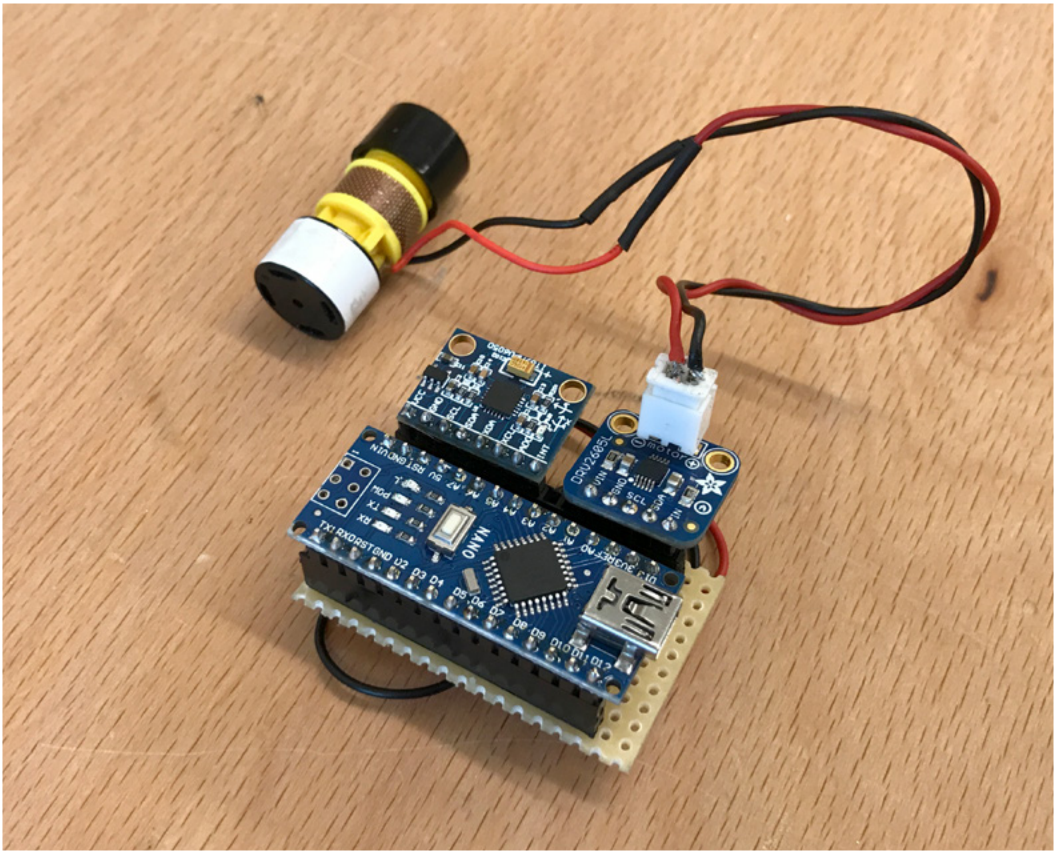
› Similar to the findings of the tape measurement plus:

› Slightly differing haptic sensations were not recognised reliably.

→ Different haptic sensations need to be designed with a high contrast to be recognised separately.

› As there are no mechanics used to measure the angle in a spirit meter, the haptic feedback was perceived as being artificial.


20 cm


NANO
DRV2605L
motor

Force simulation
Linear & rotary force

Although I put my focus on tactile feedback in this thesis, I could not stay away from experimenting with force feedback as well.
Even with very simple and low-fidelity prototypes, the ideas were quite easy to simulate and express but hard to define.

I ended up with two prototypes, one simulating rotary force and one linear force.

The rotary force simulator is based on a brushless DC-motor with a mass attached to its axis. By spinning the motor and abruptly stopping it and or giving it a counter-spin, the user holding it will get the impression of a slight rotational force. This concept could, for example, be used to indicate the rotation direction of a knob creating a more intuitive usage.

The linear force simulator is based on a solenoid with a mass attached to the moving axis. The linear force is quite substantial due to the fast and abrupt actuation of the solenoid.
A concept similar to this is used to create navigation systems for blind users.

Another interesting take is using a gyroscope to create continuous forces. [29]

Takeaways:

› The small volume makes it hard for the electronics to be embedded.

› The actuators need to be able to move the object to a certain degree for the feedback to be sensible.

→ The concept is not optimal for stationary/ fixed handles/ objects.

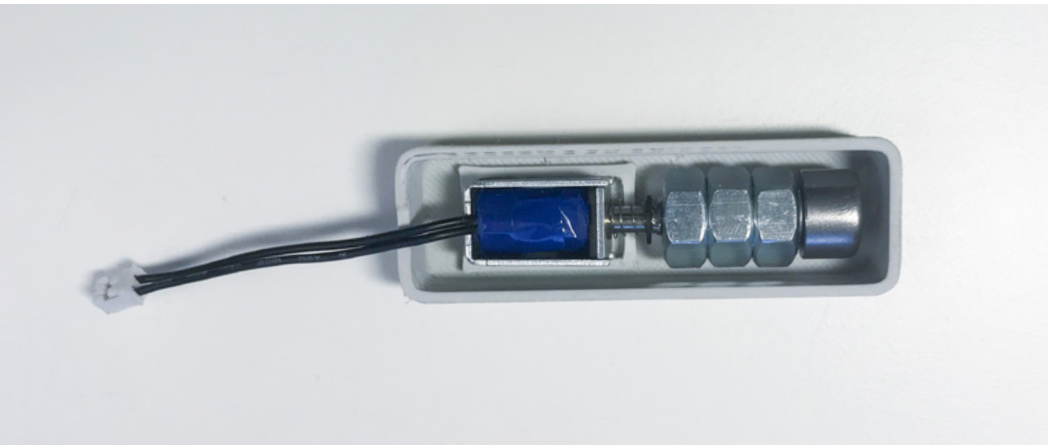
› By counteracting with the intended direction of the force, the impulse becomes more apparent; otherwise, it might be barely sensible.

→ The force needs to be quite high to be obvious/ call for an intuitive reaction.

› The solenoid produced loud auditory feedback.

→ The material use highly influences the character of the feedback.

Rotational force simulator



Linear force simulator

Skin stretch/ indentation
Avoiding vibrations

Haptic feedback can not only be created through vibrations or impulses. Furthermore the skin is able to recognize also more significant stretches.

An interesting take on this concept is making use of skin stretch, indentation or twisting on a larger scale to, for example, communicate a direction as shown in one of the helmet concepts.

The challenge with all of these solutions is that they require a rather large actuator build to produce a higher force and displacement compared to traditional haptic actuators.

Takeaways:

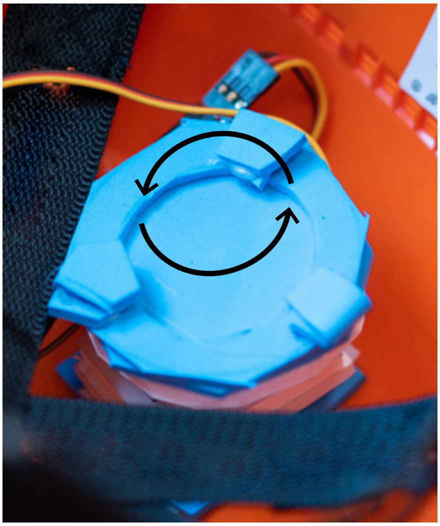
› The travel of the actuator needs to be quite high.

→ Actuators for skin stretch/ indentation become big quickly.

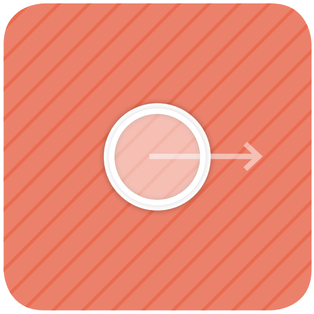
› The actuator works best when directly put on bare skin.

› It is difficult to find the right balance of pressure on the skin while allowing the actuator to move.

› Feedback through skin stretch/ twist works best on location with a higher amount of movable tissue (head vs. arm).

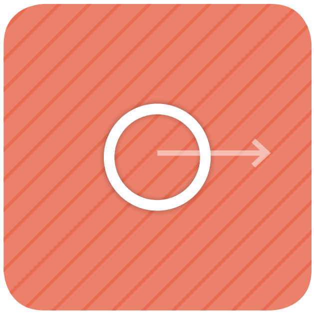


Indentation



Stretching

Twisting



Movement

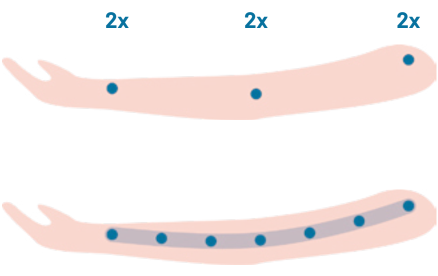
Fluent vibrations
Making it move

In comparison to the eye which can not distinguish between single frames above a rate of 24 frames/second, the skin has a practically infinite resolution.

How one can easily fool it, by combining multiple actuators and trigger them in a row. In prototype number two of the helmet, an array of LRA actuators was triggered. The individual actuator could not be identified, instead it was interpreted as a single traveling sensation.

Another example is the so-called Cutaneous rabbit effect:

Our mind interprets multiple impulses with a low spatial distance happening in a small time-frame as a moving sensation. It occurs especially in areas with low spatial acuity such as the arm. [23]

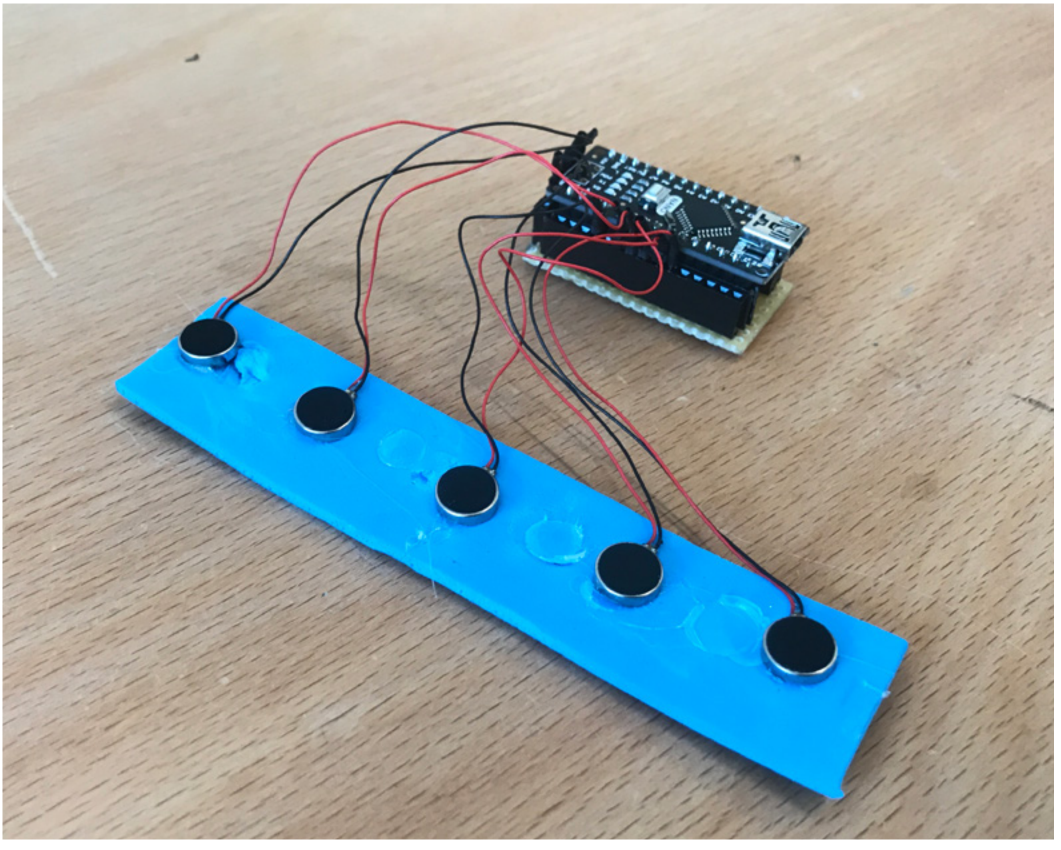


Takeaways:

› The vibration motors need to have a certain distance to be able to be efficiently processed. If the gap is too small, it results in mushy feedback.

→ There is a sweet spot when it comes to actuators/ area (head = a minimum 1.5 cm distance)

› Current haptic drivers only support one actuator. Multiple drivers [DRV2605] can not be connected to one I2C port but require an I2C multiplexer.



Sound & haptics
Creating a simulator

Sound plays an important part when designing haptic feedback. Not only is it a by-product of each actuation, but it can also be used to further shape and define the character of the feedback.

Often without actually being in contact with the object, we can accurately describe how it would feel, only by listening to the sound.

To highlight and explore this dependency, I created a simulator which lets the user define both the haptic and sound feedback individually. This allows for three scenarios:

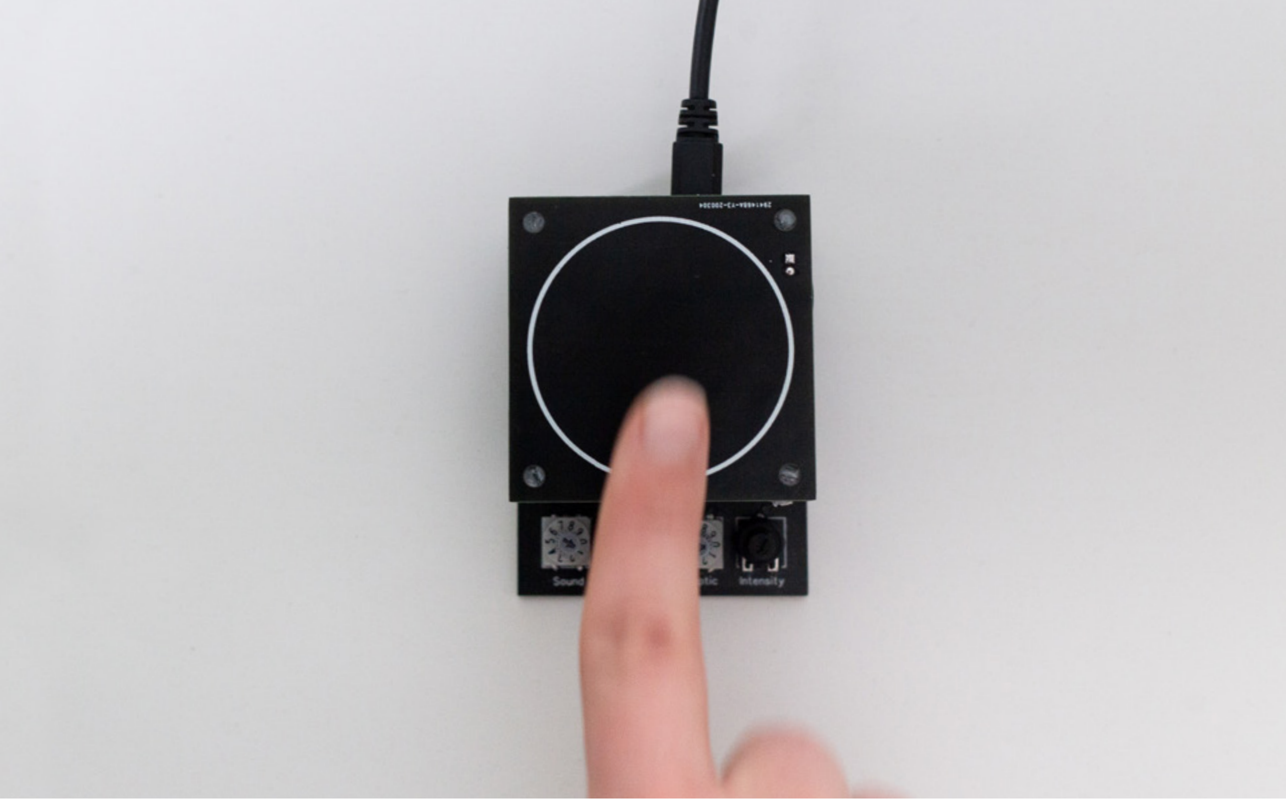
› Sound feedback only

› Haptic feedback only

› Sound and haptic feedback combined.

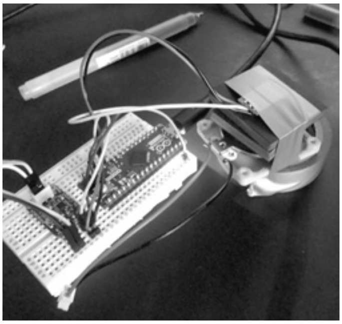
Apple taptic engine

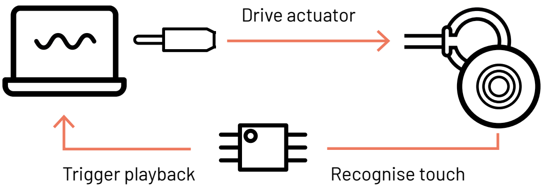
Not only makes Apple use of a highly advanced actuator technology in their phones and trackpads, but every actuation is also accompanied by a specific sound to shape the character. As both happen at the same time, the user can not separate them but combines it into one single impression.



Each modality (sound/ haptic feedback) can be adjusted individually by choosing from a set of presets and adjusting the intensity.

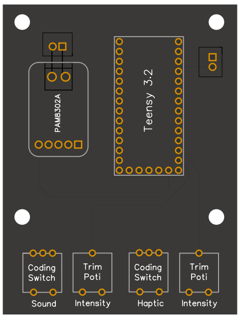
The top surface features a capacitive touch area

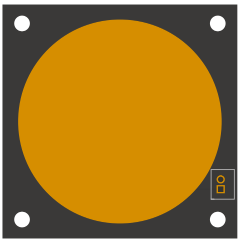




Exploration

Through a quick prototype including an Arduino Micro, a capacitive touch sensor, a surface transducer, an audio amplifier and some duct tape, I was able to explore the connection between sound and haptics. In the first step, I used the Micro as a virtual keyboard to trigger an Audacity playback. The setup allowed a very easy modulation but was coming with quite some latency between the trigger and the feedback. Also switching between different characteristics was quite cumbersome.

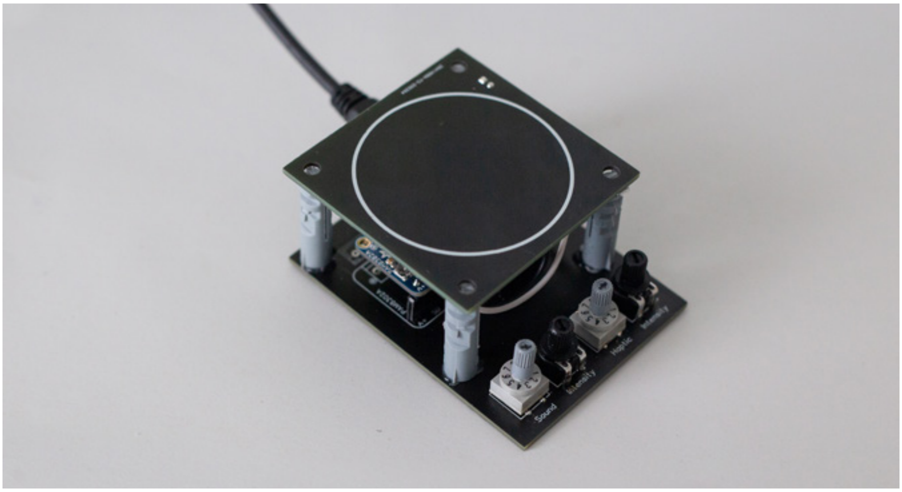


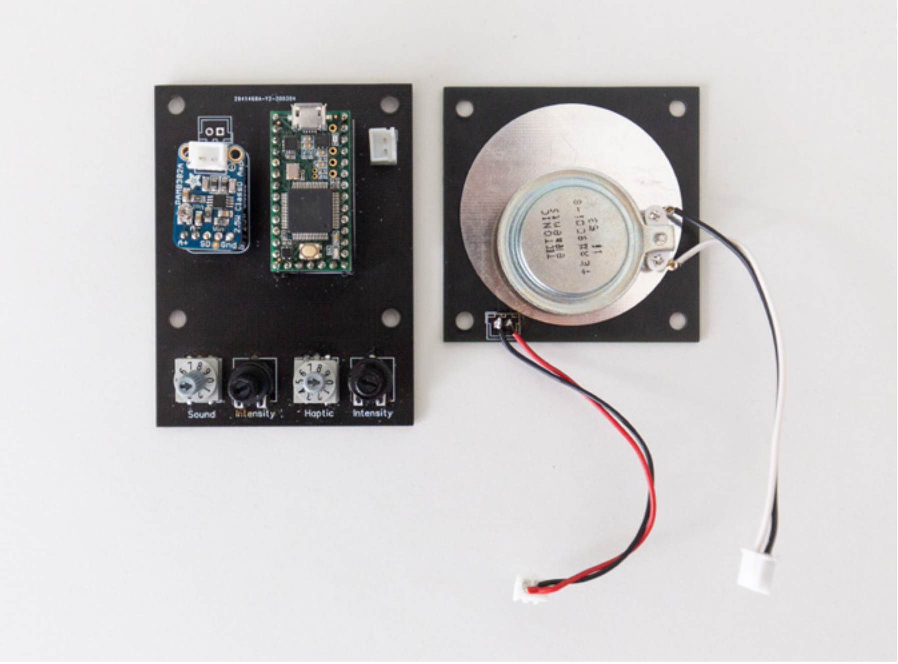


Refinement

In the second step, a custom PCB was created, based on a Teensy Micro-controller. This allowed playing sounds and haptic feedback saved on the internal memory without any latency. One can choose from ten different sound and haptic feedback as well as adjust the intensity of each.
The final package allows for effortless and intuitive exploration of the dependency of sound and haptics.

Final simulator





Excursion I
Simulating human touch

A lot of everyday interactions between two humans are simple notifications in order to create attention:

A shoulder tab, a finger poke, a tip with the foot etc.

Most of these follow basic patterns:

› They consist of very simple impulses

› They can feature patterns (2 ± one impulse)

› They usually do not emit any audible sound

› They feel soft

› They rely on tactile feedback

Regarding the rhythm, two taps seem to be a sweet spot when using finger taps. A lower amount can be interpreted as accidental or very hesitating, while a higher number might illustrate a very high urgency. Similar patterns can be identified for frequency, force and the feel of the feedback.

An intriguing thought is: How can this be applied to products to mimic a more human interaction?

More complex human interactions are usually focusing on communicating emotions and only happen when interacting with a specific group of people.

› A handshake

› Touching someone's forearm

› A massage

› A pinch with two fingers

› A punch/ kick

Comparing human to human with human-object interactions, it becomes clear why a lot of time we have difficulty interpreting and recognizing haptic feedback from objects as they differ tremendously from anything we can experience naturally.

	Hesitant → Urgent				
Number of taps	1	2	3	4	..
Frequency [sec]	0,5	0,4	0,3	0,2	0,1
Force of taps	Touch	Tap	Push	Punch	
Feel	Soft	Hard	Sharp		

Excursion III
Haptic modulation through sound

For most of the projects, I made use of sound to drive the actuators. This approach makes it very easy to modulate the feedback by adjusting the recorded or generated waveform in a suitable audio software like Adobe Audition or Audacity.

The following pages are a recap of this exploration, illustrating the findings in a simplified fashion.

A multitude of parameters can be adjusted to modulate the feedback:

Amplitude
The amplitude describes the intensity of the signal or the corresponding movement of the actuator. A positive amplitude makes the actuator move forward in its axis; a negative amplitude reverses the action creating a backwards motion.

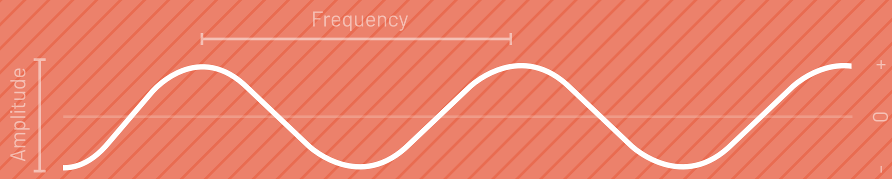
Frequency
The frequency describes how fast the wave is oscillating. Similar to music, low frequencies produce a soft, rich and deep output while high frequencies produce clear and sharp output.

Waveform
When generating an audio signal from scratch, you are bound to three basic waveforms which provide different characteristics:

Sine-wave:
A uniform wave, which is perfect to create even and smooth vibrations.

Square-wave:
The square-wave resembles a digital on/off state with the actuator instantly switching between its top and bottom position creating a rougher vibration compared to the Sine-wave.

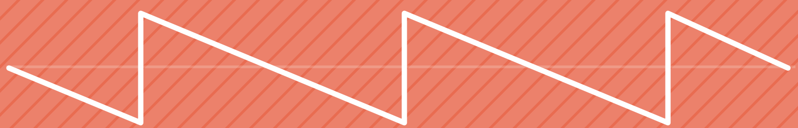
Triangle or Sawtooth:
A triangular wave has the same attributes as a sine-wave, but showing a more abrupt reverse of amplitude. The more interesting sibling is what you call a sawtooth- waveform. It features a steep rise followed by a gradual decrease of amplitude. This allows, for example, to create directional feedback by pulsing the actuator in a single direction only.



Sine-Wave

Square-Wave

Triangular-Wave



Sawtooth-Wave

Excursion IV
Characteristics

It is always a challenge to communicate and describe how haptics feel without actually making them a tangible experience.

Certain parameters play a key role in the design of haptics beside the intensity:

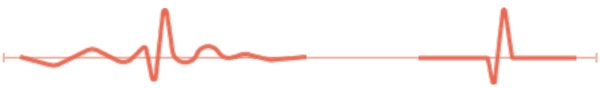
Sharpness
The feel or generally described as "sharpness" is based in the frequency. Unfortunately, without actually experiencing the difference, it is tough to get a good understanding. Very sharp feedback is similar to the vibration of an electric toothbrush, while a very soft feel comes closer to the rumble of the steering wheel when driving over a street marking.

Complexity
The complexity can be altered through multiple parameters such as adding reverb, ramps and creating patterns. It is crucial to start simple and keep it that way whenever possible. Complex feedback will require a steep learning curve for the user, and the chance of misinterpretation and fatigue is very high.
This is just an excerpt of possibilities to illustrate opportunities.

Feel

Attribute	Low frequency	High frequency
Soundwave		
Adjectives	Soft, Smooth Warm Heavy Thick	Hard, Rough, Rigid, Stiff, Harsh Cold Light Thin

Complexity

Attribute	Long / Reverb	Short / Simple
Soundwave		
Adjectives	Wet Fluid Complex	Dry Solid Clear

Excursion V
Natural expression or schemes

Another advantage of the close relationship between sound and haptics is that natural expressions or schemes known from sound design can be directly applied to haptic cues.
While we do not have the dimension of designing minor or major chord progressions, we can take the varying intensity to modulate the character of the feedback. A pattern with increasing intensity, for example, is perceived as being positive, the inversion as negative. [17]

While these are of great help, they are also context dependant, and it is highly essential to verify the success in the field.

Ascending
/ Success

Failure

Descending
/ Failure

Flat
Neutral

In progress

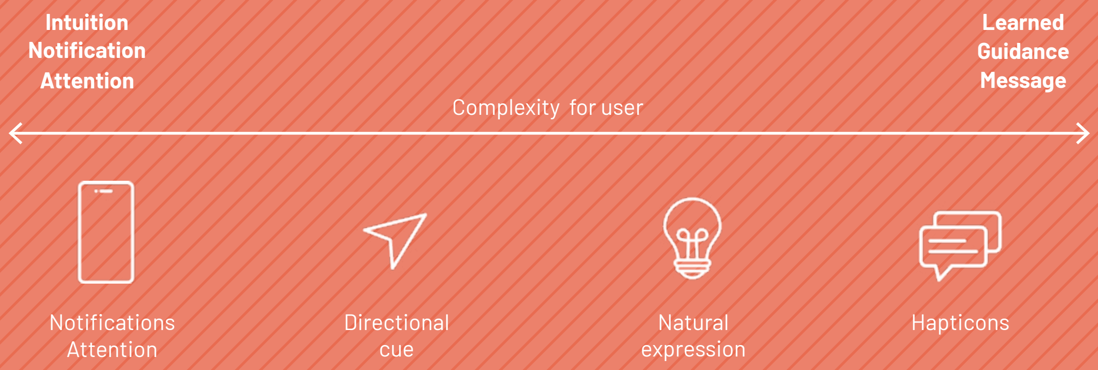
Excursion VI
Defining complexity

Every interpretation of haptic feedback was learned at some point in time. As previously mentioned, we have a far-reaching internal library which unconsciously tells us how things should feel based on our experience.
The illustration shows how different haptic cues require a different level of competence to understand.

A directional cue can be a force shifting from left to right, or an impulse in the left hand.

Hapticons are haptic patterns such as a custom vibration pattern which your phone will emit when a particular friend is calling. They can be utilised to communicate also more complex information [even the complete alphabet] [17], but they have to be learned and are only understood by a specific group of people.
One important factor is the amount of times the user is experiencing the feedback. If he is exposed to it multiple times a day, it might be beneficial and quickly become intuitive, while if it is only felt once a week, the user will have a tough time learning it.

The simpler the feedback, the easier it can be interpreted, and the more powerful it becomes.


Intuition
Notification
Attention
Learned
Guidance
Message
Complexity for user
Notifications
Attention
Directional
cue
Natural
expression
Hapticons

Haptic checklist
What to think about beforehand

As indicated at the beginning of the chapter, while going through the exploration process, I evaluated each application and summarised my findings in a checklist which I again re-evaluated in the following application.
The result is a collection of topics to consider when defining haptic feedback before entering the prototyping phase. This highly accelerated the design process and helped to avoid pitfalls along the way. The questions are framed to identify new applications but can be adapted for different purposes.

It is the result of both the findings throughout the applied exploration as well as takeaways from the user interviews. It is not meant to be read as a list of rules but as guiding principles.

Interaction	**Current Information**	*Which information is currently communicated? Which modalities are used? [Visual feedback about the measurement, ...]*
	Functional Opportunities	*Which information can be replaced or enhanced through haptic feedback?*
	Feedback opportunities	*How can haptic feedback be utilised to communicate them? [Tactile, kinaesthetic, impulse, vibrations, friction, directional]*
Context	**Body interaction**	*Which area of the body is supposed to sense the feedback? How is the body in contact with the object? [Handheld, wearable,]*
	Contact level	*During which interaction is the body in contact with the object? [Active contact/ occasional contact/ passive contact]*
	Context	*Which context is the feedback supposed to be felt in? [Location, what is the user doing while receiving the feedback, distractions, target group, previous experience]*
	Object	*Which material is the object made of that needs to pass on the feedback? [Hard plastic, rubber, metal, fabric..]*
	Advantages	*Which advantages come with the object/ context? [Large grip area, 360° contact..]*
	Challenges	*Which challenges come with the object/ context? [Small volume, mechanic noise]*
Definition	**Character**	*How should the feedback be perceived? [Strong-weak, soft-sharp, precise - mushy, technical, human, natural, synthetic]*
	Importance	*How important is the information?*
	Learning	*How often is the user exposed to the feedback? [Once a minute, an hour, a day, a week, a month] How complex is the feedback?*
	Advantage	*Why is haptic feedback useful in this case/application?*
	Technology	*Which technology can be used to produce the feedback? [LRA/ ERM/...]*

Conclusions

Research synthesis
Challenges and pain points

Studying haptic feedback in an applied manner was extremely important to grasp it's potential and discover its advantages. Most of the knowledge I acquired by building prototypes and putting the theory into action.

The takeaways were manifold and go hand in hand with the identified pain points and challenges of the theoretical research.

Understanding

Experience

Feeling the feedback while designing it is inevitable. Details get lost in translation by using speech or sound.

Application

Opportunities

One can easily forget about the plethora of possibilities and capabilities and it's difficult to nail them down.

Getting started

Understanding

A basic level of knowledge in physiology and human perception is highly beneficial while creating the feedback.

Designing

Prototyping

The lack of knowledge and simple to use solution makes prototyping especially tricky.

Implementation

Technology

There are many possibilities to prototype and create haptic feedback, and each approach will result in different experiences.

Application

Customisation

As stated before, every feedback needs to be tailored to its application, and there can be no general solution.

Haptic design process
From start to finish

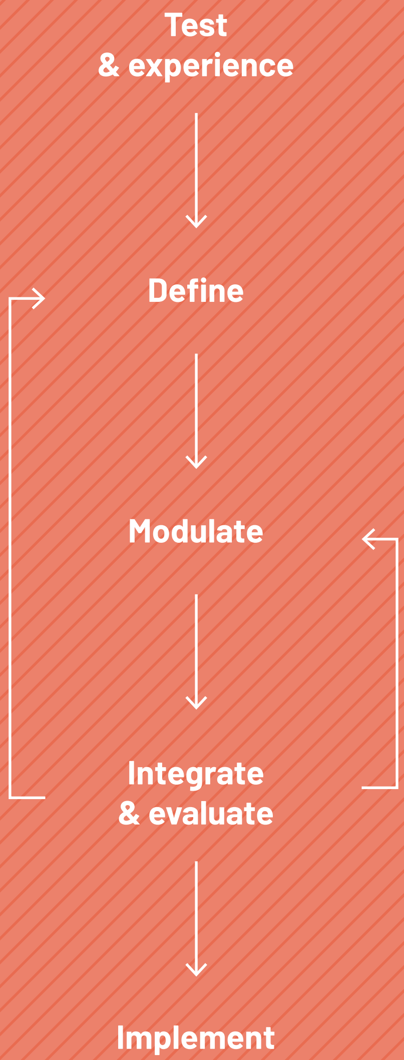
Through user interviews and personal experience, while working with haptic feedback, a general idea of the haptic design process emerged.

Two things are especially important and came up frequently throughout this thesis:

One first needs to define the feedback before starting to prototype. The more detailed this is done beforehand, the easier the upcoming steps are, and pitfalls or gimmicks can be avoided.

Each haptic feedback needs to be tailored to its application. There can not be a general solution across multiple objects, user groups or contexts.

This results in a highly iterative design process where ideas and sketches need to be evaluated constantly.


Test
& experience
Define
Modulate
Integrate
& evaluate
Implement

Re-evaluation
Where to go from here?

The most important takeaway for me at this stage was that most often, one can not simply put haptic feedback in an object and achieve great results, but has to go through the complete design process to create not only practical but also meaningful experiences.

While I set myself out in the beginning to demonstrate the abilities of haptic feedback, I realised especially throughout the interviews that one of the biggest challenge and the main reason why we have very few applications available, is the lack of easy to use tools and guidance for designers.

While both aspects were valid, I decided to shift my focus to ease access to haptic feedback in the first step.

01

How might we ease access to haptic feedback for designers?

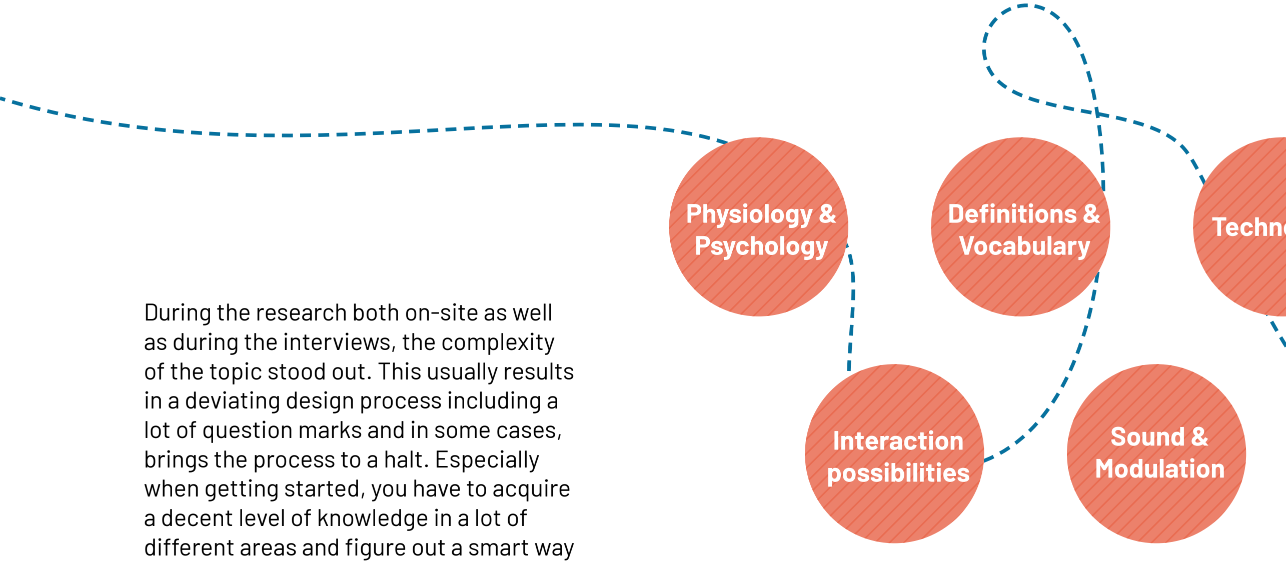
02

How might we utilise haptic feedback to enhance physical product interactions?

.. and preserve an analogue and human interaction?

Concept

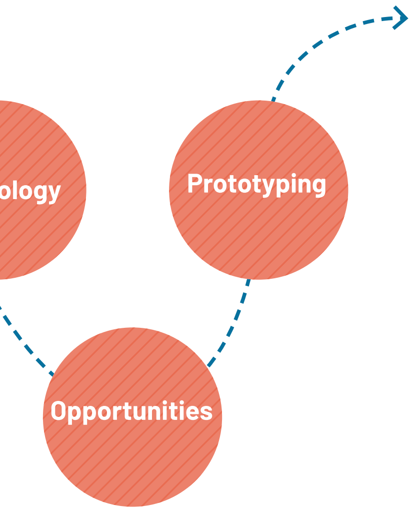
Concept idea
What do you need to know?

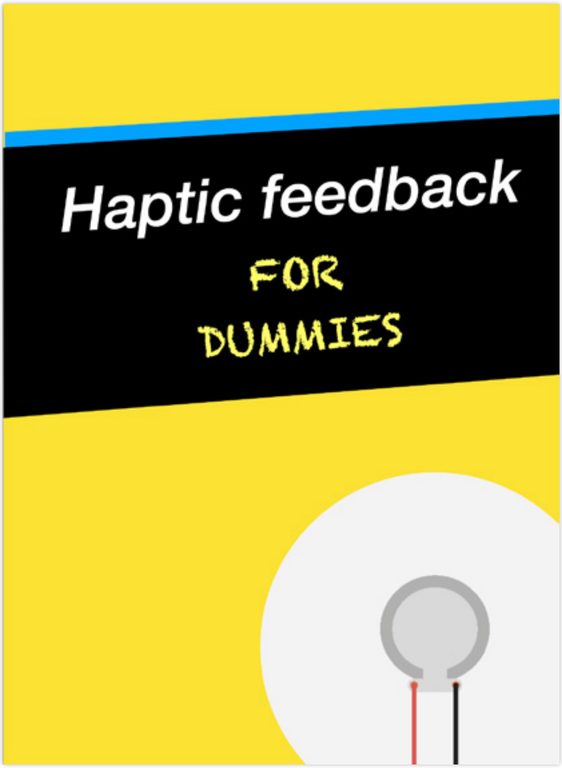


During the research both on-site as well as during the interviews, the complexity of the topic stood out. This usually results in a deviating design process including a lot of question marks and in some cases, brings the process to a halt. Especially when getting started, you have to acquire a decent level of knowledge in a lot of different areas and figure out a smart way to move forward.

The outcome, therefore, needed to provide the basic theoretical knowledge to get started, a prototyping environment which should only require a minimum of previous experience and a showcase of opportunities and possibilities to inspire future applications and scenarios.

In the next step, I analysed which requirements are needed in each stage of the process.


ology
Prototyping
Opportunities


Haptic feedback
FOR
DUMMIES

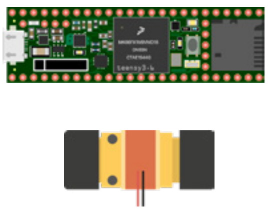
Process analysis
First stage ideation

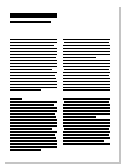
	Goal	Method
Ideate & experience	Acquire a sense for the characteristics and possibilities of an object and actuator	Different actuators are tested and compared on different positions
Define	Defining the characteristics of the feedback based on the interaction, context and scenario	Analyse the context (body interaction, target group, environment..) and define the feedback as detailed as possible
Modulate	Modulate the feedback according to the definition	Choose suitable actuators, modulate feedback (with/ without being integrated in model)
Integrate & evaluate	Comparing the achieved sensation with the defined characteristic	One or multiple actuators are integrated into the physical object and tested in the (simulated) final context
Implement	Create the most immersive experience by implementing the actuator and feedback into the final prototype	Create standalone package of actuator, electronics and battery

Challenge	Need	Opportunity
Identify actuators on the market, drive the actuator, integrate it into the object, identify possibilities	Overview of technology, a plug and play solution to prototype, haptic presets as a starting point and simple modulation	Plug & play hardware interface haptic presets to experiment and compare, an overview of components
Identify parameters, lack of comparison/ examples	Defined parameters to play with, inspiration and comparison, principles to follow	Showcase opportunities and examples, provide easy to understand knowledge, provide checklist
Identify the right actuator, identify parameters to modulate, figure out how to drive the actuators and modulate the feedback	Simple and quick toolset to modulate feedback with limited parameters and/ or guidelines	Analog or digital solution which allows for easy and quick modulation for any actuator
Creating a realistic model and experience, modulate feedback while being integrated	Small actuators, easy to use electronics, possibility to modulate feedback while integrated into the object	Provide a small package to be integrated, while still being able to modify the feedback
Creating an electronics package, large size components, being able to alter the feedback once integrated	Small and standalone electronics, wireless or easy to access possibility to modulate feedback	Provide a small standalone package to be integrated, configurable wireless

Concept refinement
Definition and framing

The takeaways and opportunities indicated four major directions to work with:



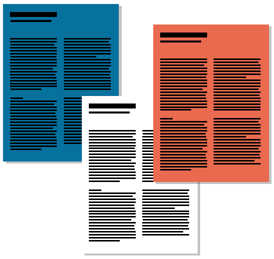


Getting started
Handling

Prototyping haptic feedback is unavoidable, but a speciality even for skilled designers. How can the process be made as simple as possible while still providing tools to create custom feedback?

Implementation
Application

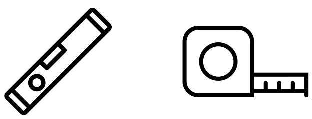
No only is it necessary to know how to create feedback, but also which information can be communicated and how one can modulate it to express a certain character or branding experience.



Getting started

Basic knowledge

A theoretical introduction which should by no means be a complete compendium, but rather act as a basic foundation and a map guiding through the design process.



Implementation

Opportunities

Due to the lack of real-world examples, a set of showcases provides inspiration for the design process including basic principles to build on and work with.

Target group
Definition and framing

The solution is focusing on providing support for designers working with physical objects and without any previous experience in the field of haptic feedback, coding or electronics. However it is also important to provide a concept which does not become obsolete quickly, but can be used throughout the process.

The target group can involve both designers working in a professional environment as well as the application in an educational environment.

To get someone started working in the field as quick as possible it needs to be:

Easy to understand
Intuitive and straightforward to use
Quick to integrate
Flexible in its application
Approachable and familiar

Physical Pete

Pete is an industrial designer with no experience in haptics or coding.

Goal:
Identify the opportunities and evaluate if haptics can be of any advantage in his current project.

Beginner

Ideation

Basic foundation

Coding Carol

Alice is an interaction designer. Coding is part of her daily life, but she only used haptic feedback for a quick prototype before.

Goal:
Get a better understanding of how to utilise haptic feedback and define it to her individual needs.

Soldering Sam

Sam is a design engineer who has gained experience through multiple projects.

Goal:
Create functional prototypes and translate the design into the final product.

Expert

Define Integrate Implement

Detailed insights

Ideation
How to tackle the challenges

Various approaches offered different solution for the pain points. In the end I decided not to go for one but combine multiple in a single ecosystem (highlighted in red)

Opportunity areas

Case studies highlighting how haptic feedback can be used and which advantages they offer.

Abstract objects

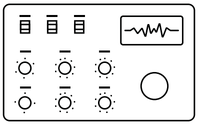
Utilising abstract product examples or archetypes featuring different haptic feedback examples.

Haptic blocks

Small interactive samples, illustrating certain aspects of haptic feedback such as different characteristics or technologies.

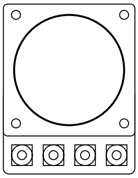
Creative kit

A set of cards or similar, helping inspire the implementation and usage of haptic feedback.



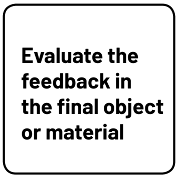
Toolkit

A toolkit which lets you design and play haptic feedback. This could be physical, digital or a combination.



Simulators

A set of simulator which highlight advantages and opportunities.



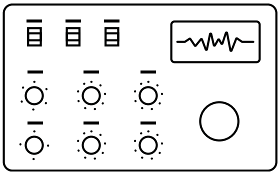
Design principles

Design principles to follow while working with haptic feedback - do's and dont's of the process.

Knowledge

A compendium of basic knowledge one needs to have to get started.

Final direction
Concept definition

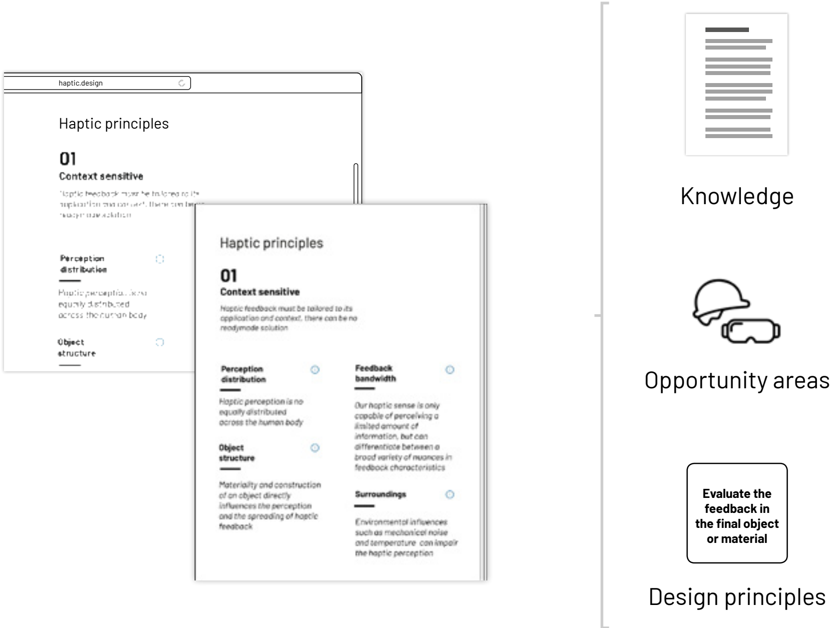


Prototyping toolkit

For designers who want to **integrate** haptic feedback into an object **without having to acquire expert knowledge.**

The final concept direction combines multiple concept ideas into two parts:

A toolkit to support the designer in driving actuators, modulate feedback and integrate it into prototypes, without requiring any expertise in coding or electronics...



Knowledge base

For designers who want to **start working** with haptic feedback and **take full advantage without investing days** in research.

... and a knowledge base providing condensed and easy to understand background information, opportunity areas showcasing capabilities, as well as a collection of design principles guiding through the process.

Prototyping toolkit

Toolkit
Definition

It is unavoidable to feel haptic feedback during the creation process for multiple reasons:

One needs to be able to evaluate the feedback to create good results.

As every object, actuator and interaction differs, haptic feedback needs to be tailored to its application.

Showcasing possibilities is only possible through physical examples.

The sooner prototyping takes place, the easier it becomes to take actions to successfully implement it into the object.

On the following pages, a sample study is shown, highlighting the steps where a toolkit comes into play.


STIHL

Step one
Test & Experience

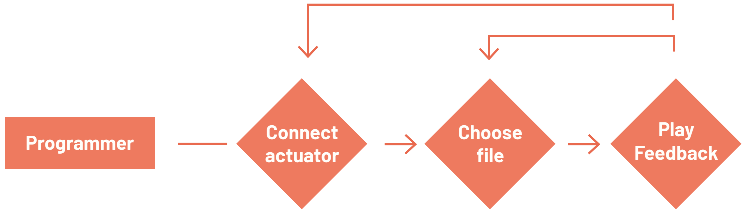
Acquire a feeling for the characteristics and possibilities of the actuators. Starting with haptic presets and rudimentary modulation.

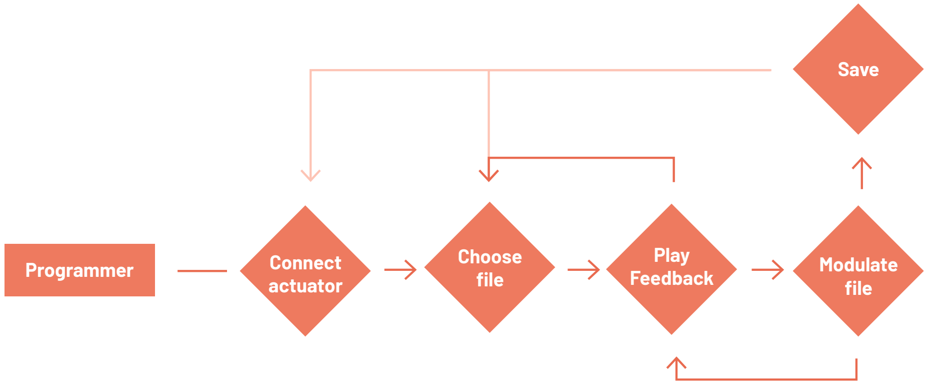
Step two
Modulate, Integrate & Evaluate

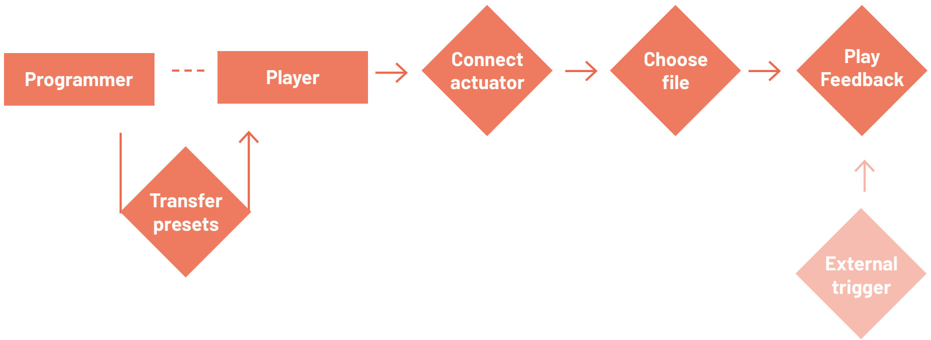
Integrate the actuator in the physical object to evaluate the feedback and identify the right actuator. In the best case, the modulation can take place without modifying the prototype to allow quick iterations.

Step three
Implement

Create a standalone prototype to provide the most immersive experience. The feedback is triggered through an internal sensory system or a wireless connection.


Programmer
Connect actuator
Choose file
Play Feedback


Save
Programmer
Connect actuator
Choose file
Play Feedback
Modulate file


Programmer
Player
Connect actuator
Choose file
Play Feedback
Transfer presets
External trigger

Case study
@ Designpartners

Designpartners is a design consultancy based in Dublin, Ireland. For an internal project, they utilised haptic feedback integrated into a glove to guide the user while riding a bike.
What made this project especially interesting was that they used physical prototyping from an early stage and throughout multiple user tests.

I had the chance to talk with a design engineer involved in the project about my concept ideas and how the process can be improved.

For the prototype, they made use of an Arduino and a LRA, connected to a TDK DRV2605 driver.

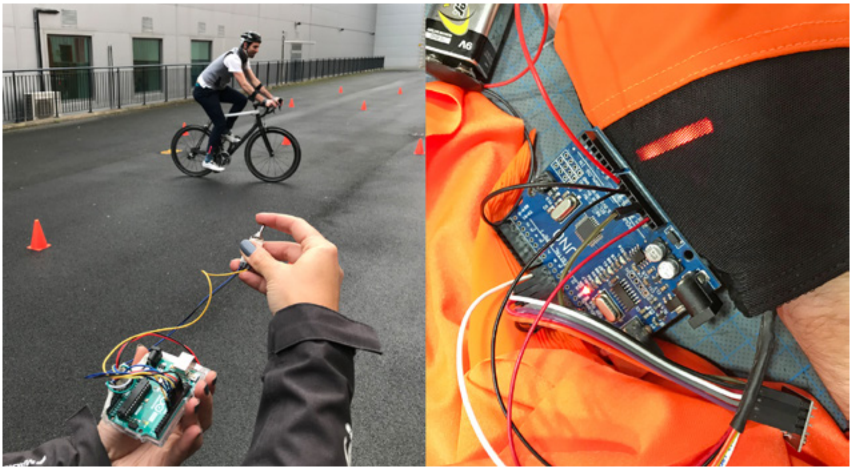
The optimal spot was evaluated over the course of several prototype iterations by altering the placement on the body.

Different actuators were tested, as well as different fastening methods and materials, which had a great impact on the feedback characteristic and impact.

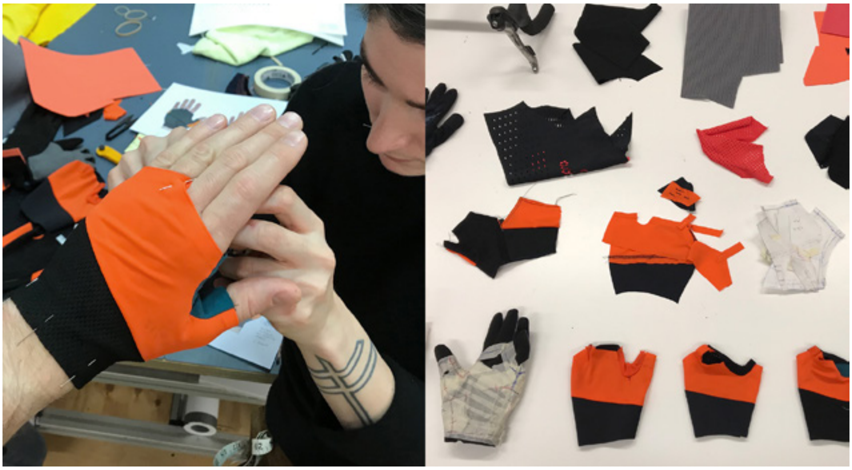
Again, the use case emphasised the highly iterative process and the importance of testing and evaluating the feedback in the final context and right from the beginning.

"[...] we distinguished each signal by testing various sequences, intensities and frequencies on various haptic motors.

The primary navigational signals simulate rumble strips on roads to naturally direct users to upcoming turns, whereas incoming digital messages are shorter, sharper sequences, clearly differentiating navigation from notification" [28]



Triggering the feedback wirelessly through an arduino



Prototyping with the final material

Requirements
Defining the functionality

Hardware
Standalone

A standalone tool allows to integrate and evaluate the feedback without having to rely on a constant [cable-] connection to the computer.

Hardware & Software
Complexity

Most designers are not well trained in working with electronics, code or haptics. The number of actuators to choose from, ways to drive, and parameters to modulate results in a big hurdle one needs to overcome in order to get started.

Hardware
Size

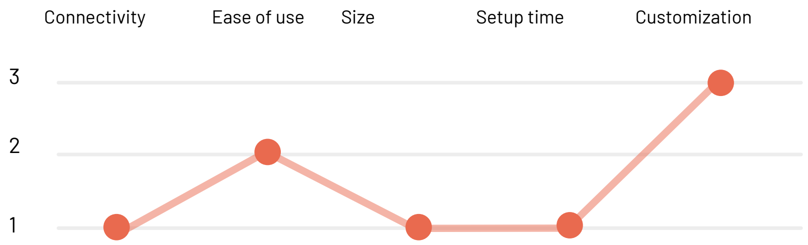
Implementing actuators in the physical objects is crucial. The smaller the electronics, the easier it becomes to create live like simulations of object interactions.

Feedback
Customization

Presets of various haptic sensation are a great way to get started, but very quickly the need for customization arises when creating tailored experiences.

Hardware & Software
Setup time

Creating a prototype from scratch, soldering cables and sourcing components can be difficult and time-consuming. The easier and quicker this takes place, the lower the bar becomes to include it in a project.



To compare existing solutions I created a ranking system, including the listed aspects [the higher score, the better].

Connectivity: Can all functionality be accessed through a wireless connection?

Ease of use: Do you need knowledge in coding or electronics to use it?

Size: How big are the components?

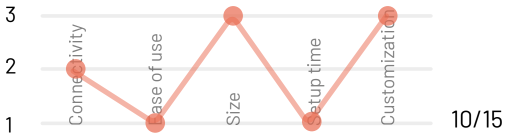
Setup time: How much time does it need to set up the prototype?

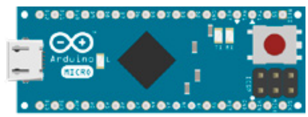
Customization: Can you customize the feedback? Can you attach different types of actuators?

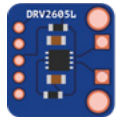
Arduino Micro + Adafruit DRV2605L

Microcontroller

- 120 Presets for vibration motors (ERM/LRA)
- Requires coding and electronics knowledge
- Complex process for custom feedback
- High customisability (wireless/ cable/ battery)



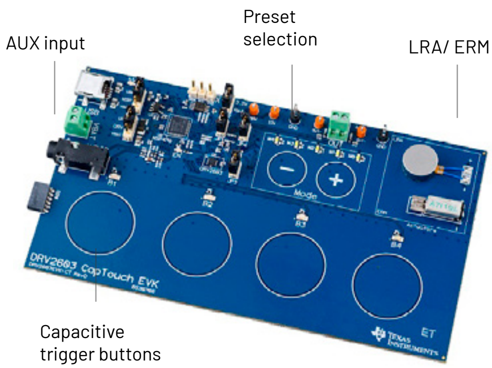


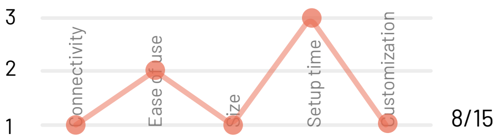


TDK DRV2603 Evaluation Board

Evaluation module

- 120 Presets for vibration motors (ERM/LRA)
- No visual feedback
- Complex process for custom feedback

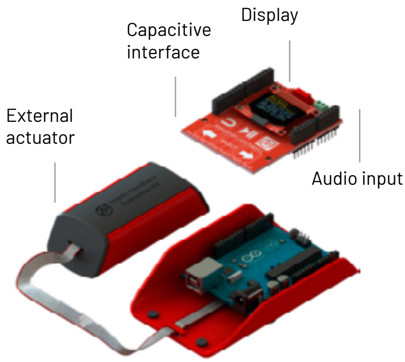


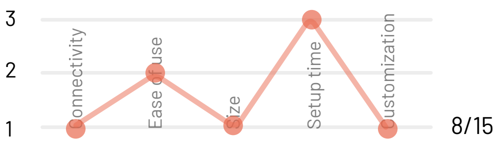


TDK DRV2603 Evaluation Board

Evaluation module

- 120 Presets for vibration motors (ERM/LRA)
- Requires coding and electronics knowledge
- Complex process for custom feedback

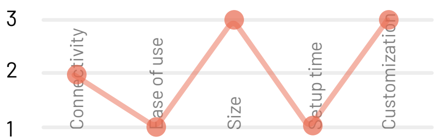




Teensy 3.6 + Adafruit PAM8302A

Microcontroller

- Audio amplifier driven by a microcontroller
- Requires custom or preset sound-files
- Standalone (SD card) or real-time (Audio in) playback



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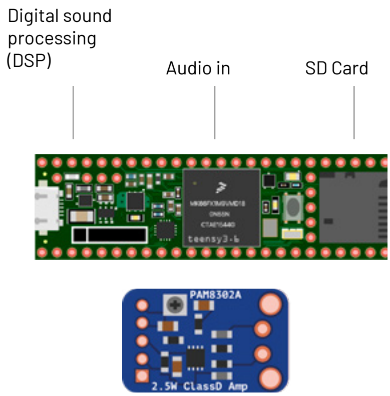
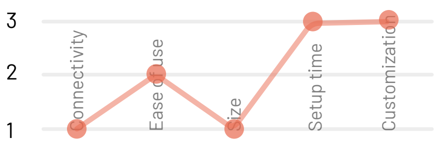


Techtile Toolkit

Modular audio system

- Simple audio amplifier
- Requires external audio source
- Modular system including microphone, speaker and actuators



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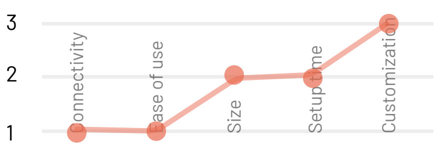
Lofelt evaluation kit

Evaluation module

- Audio amplifier and DSP
- Modulation of feedback happens during file creation
- Requires external audio source



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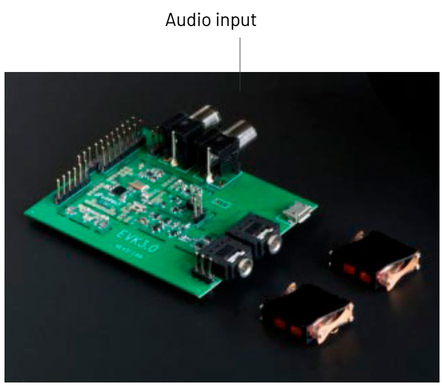


Toolkit
Recap and next steps

Although there are some toolkits available on the market, they come with a significant drawback in size and customisability, which made them hardly usable in the defined design process.

The approach of prototyping ideas, gather findings and implement them into the next iteration resulted in quick and tangible results throughout the first part of this thesis. In the next step, I took the same approach and created a first functional mockup of how a toolset could look and feel like.

At this stage, I found the usage of sound to drive the actuator particularly interesting due to the ease of use as illustrated before.

Takeaways

Findings throughout the research phase.

Prototype

Create quick but functional prototypes of the toolkit.

Integration

Use the toolkit in case studies.

Evaluation

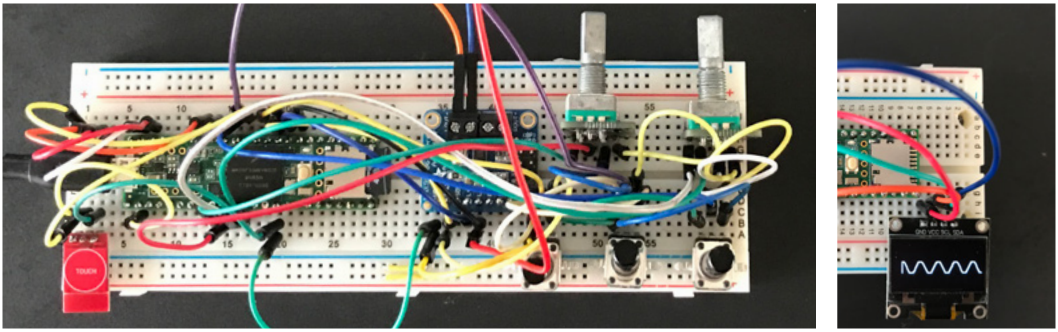
Analyse functionality and usability of the case studies and implement improvements in the next generation.

Toolkit prototyping
Version 1.0

Microcontroller
Teensy 3.6

Audio amplifier
Adafruit 3.7W

Mode/ pattern selection



Play button
Capacitive button

Sound modulation

1,3' OLED display

The first iteration of the toolkit was breadboard based. The main benefit of this prototype compared to any other available solution was to be able to alter the feedback directly through the potentiometers and have a visual representation of the soundwave in real-time.

Working with this setup was great to test features such as different modes, but the breadboard layout made the prototype fragile and prone to fail when tested in the field.

Illustrated on the right-hand side are the three different modes to create feedback.

Mode_01:
Playback sound from PC

Play file → **Set volume** → **Set low pass** → **Set resonance**

Play file
Plays file from USB IN

Set volume
Sets volume of the output [0-1]

Set low pass
Cuts off frequencies above set border [0-1000Hz]

Set resonance
Amplifies frequencies below set border [0-5]

↳ **Drive actuator** → **Visualise**

Drive actuator
Actuator is driven by the amplified sound

Visualise
Visualised audio output though the display

Mode_02:
Play a preset sound

Play file → **Set volume** → **Set repetition** → **Set low pass**

Play file
Plays file from SD card

Set volume
Sets volume of the output [0-1]

Set repetition
Sets repetition of the playback [1-10]

Set low pass
Remove frequencies above threshold [0-1000Hz]

↳ **Set resonance** → **Set pattern** → **Drive actuator** → **Visualise**

Set resonance
Amplifies frequencies below set border [0-5]

Set pattern
Repeats playback with a predefined pattern and varying volume

Drive actuator
Actuator is driven by the amplified sound

Visualise
Visualised audio output though the display

Mode_03:
Generate waveform

Play sound → **Set waveform** → **Set frequency** → **Set repetition**

Play sound
Starts generator

Set waveform
Set audio waveform [sin, square, sawtooth]

Set frequency
Sets frequency of the soundwave [1-1000]

Set repetition
Sets repetition of the playback [1-10]

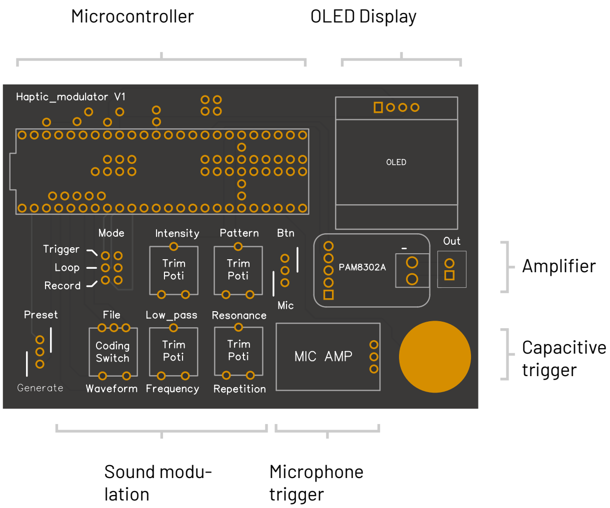
↳ **Set pattern** → **Drive actuator** → **Visualise**

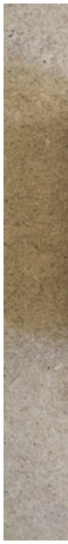
Set pattern
Repeats playback with a predefined pattern and varying volume

Drive actuator
Actuator is driven by the amplified sound

Visualise
Visualised audio output though the display

Toolkit prototyping
Version 1.5



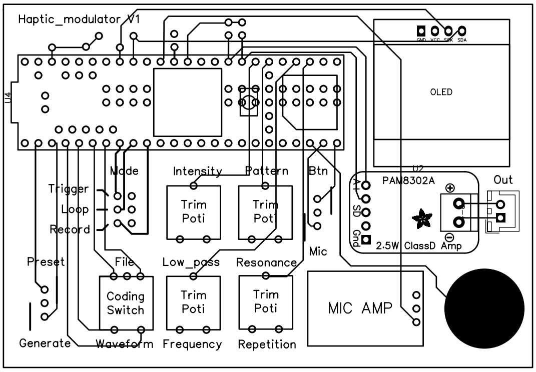


The first big iteration was moving from the breadboard into a custom PCB layout. In addition to the previous functions, I included rhythmical presets, which can be combined with any of the cues to easily create patterns.

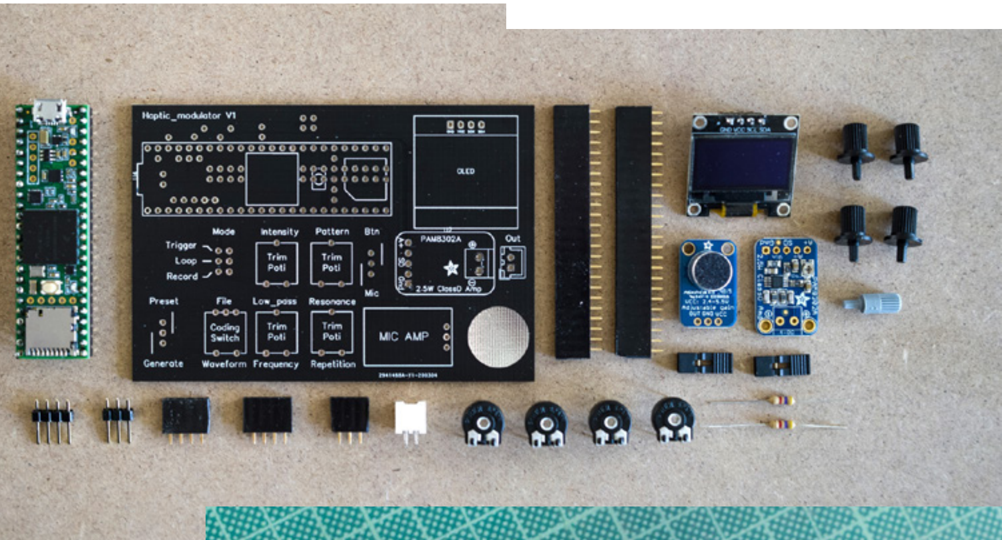
It also features a microphone input to allow recording of a feedback or rhythm.

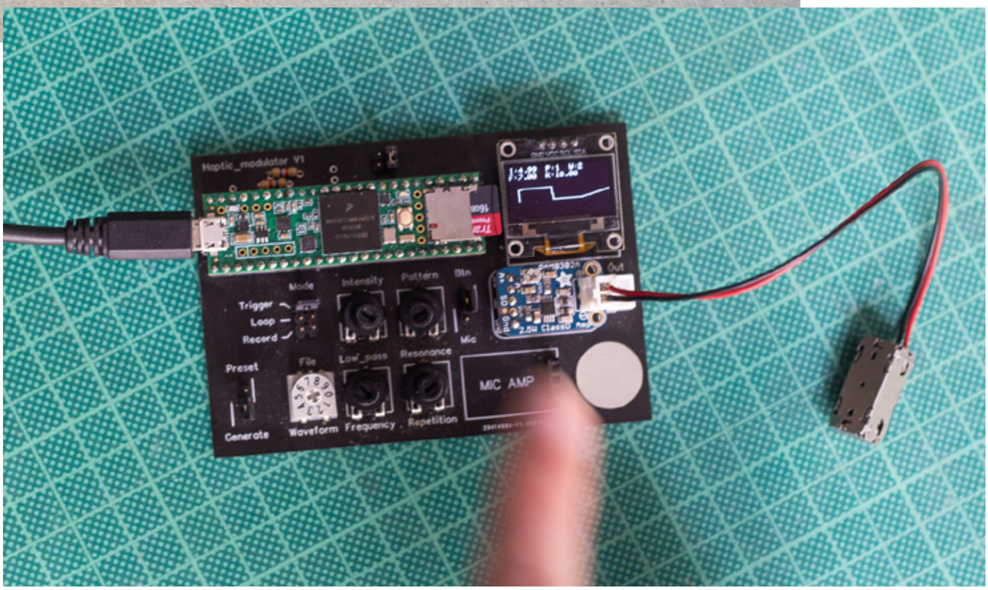
Although I had previous experience in the field of electronics, creating a complex prototype like this was both a challenge and a great opportunity to dive deeper into the topic.

Raw PCB layout

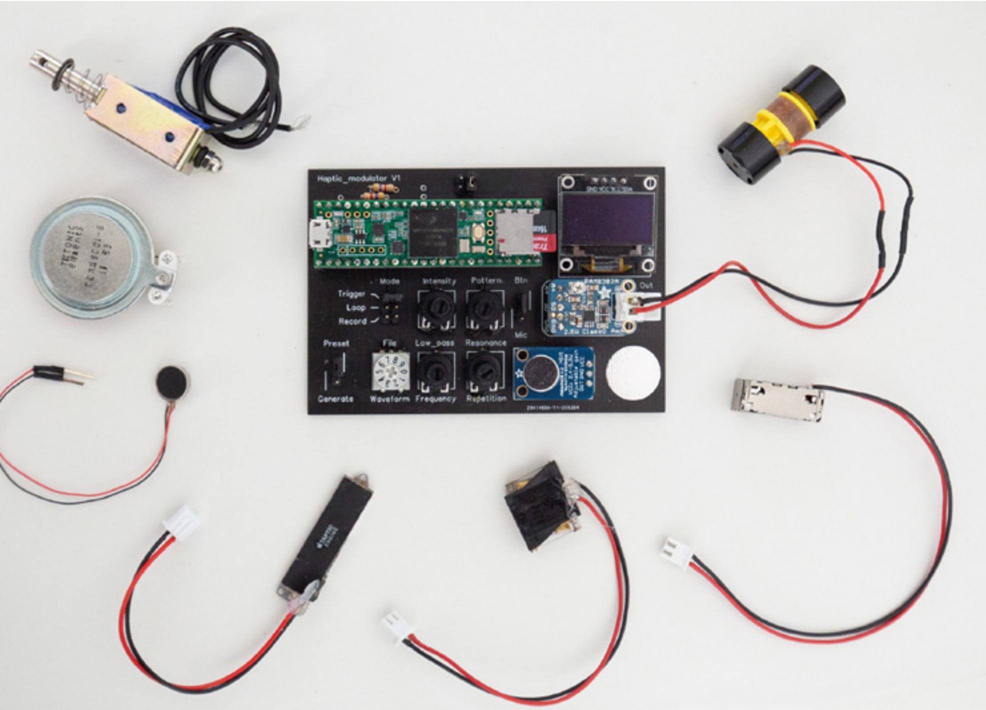


Components before soldering

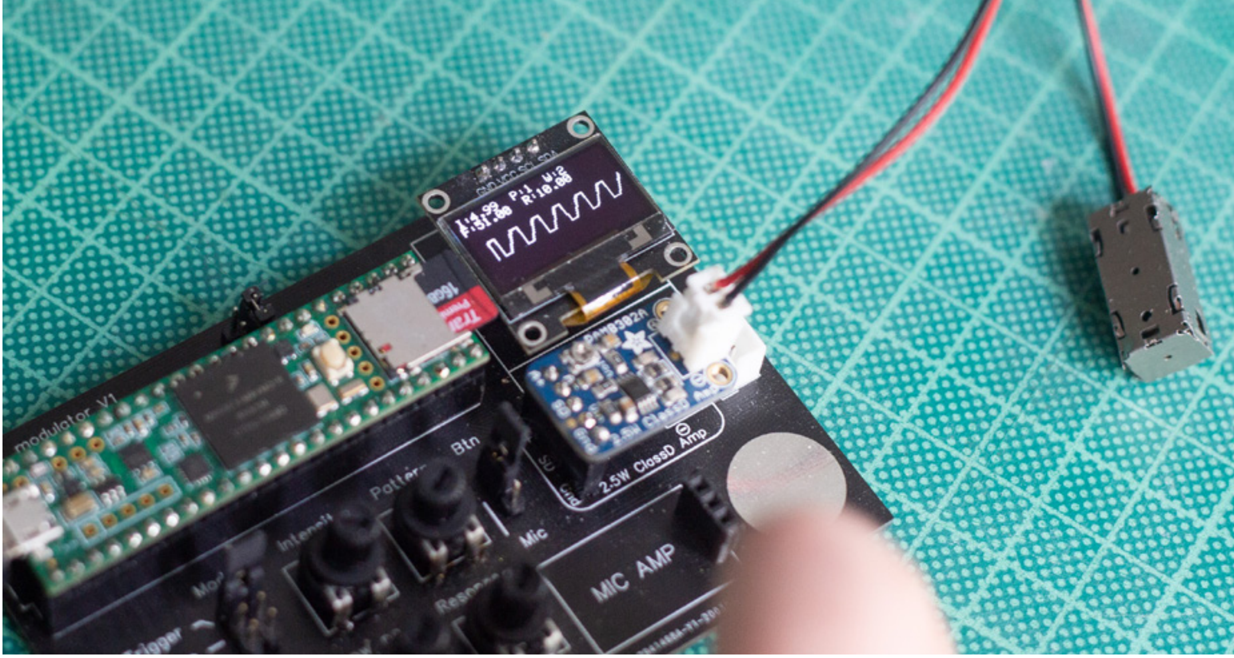




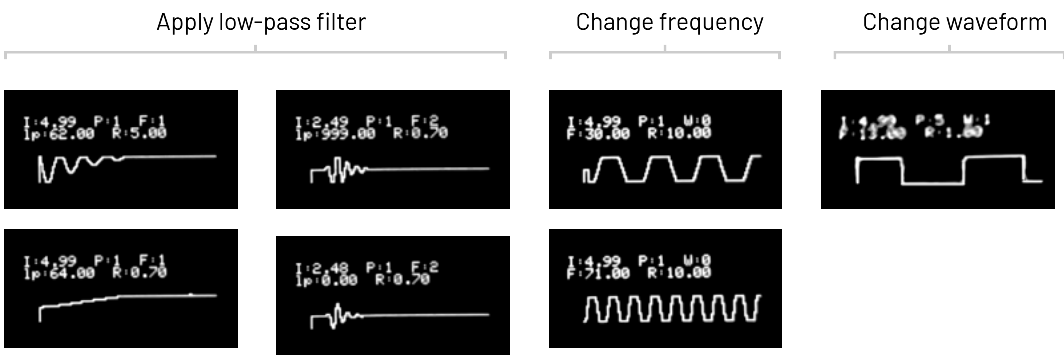
Final board with an attached actuator



Although a large variety of actuators can be driven with the toolkit, using sound also came with the downside that it is not possible to reach the same level as crispness with LRAs and ERMs compared to using a dedicated driver circuit [see p.54].
The visuals were a great help and widely appreciated. As it is only an approximation, at the same time it also lead to confusion as different values lead to different results based on the actuator type.



Parameter visualisation



Although the displayed wave is not a perfect representation of the file being played, it gives the user a good feeling of how different parameters affect the feedback.

Toolkit recap
Keep and tweak

Working with sound and physical input is great for the exploration of haptics.
At this stage, it especially became apparent how powerful it is able to modulate the feedback freely with an immediate result.

Besides this, the current setup also had some limitations:

- The programming and playing unit was combined into a single device..
- .. which required physical access to modulate the feedback.
- The number of knobs and parameters to choose from was already quite high.
- Certain characteristics such as very crisp haptic cues could not be achieved with sound and LRAs/ ERMs

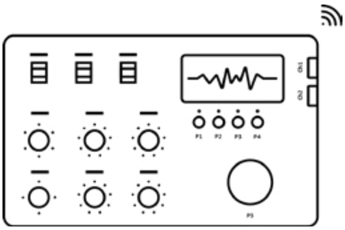
The first change after this evaluation, was to change the driving circuit, switching to a TDK DRV2605 driver instead of using sound to avoid restrictions during the modulation and create consistent results.
A second step involved splitting the toolkit into two devices: The programmer and the satellite.

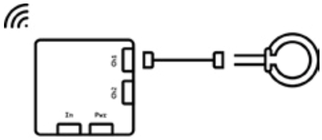
Taking this step also led to the question of the right format of the tool-kit. Should it be physical, digital or a combination of both?

A hardware solution with physical knobs has the great advantage of staying in the same modality during the modulation, simplifying the cognitive processing during the design process.

We do, on the other hand, also have a powerful device in our pockets in the form of a smartphone, which could be used instead. Using it would also ease the implementation of a sharing functionality and limit the environmental footprint of introducing a new hardware device.

On the following pages, different concepts are illustrating pros and cons.





Programmer

Responsible for creating and modulating feedback. Includes a file management system and connects wirelessly to the satellite.

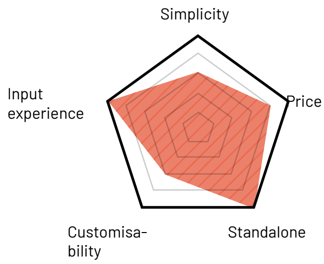
Satellite

Execute the modulated feedback and powers an attached actuator. Can store feedback files internally.

Hardware only

A standalone hardware toolset to design, program and trigger the feedback.

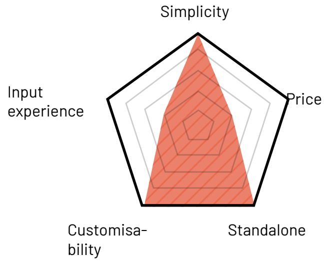
It incorporates wireless communication to the satellite, an internal display as well as input through a physical interface.



Digital only

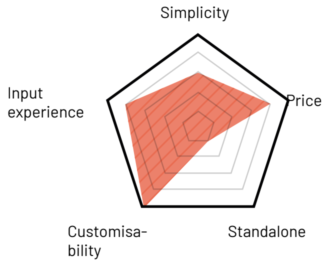
A digital smartphone application.

It visualises the feedback, the programming interface and adds wireless communication with the satellite.



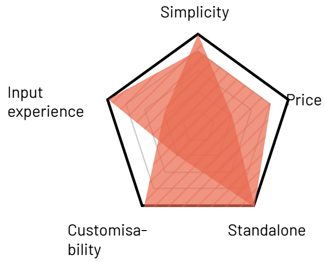
Best of both

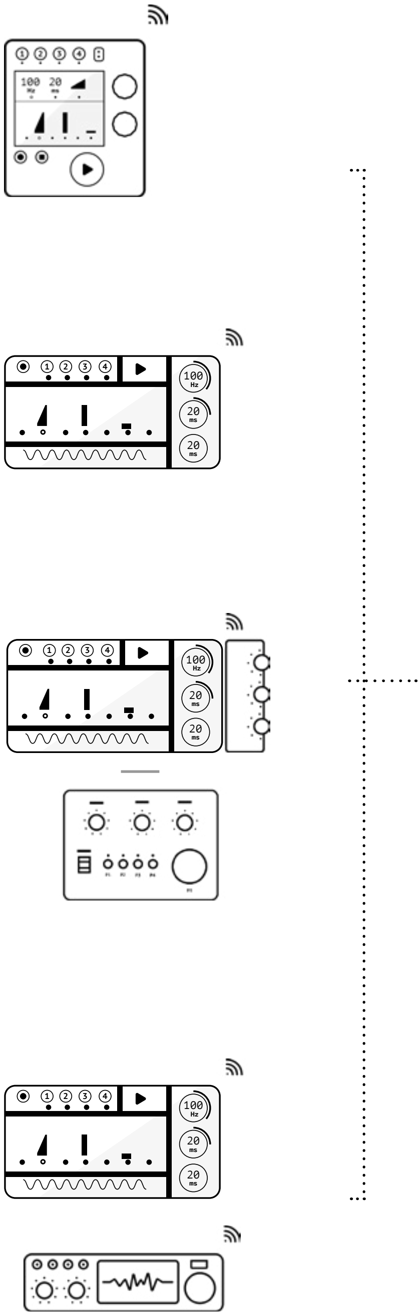
In addition to the smartphone application, a physical accessory [dongle or separate device] adds a tangible user interface.

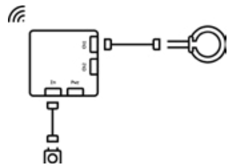


As you need

A standalone hardware toolset with limited functionality to get started. It can be extended by a digital application to access more complex functionality.







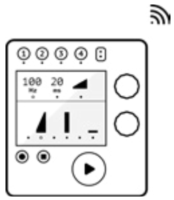
The satellite is able to drive the actuator with the designed feedback. It can be integrated into the prototype and needs to be as small as possible.

It incorporates:
Wireless communication
Internal memory
External trigger input
Actuator output [2 Channel]
Power input

Evaluation
Concept refinement

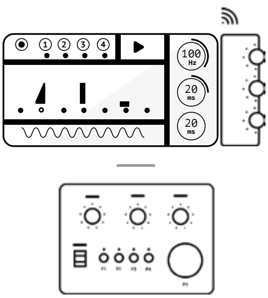
Hardware only

While there is an undeniable advantage in using physical input, a pure hardware solution becomes non-intuitive once a certain level of functionality is reached. Also exchanging feedback with a digital platform and communicating with multiple players becomes complicated.



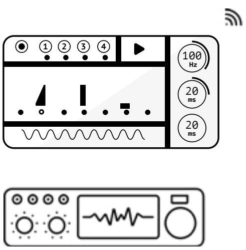
Best of both

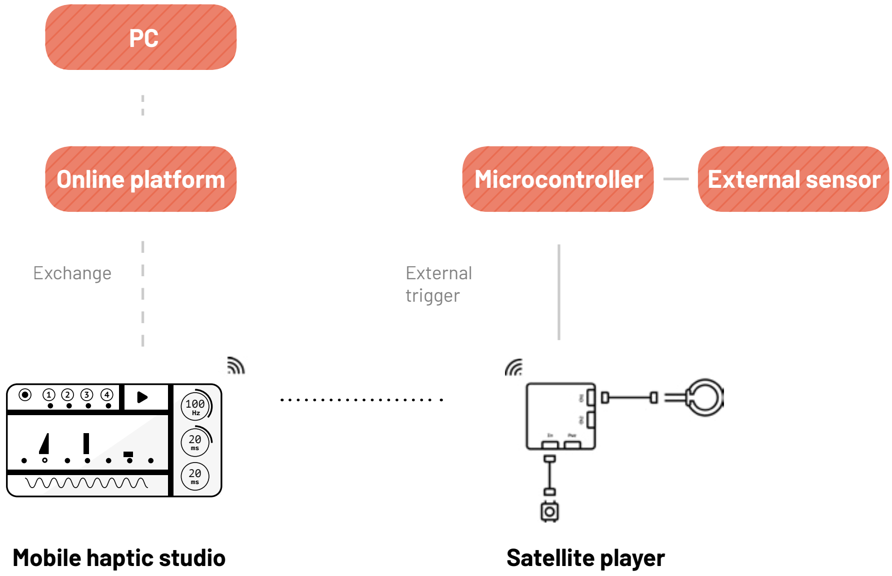
Using the phone as a display only and providing an additional hardware accessory seemed like the right choice in the beginning. While evaluating different scenarios, it became apparent that it makes it rather complicated than adding an advantage. When to use which? Do I bring both devices to a user test?



As you need

While it can be a great help in the beginning, the limited functionality makes the physical device redundant in a lot of applications.
It also has the same challenges as the previous concept.





Digital only

The chosen direction includes the physical satellite player as well as a digital smartphone application. Although the advantage of a tangible interface is not provided, the digital solution can solve all requirements and present the information in a much simpler fashion tailored to the users' needs. The smartphone as a final medium was chosen, as a lot of physical prototyping happens in workshop environments where taking a laptop is challenging. It is also the optimal solution for user tests in any context in- and outdoors.

Validation
Concept feedback

I had the chance to run the concept by some of the users and contact persons I reached out to in the beginning.
The feedback overall was really positive: Especially an easy to use toolkit was something people were really interested in playing with.

Inhouse, Apple

Interaction Designer

» I am not aware of something similar that is available on the market. It can be difficult to create a solution which aims to provide at a very basic functionality, while making sure that it is still of relevance. «

Consultancy, Intuity

Interaction Designer

» A standalone solution which is easy to play and work with would be a great addition. It makes sense to use already available hardware to keep the complexity and price low. «

Consultancy, Above

Creative technologist

» Going digital, in this case is the right way to create a convenient and future proof solution. «

The digital experience

Digital experience
Requirements

To define the functionality for a quite broad user group and applications, I created three different concepts covering a varying amount of functionality.

Explore & play offers a collection of haptic presets one can trigger and only alter in their intensity, repetition, and playing direction.

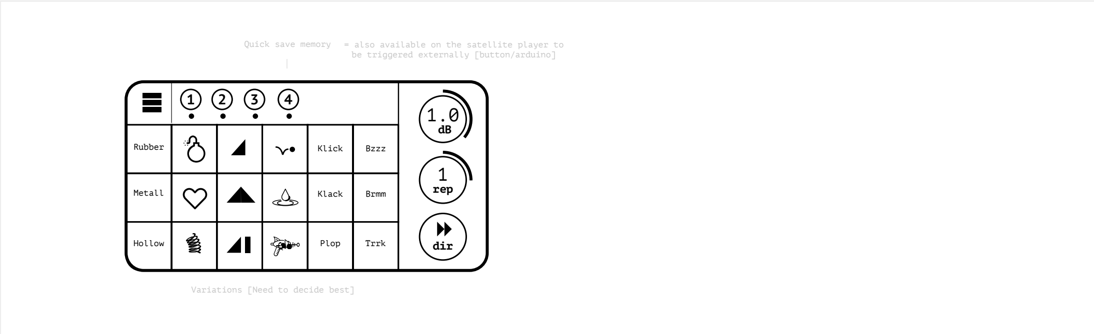
First steps allows the user to create simple patterns by combining a haptic sensation [click or vibration] and a rhythmic pattern.

Full control offers complete customizability of each haptic sensation and the pattern through multiple parameters.

Talking to users, it became clear that even though the first two concepts are straightforward to get started, they quickly become redundant. In the end, I decided to focus on the third concept offering the highest amount of possibilities, but it can help you throughout the whole process.

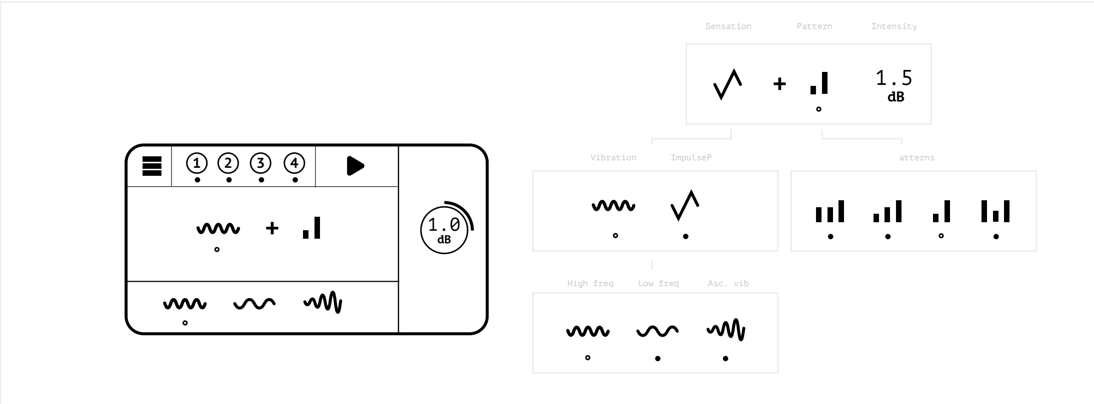
Explore & play

Preset Player



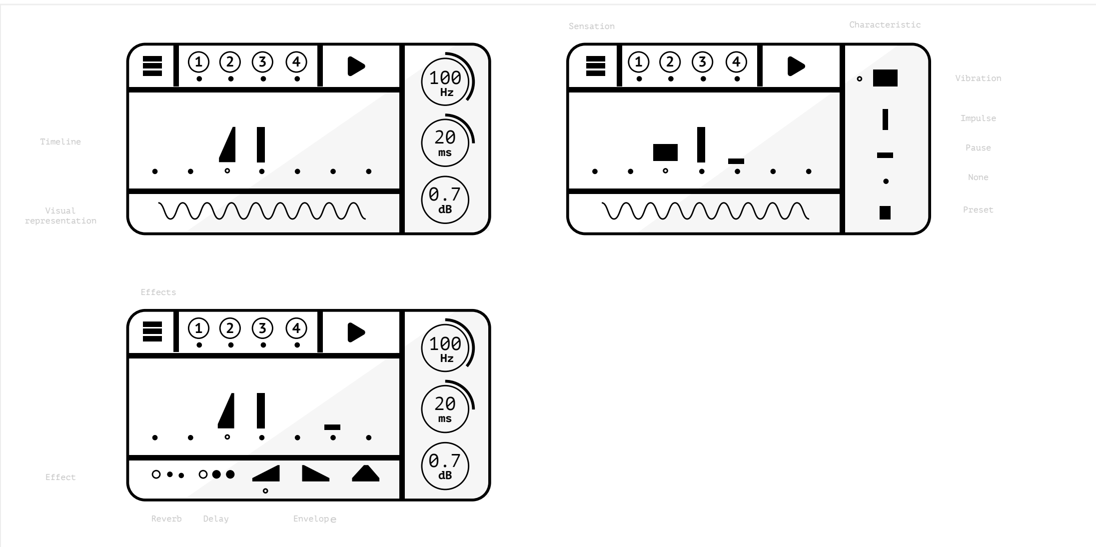
First steps

Simple Player

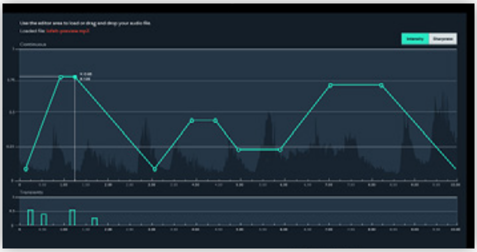


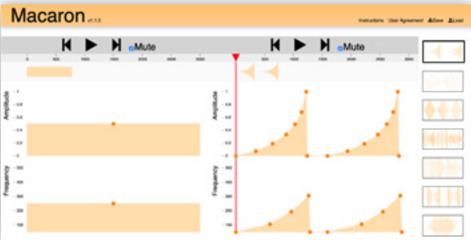
Full control

Pattern creator

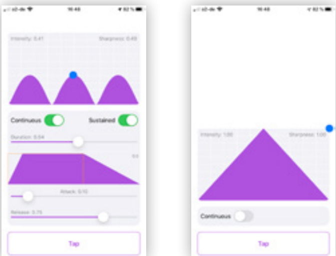


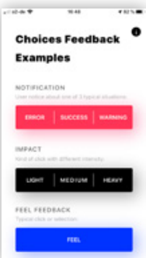
Current software interfaces
Market analysis


Lofelt composer

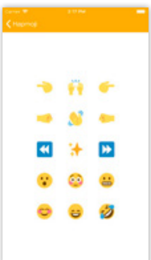


Macaron Editor


Haptic iOS App



TapticMe iOS App

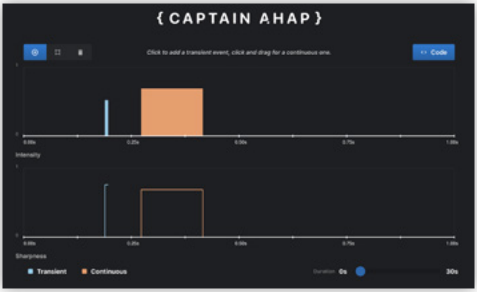

Hapmoji iOS App

Direct curve manipulation

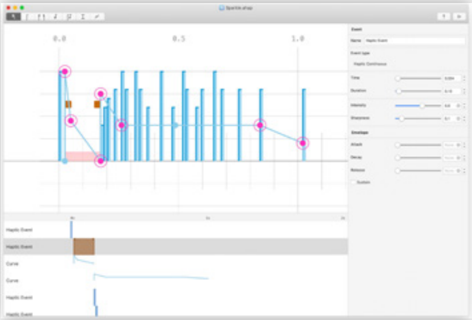
To design the feedback, the user directly manipulates a curve. The horizontal axis indicates time, while the vertical one shows intensity and frequency. Macaron editor allows the highest customisation by adding any number of control points to the curve, which also makes it rather complex to use.

Preset player

Both applications are featuring a collection of different haptic sensations, which cannot be adjusted.



Captain AHAP


Haptrix

Direct Block manipulation

Instead of adjusting a curve, most of the manipulation is done through placing and scaling blocks of two types [transient/ klicks or continuous/ vibrations]. The horizontal axis indicates time, the vertical intensity and frequency [sharpness]. Haptrix allows overlaying the haptic blocks with a second envelope curve to define the feedback further.
Both of them export an .AHAP text file used by the Apple iOS.

This output could potentially be converted into another format which can be interpreted with a TDK haptic driver.

WaveformGenerator iOS App

SoundGenerator iOS App

MutiTone iOS App

Value manipulation

The feedback is customised by adjusting values through sliders, dials or direct character input. The interaction is really minimalistic when only a few parameters can be adjusted [WaveformGenerator, SoundGenerator] but becomes very complex with an increasing number.

Haptic Studio

Input modalities
Exploring interactions

Which is the easiest and most comfortable interaction to design haptic feedback?

Usually, textural programming is used to define haptic feedback in professional environments. Lately, more visual-based applications appeared on the market where the feedback can be defined through adjusting diagrams and curves.

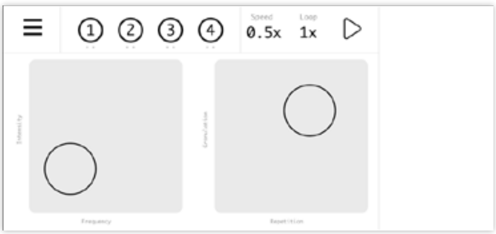
What could be a more intuitive way?

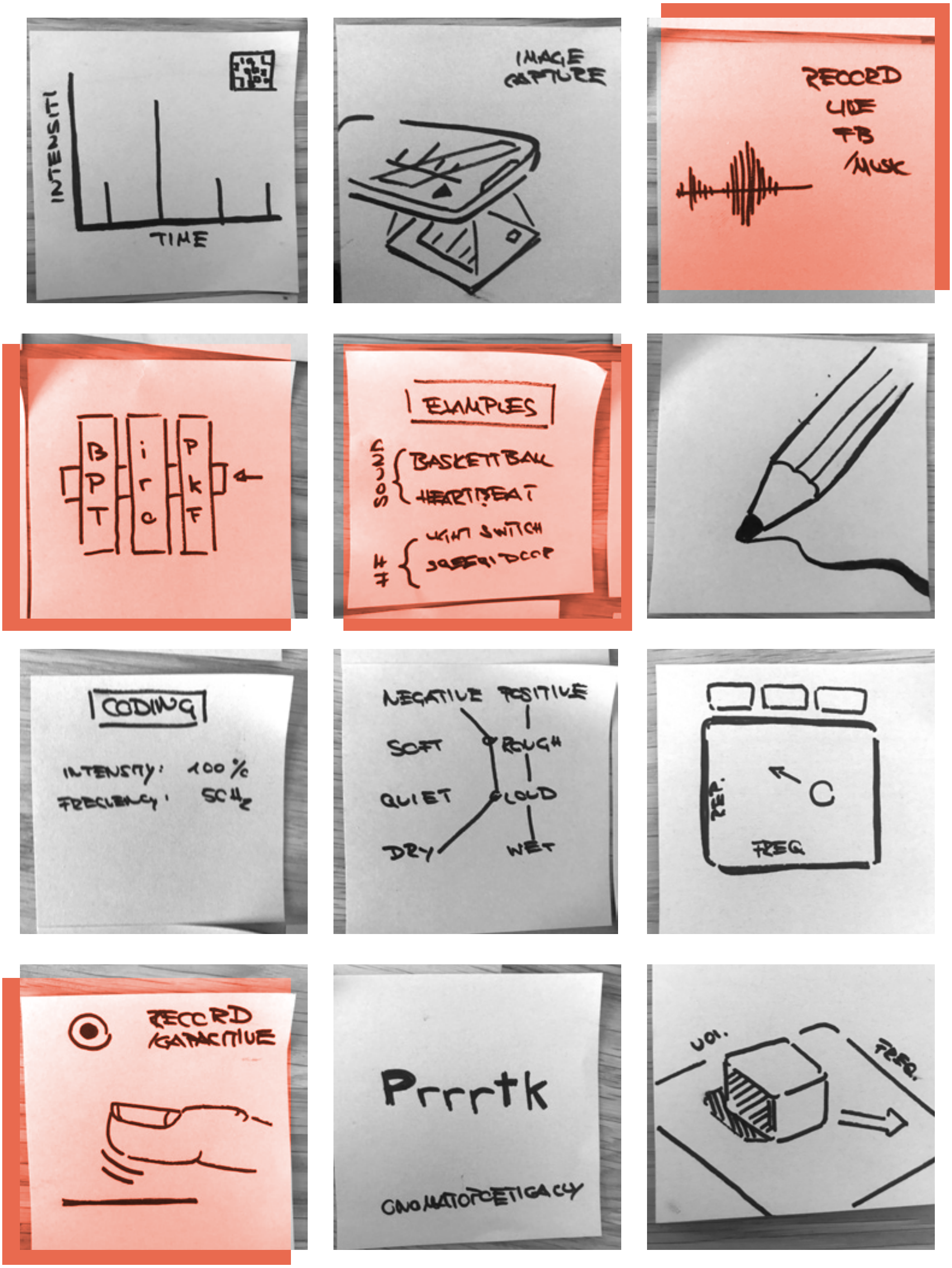
We mostly rely on describing haptic feedback by verbally expressing the accompanying sound (Onomatopoeic). One could use a direct recording of this as the input. A more exciting variation would be to combine the letters individually like writing text—[Prrtk - A vibration followed by a klick].

Also using haptic as the input modality is very intuitive. We could use our fingers to tab-record the rhythm and/or intensity of the feedback.

Referencing haptic feedback comes naturally to us as well. By describing objects like pressing a light switch or feeling a heartbeat, we can easily communicate a specific characteristic.

While all of these methods have exciting aspects, they would have to be tweaked afterwards to fine-tune the feedback. There is also big room left for interpretation which will result in confusion along the way.

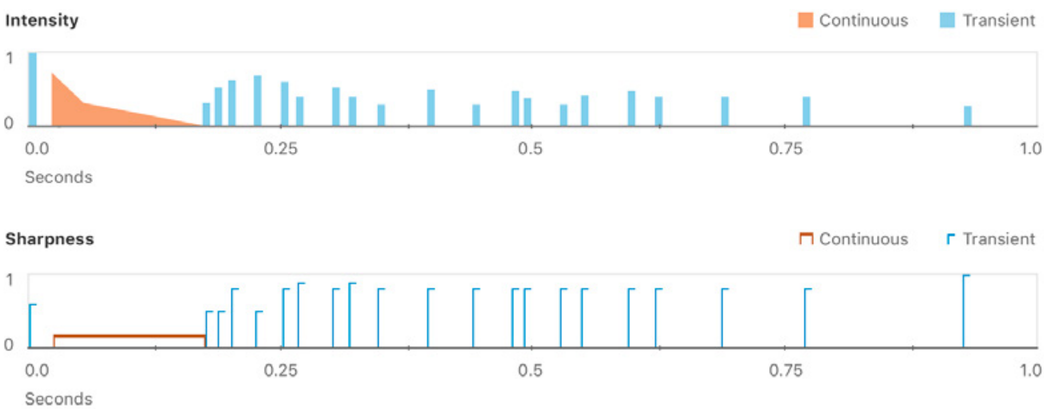




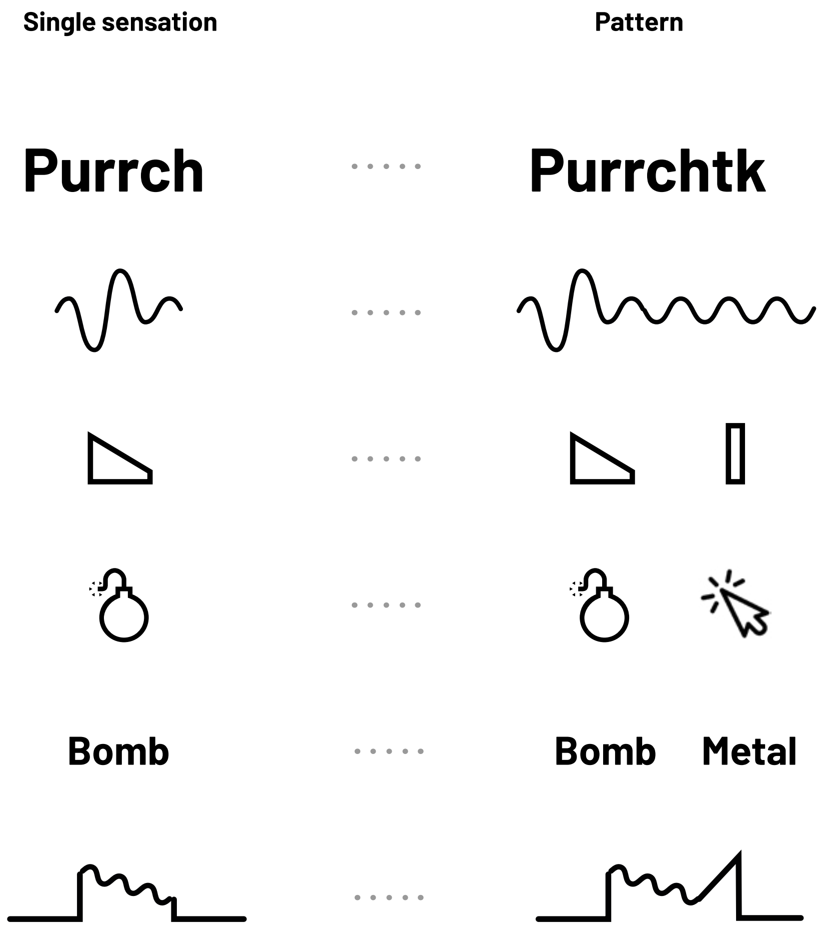
Exploration of different input modalities to define the feedback [Textural, visual, auditory, haptic]

Visual style
Haptic patterns

Although the feedback may consist of only a single sensation, the majority of applications require a combination of multiple ones (a feedback pattern).
Some visual styles work better for describing a single sensation while some work better when used in patterns and vice versa. It became clear that there has to be a compromise made between functionality and intuition. Using characters, for example, was highly appreciated in the feedback, but it quickly becomes limiting when trying to fine-tune it.
The waveform is the most accurate representation followed by the geometric shapes and therefore chosen to continue with.



Haptic feedback visualisation by Apple

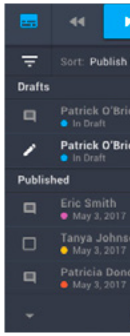

Single sensation
Pattern
Purrch
Purrchtk
Bomb
Bomb
Metal

Parameters
Keep and tweak

The amount of parameters available to the users to adjust, has a direct effect on the complexity of the application.
At the same time, limiting the possibilities has an impact on the number of use cases where it can be applied to.
Fortunately, most applications do not demand complex patterns, and in general haptic feedback works best when kept as simple as possible.
Shown to the right are the chosen parameters and effects which are needed to provide a basic functionality when modulating haptic feedback.


Click
Vibration
Pause
Pattern
Intensity
Intensity
Duration
Duration
Re-arrange
Reverb
Reverb
Ramp
[Intensity level]
Granularity
Delay
Delay
Pulse
Encapsulate files
Set frequency
Set frequency
Ramp
[Frequency]
Ch 1
Ch 2
Panning
Advanced features
Advanced features

Visual expression
Moodboard

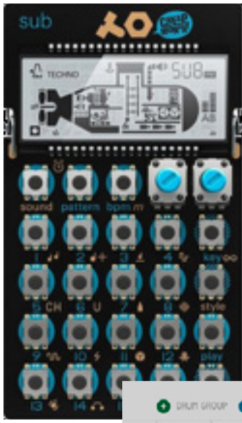


The overall appearance of both the UI and the toolkit should be a mixture of three aspects:

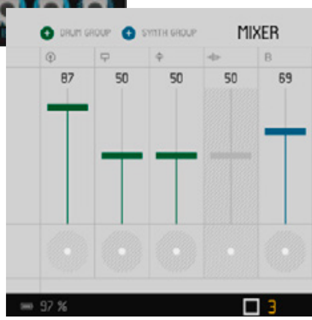
Being a prototyping tool, it needs to express a certain degree of rawness, so that the user is encouraged to experiment with it. This is achieved by using simplified visualisations, flat style and making use of white space.

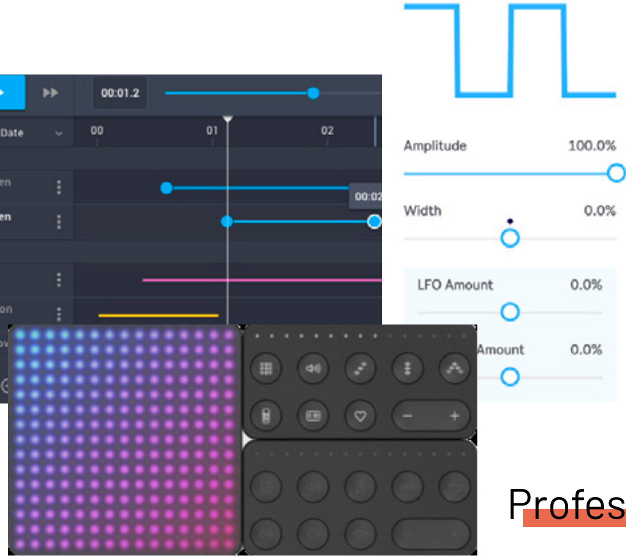
Electronics prototyping can be intimidating to people without any experience in the field. The appearance, therefore, needs to be approachable by making use of colour and soft shapes.

In the end, it is also meant to be used in a professional work environment, hence has to express its capabilities.

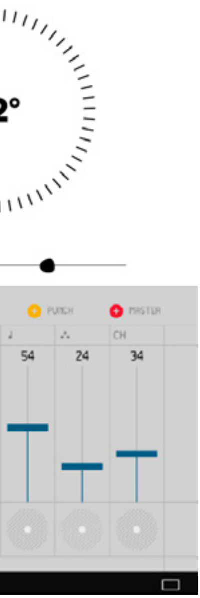


Raw

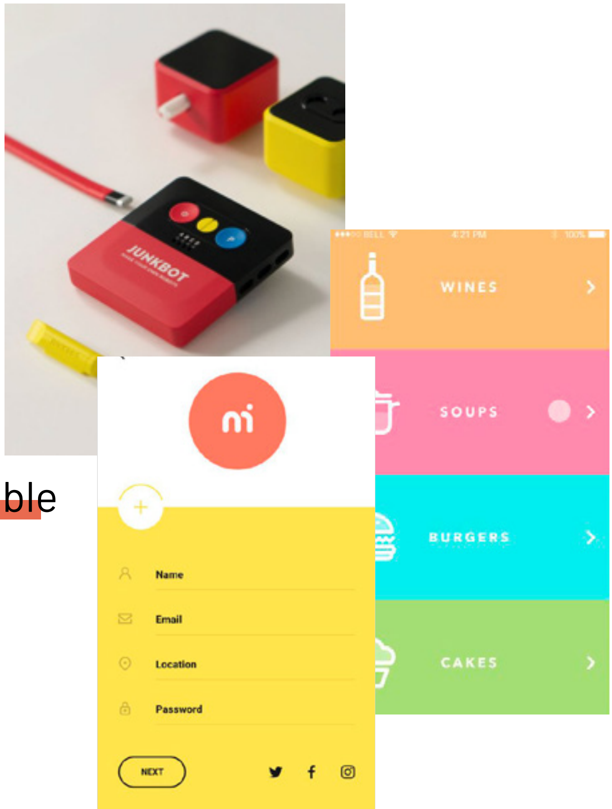




Professional



Approachable



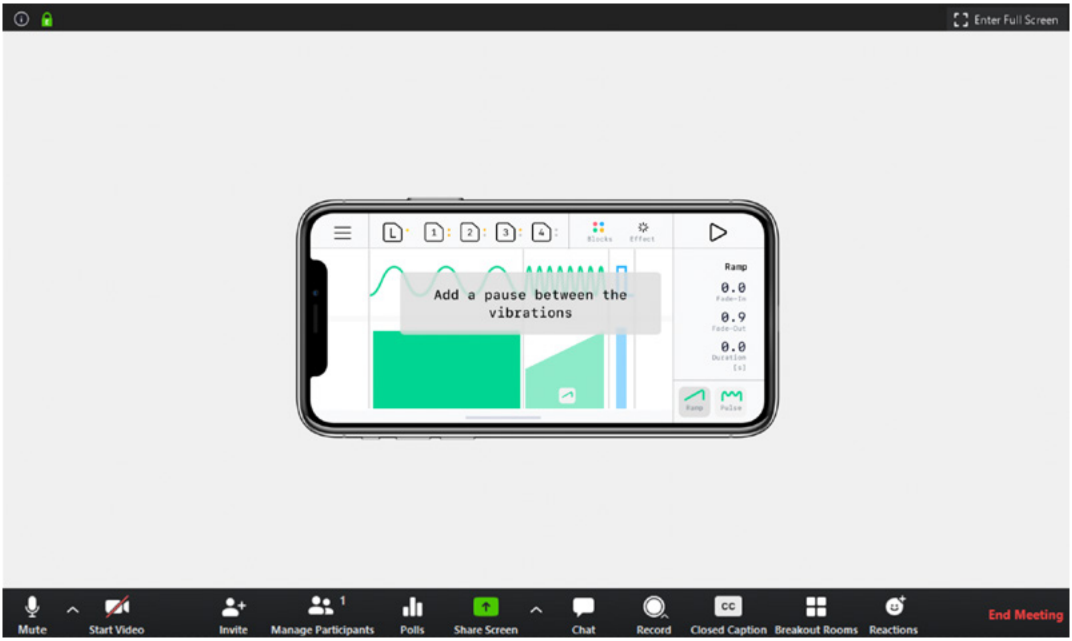
Wireframing and evaluating
Sketching a digital experience

Having spent months working on a very detailed level, made it difficult to create something which is both approachable and offers the right level of possibilities.

I had the chance to get feedback from multiple users, both experts in the field, as well as complete beginners. Due to the pandemic, unfortunately, those evaluations could only happen digitally.

For these user test, I created interactive prototypes in Figma and added small tasks to both verify the interaction and avoid having to create a fully functioning application.


Vibration
0.3
0.4
0.3
Vibration
0.3
0.9
0.1
Vibration
0.5
0.9
0.3
Ramp
0.5
0.9
0.3


Enter Full Screen
Add a pause between the vibrations
Ramp
0.0
0.9
0.0
Mute
Start Video
Invite
Manage Participants
Polls
Share Screen
Chat
Record
Closed Caption
Breakout Rooms
Reactions
End Meeting

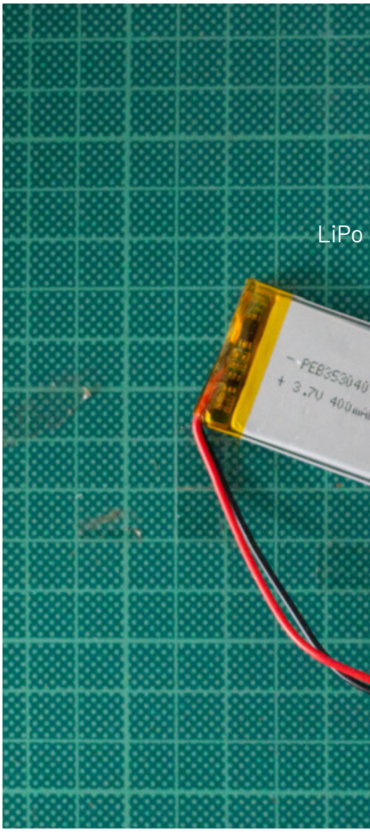
Physical evaluation
Wizard of OZ prototyping

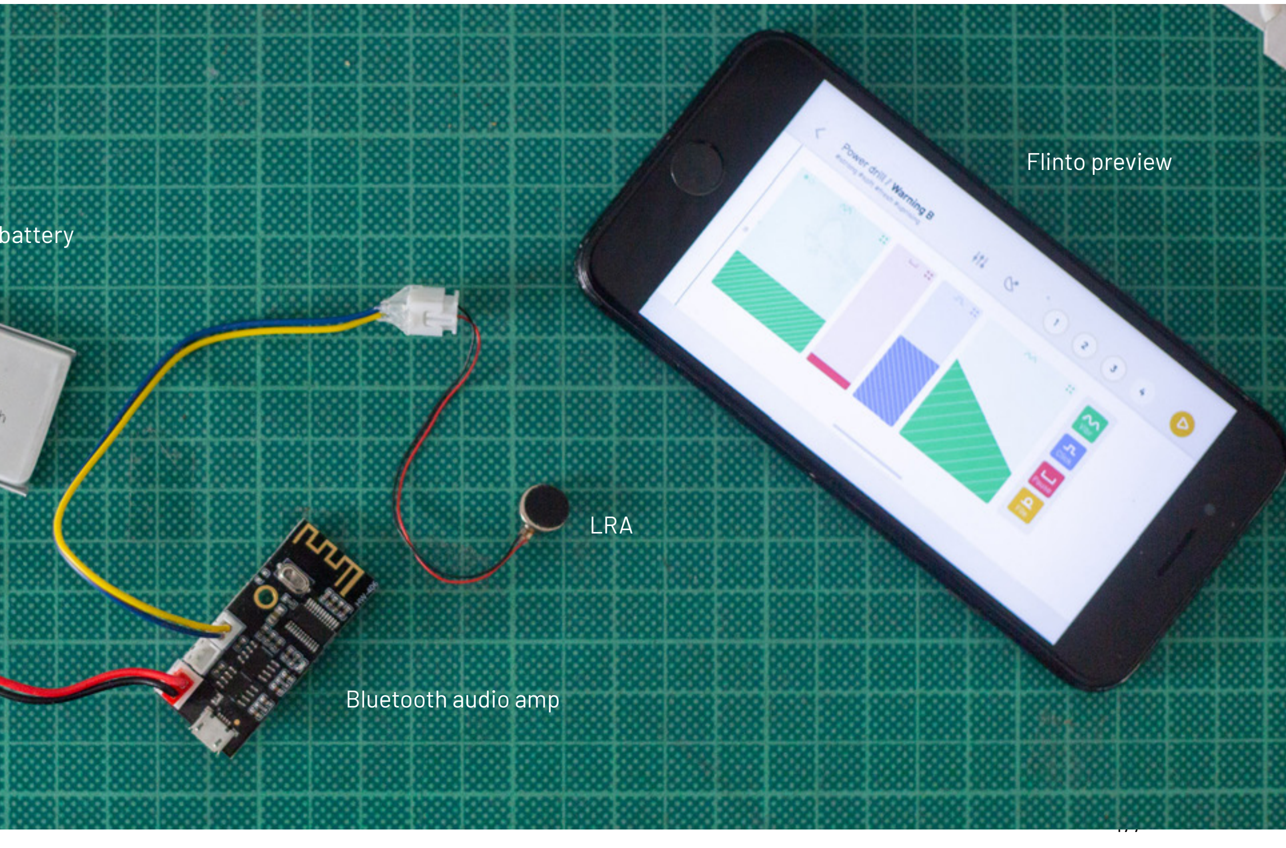
Prototyping the application on a physical level seemed to be an unachievable goal from the beginning. Creating both an interactive app as well as a functional PCB powering the actuator and making them communicate wirelessly was not something that could easily be achieved in the amount of time and scope of this thesis.

Fortunately, while working with micro-interaction on the UI, I came across Flinto. This application not only allows you to create visual transition but also adds sound to screen interactions.

By connecting my prototype via Bluetooth to an audio amplifier, I was able to connect and drive a small haptic actuator.

While this is only a very rudimental experience, it was definitely enough to create a wizard-of-OZ type MVP (Minimum Viable Product).

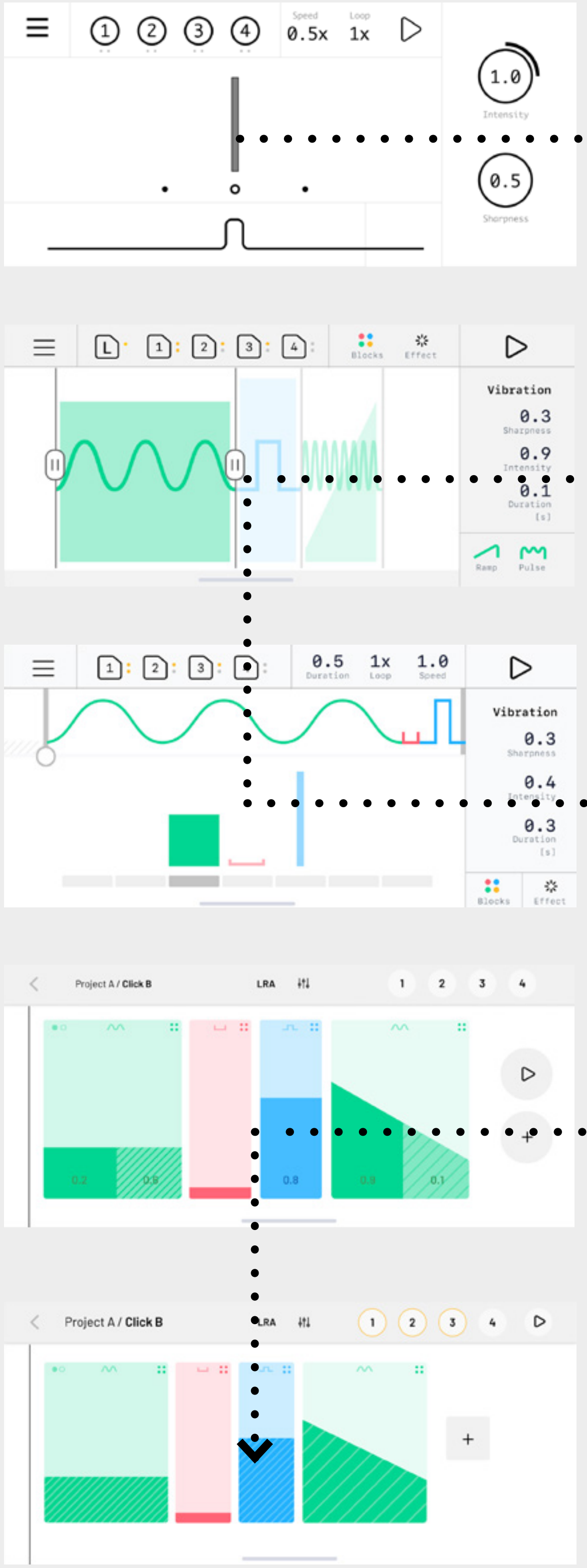


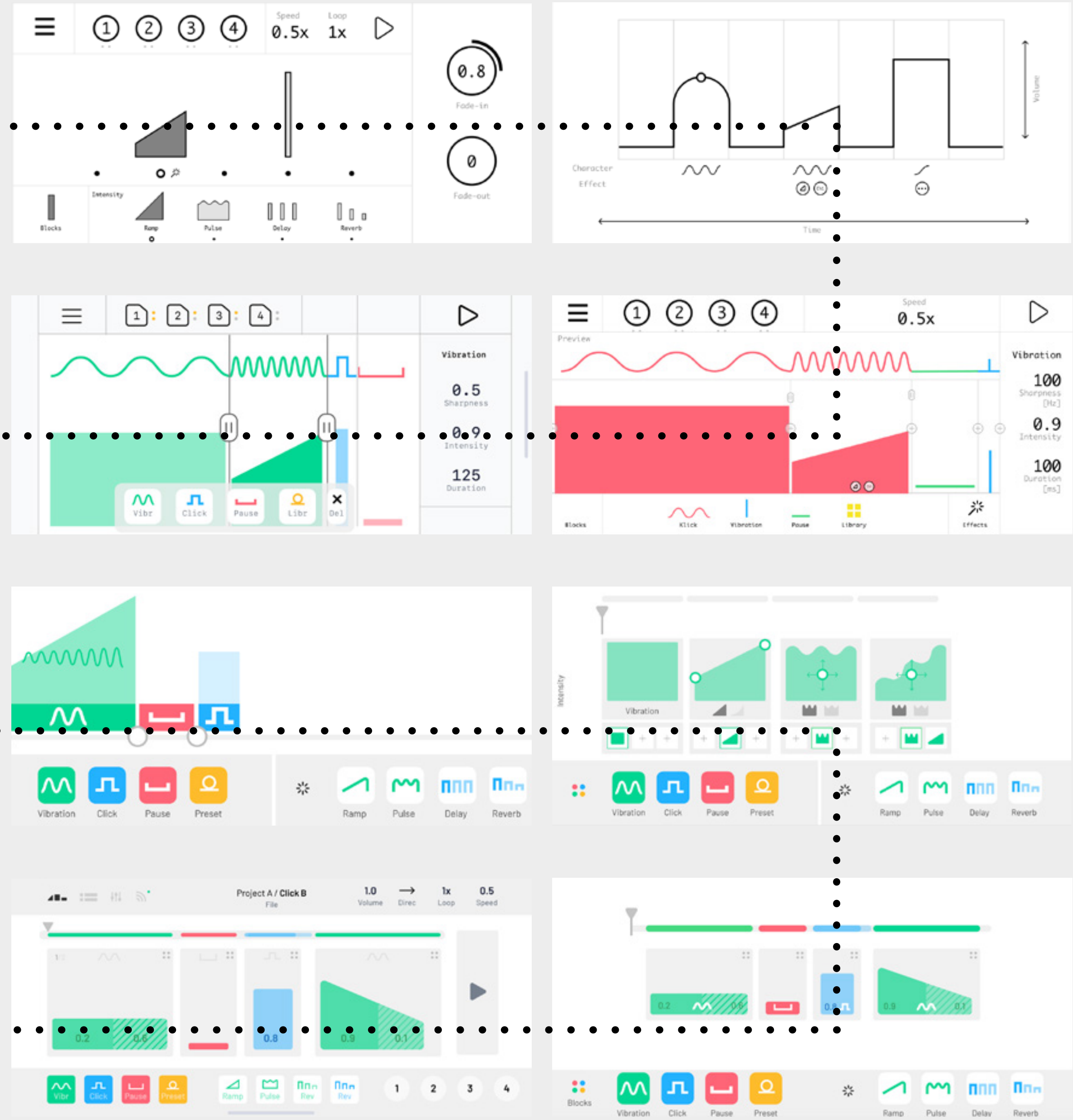

Flinto preview
battery
Power drill / Warning B
LRA
Bluetooth audio amp

User interface

Creating the interface has been a challenge in many ways. With little experience in the digital realm, I also had to acquire knowledge in various new applications and methods at the same time as designing the UI. There were only a few examples of apps available that had a similar approach as my concept.
The main difficulty, however, was to identify the right level of complexity and to simplify it as much as possible for easy and intuitive usage.

One approach which stood out early was the concept of haptic blocks, which could be combined and arranged through drag and drop to create haptic patterns. By colour-coding the blocks, it was also easy to read the pattern without actually experiencing the haptic feedback.





Speed
Loop
0.5x
1x
0.8
Fade-in
0
Fade-out
Blocks
Intensity
Ramp
Pulse
Delay
Reverb
Character
Effect
Time
Volume
Vibration
0.5
Sharpness
0.9
Intensity
125
Duration
Vibr
Click
Pause
Libr
Del
Preview
100
Sharpness [Hz]
100
Duration [ms]
Klick
Library
Effects
Vibration
Click
Pause
Preset
Ramp
Pulse
Delay
Reverb
Project A / Click B
File
1.0
Volume
Direc
1x
Loop
0.5
Speed
Blocks

App architecture
Framing the functionality

The mobile application is divided into two main sections: The library and the editor. Laying out the app architecture eased the design process tremendously.

Library

File management; Saving and loading files, access presets (general and manu-facturer-specific)

Project
- Delete
- Duplicate
- Re-name
- Upload to satellite
- Create new
  - Set project actuator setting
  - Connect to Satellite

File
- Delete
- Assign to project
- Duplicate
- Re-name
- Open in editor
- Share
- Create new
  - From scratch
  - Based on pattern preset

Brand presets
- Play
- Add/ update
- Create new file including brand preset

Editor

Designing the feedback by adding and arranging haptic blocks onto a timeline

- Create pattern
  - Add block
    - From scratch
    - From library
  - Adjust pattern
    - Remove block
    - Change order
- Adjust block
  - Change preset
  - Set intensity
  - Set sharpness
  - Add/ remove effect
  - Assign satellite channel
- Adjust playback
  - Speed
  - Direction
  - Loop
  - Global intensity
- Evaluate haptics
  - Play haptics on satellite
  - Enter setup (Satellite)
  - Compare to project files
- Change project setting
  - Change actuator
  - Change actuator mode/ settings
  - Connect to satellite

Setup

Configure the application to be able to drive the attached actuator

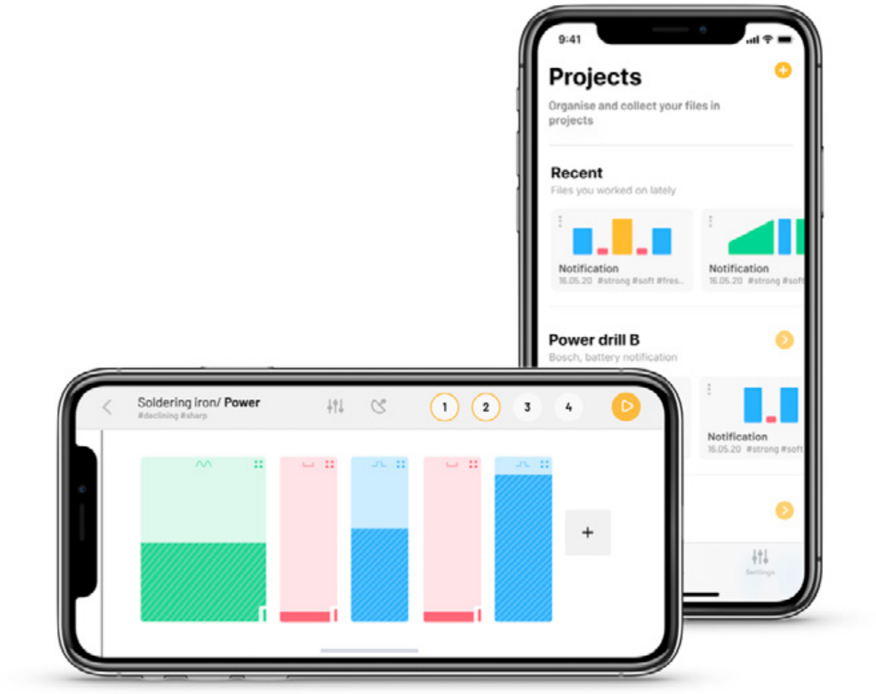
- Satellite
  - Connect
  - Disconnect
  - Rename/ Add description
- Actuator
  - Connect
  - Disconnect
  - Rename/ Add description

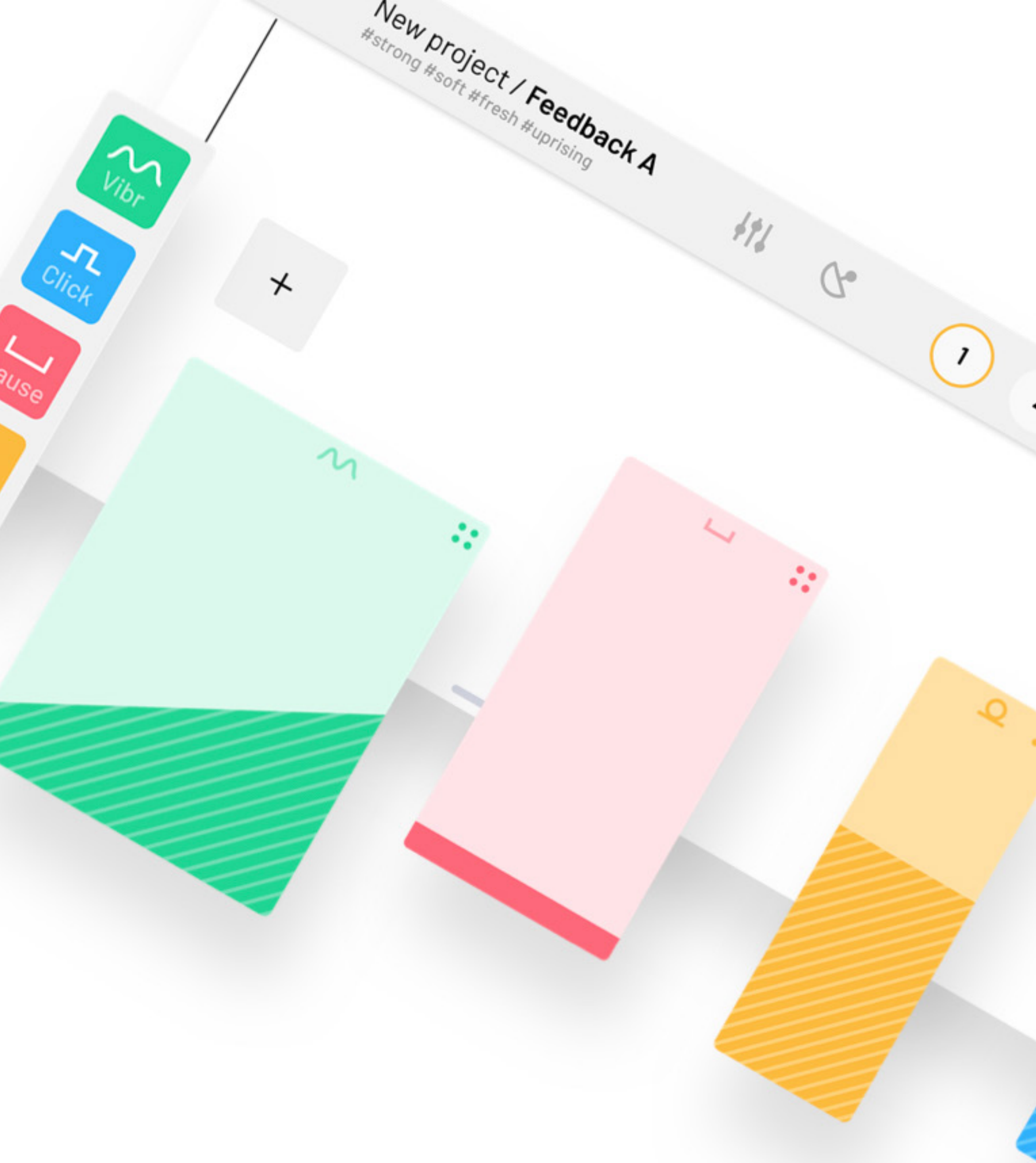
Evaluate

Validate, test and compare various designs

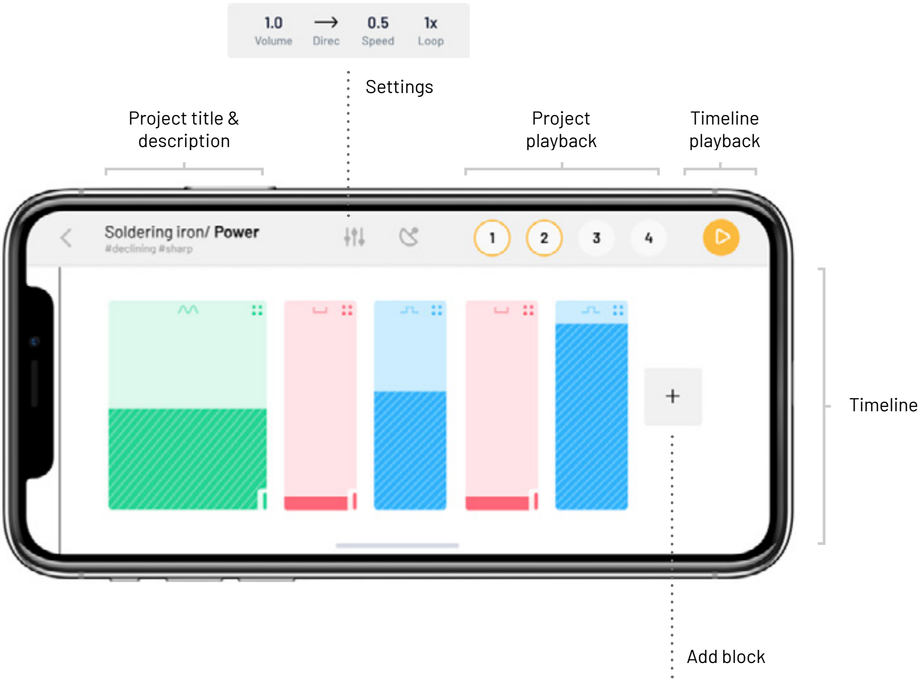
Choose project to evaluate
Enter setup (Satellite)
Play feedback on satellite
Rate feedback

Final outcome UI
The digital experience

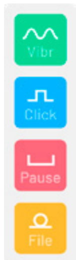


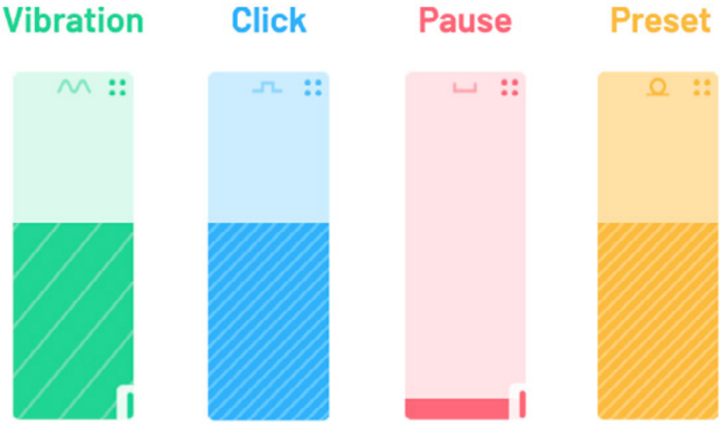

New project / Feedback A
#strong #soft #fresh #uprising
Vibr
Click
1

The editor
Creating haptic patterns



Inside the Editor, haptic patterns can be created by adding and arranging the haptic blocks to your needs. At any time the feedback can be triggered on the satellite unit to experience your design in real-time as well as compare it to other ideas in the project.





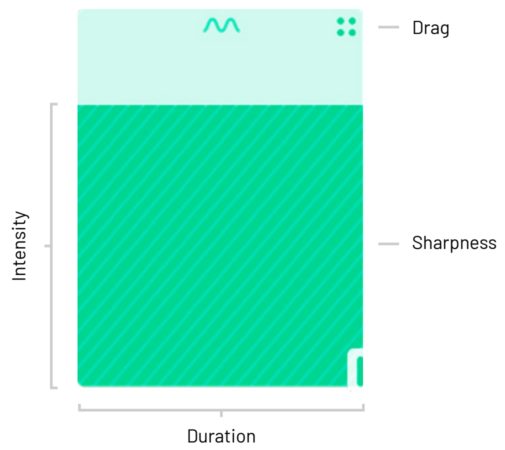
Four different haptic blocks to choose from

Block adjustment
Design tailored feedback

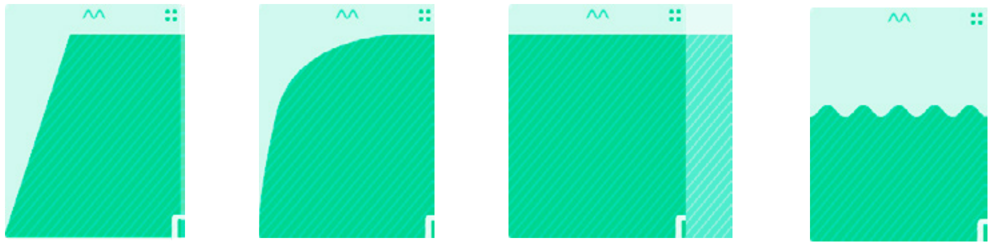
Each block can be adjusted individually, which allows to tailor the feedback to the application.
This can be done either through a direct gesture-based adjustment (intensity, sharpness, duration and placement) or through the advanced settings menu which can be accessed by tapping on each block.

The intensity is illustrated through the height of the bar, the sharpness through the density of the texture and the duration by the width of the block.

Up to three effects can be applied simultaneously:



Gesture adjustments

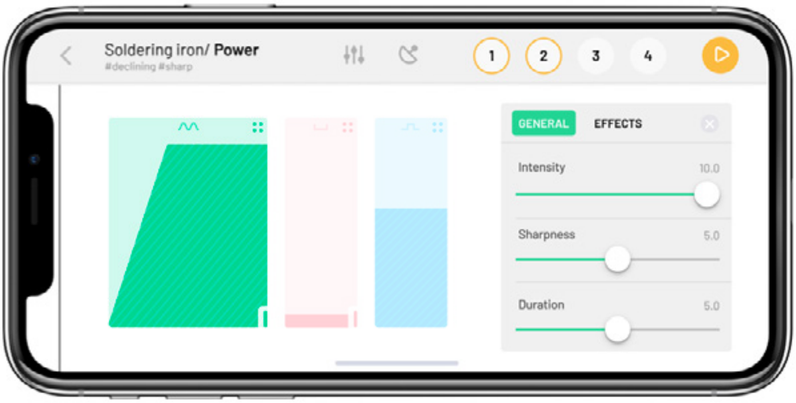


Linear ramp effect

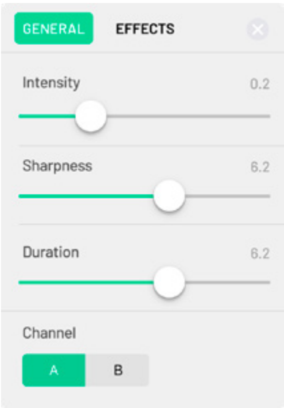
Logarithmic ramp effect

Reverb effect

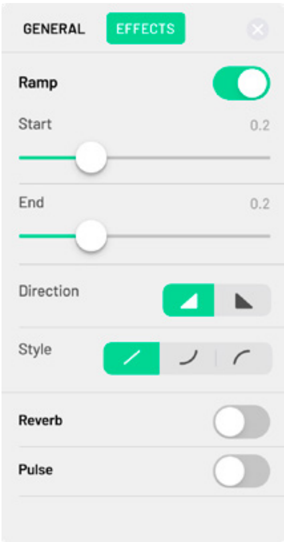
Pulse effect



Advanced settings (vibration block)

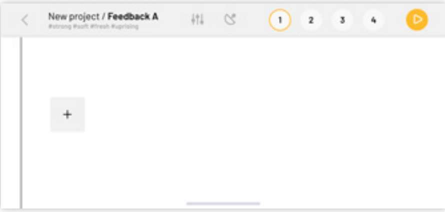


Main adjustments

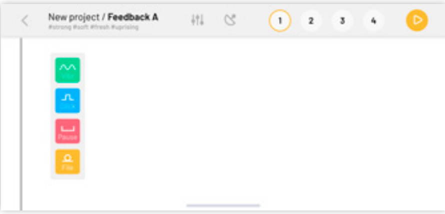


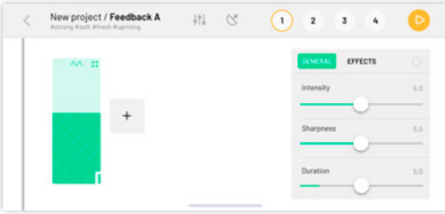
Effects

Design process
From start to finish

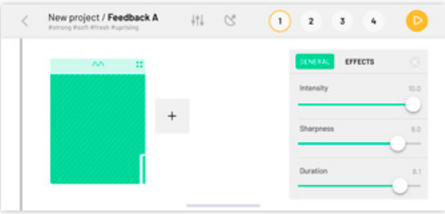


Startup

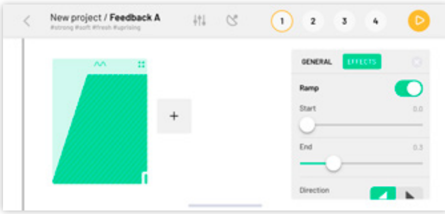




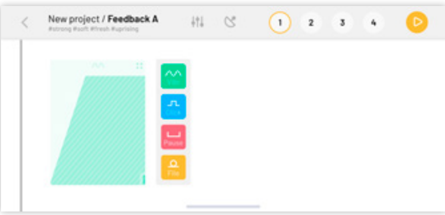
Add "vibration" block

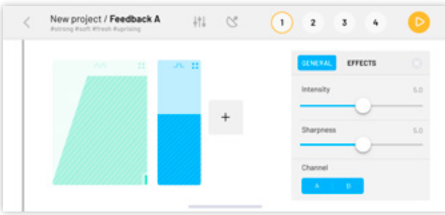


Adjust settings

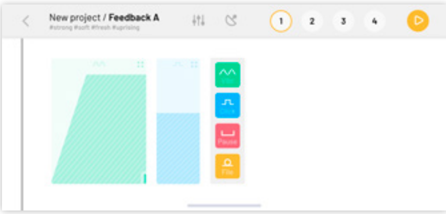


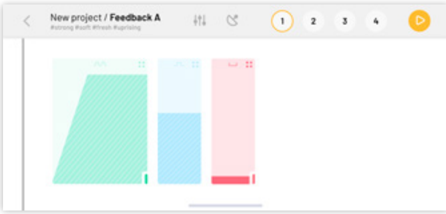
Add effect



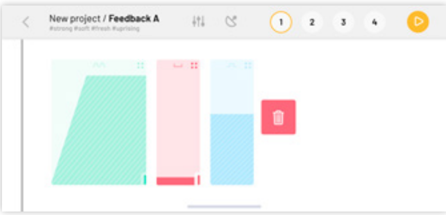


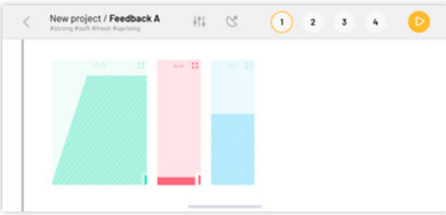
Add "click" block



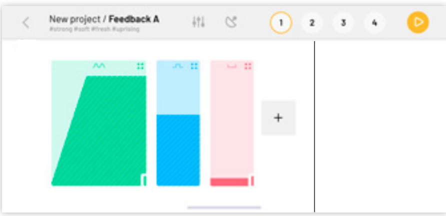


Add "pause" block

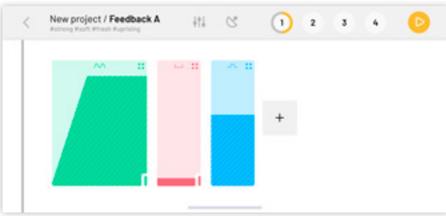




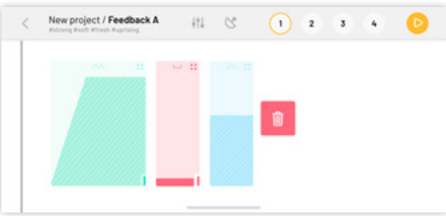
Move "pause" block

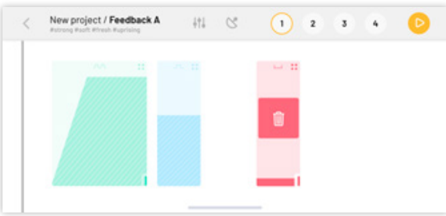


Play timeline on the satellite



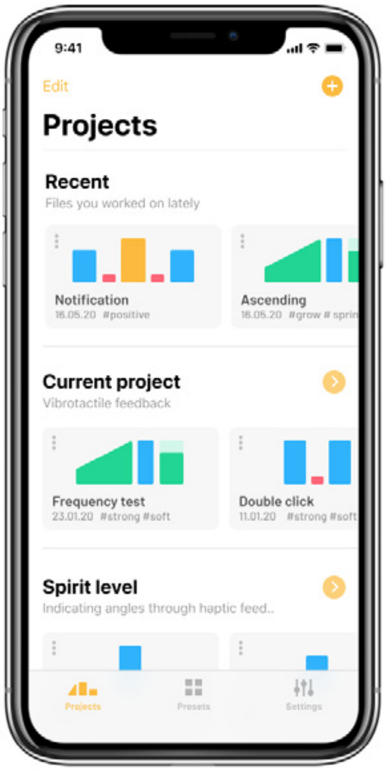
Play design "1" on the satellite



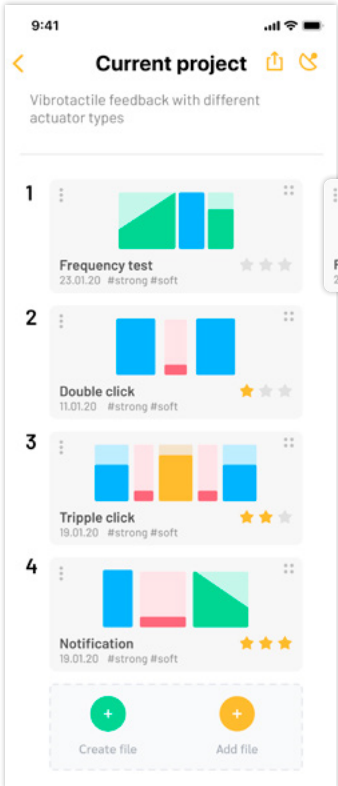


Remove "pause" block

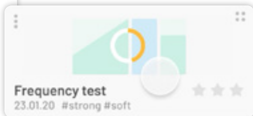
The library
Memory and inspiration



Project overview

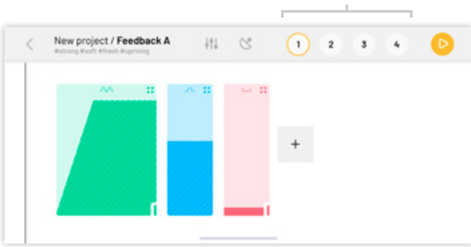


Project view

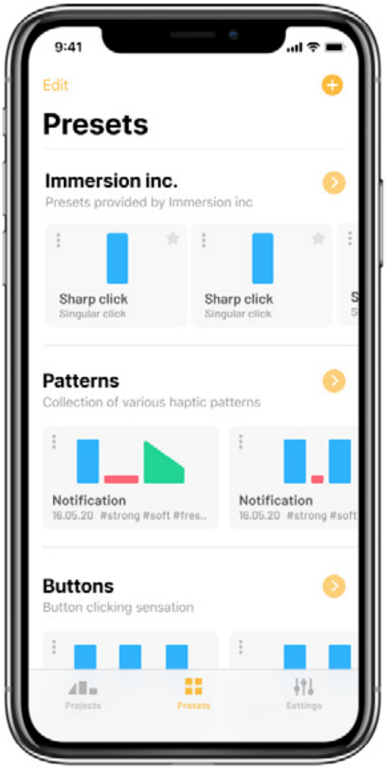


Direct playback

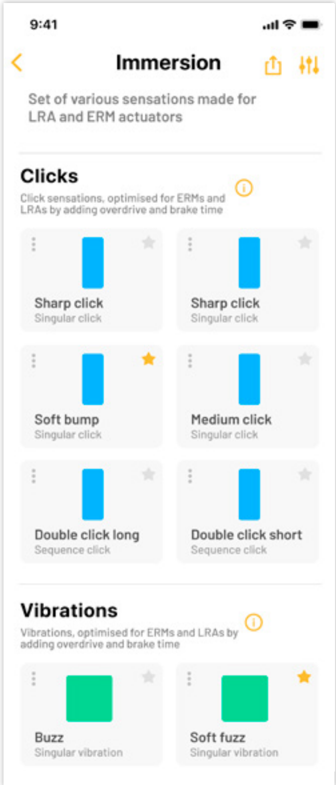
Project short-dial



All projects are stored in the library, which offers both a visual hint of the feedback as well as a playback and rating functionality. In each project an unlimited amount of files can be placed. The first four slots can be directly triggered from inside the editor.



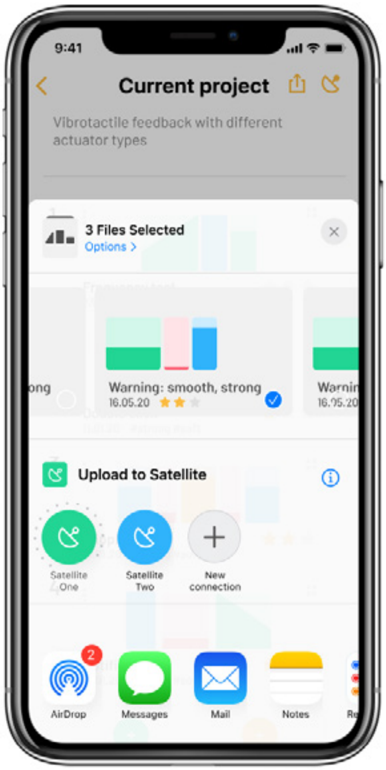
Preset overview

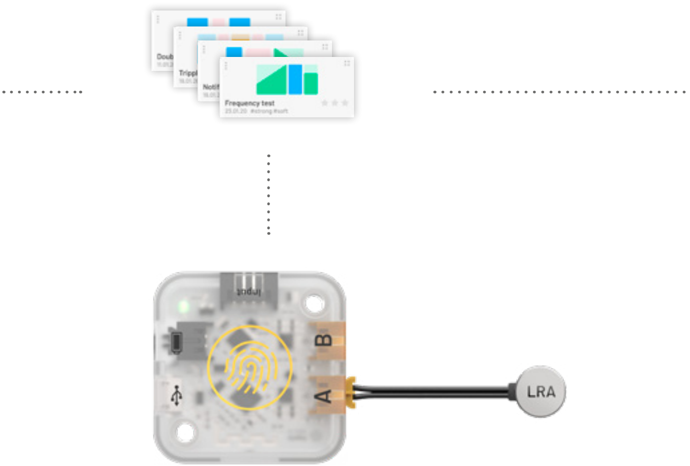


Preset view

In case you are looking for inspiration, different preset-collections can be a starting point. Different sets include patterns or singular haptic cues. They are provided by Hapticlabs or the original manufacturer.

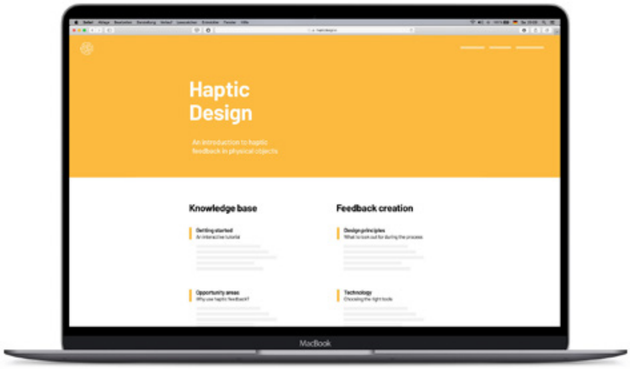
Sharing your creation
Exporting the feedback





Upload to internal memory of the satellite

The patterns and projects can be uploaded to the local memory of the satellite, shared with the online platform or exported as code for the final implementation.



Share via the online platform

Export as code

The satellite

Satellite player
Component configuration

The satellite is the bridge between the user and the object. Its purpose is to drive the connected actuators with the feedback designed in the smartphone application. The PCB was designed to be as small as possible while still keeping all components on a single layer to achieve more durable handling.

The following functionality is included:

Receive wireless signals
Bluetooth was chosen as the appropriate protocol due to its low power consumption, ease of integration and the possibility to still use wifi to connect to online services. Using wireless technology always adds latency to the system. However, in the early prototyping phase, this can be neglected.

Power management
Through the Micro USB-port, the board can be powered, and an attached battery be charged.

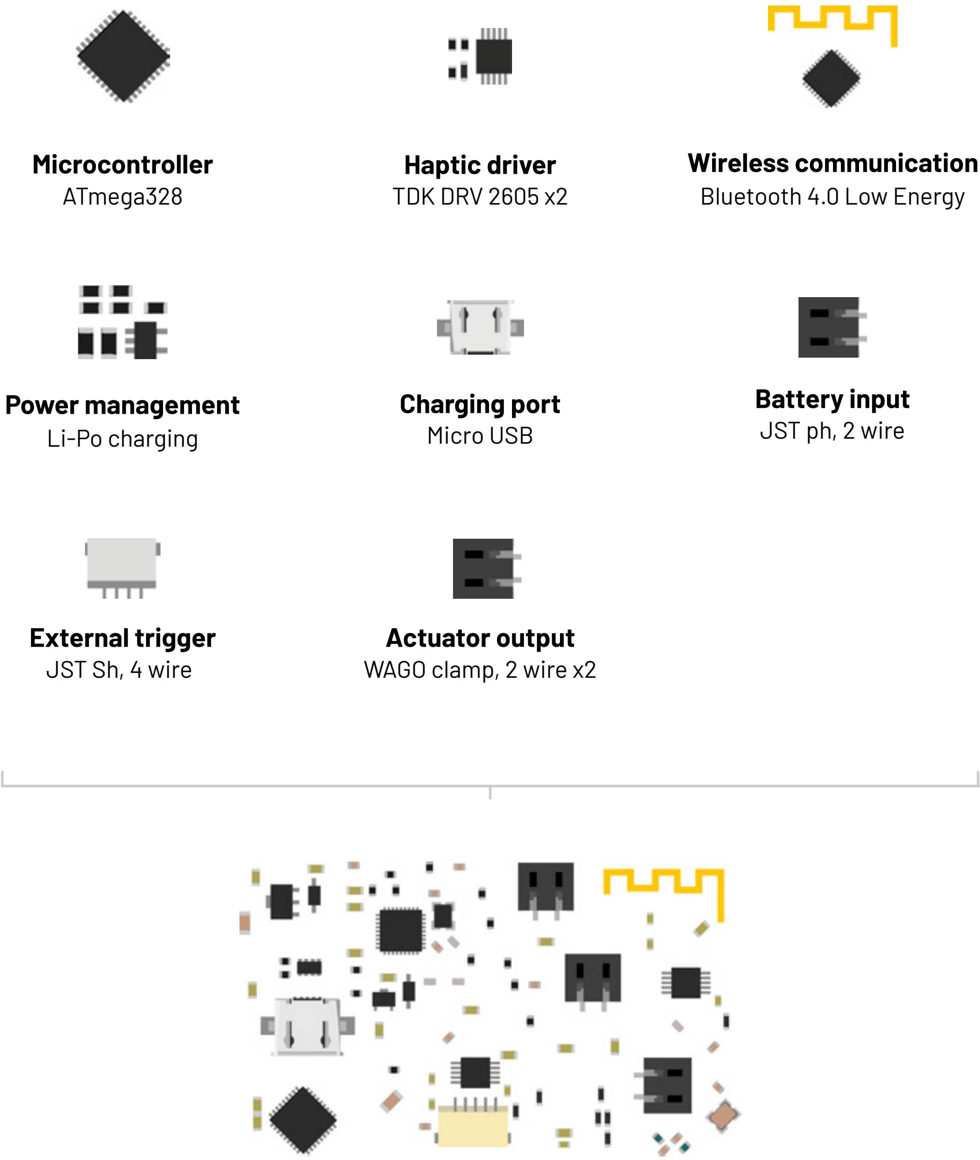
Battery based power management
To create a standalone device, an internal battery management is included which allows the connection of conventional Li-Po batteries.

Driver output
To cover a large variety of applications, two actuators can be attached and driven at the same time through two TDK DRV2605 drivers. This allows comparing different technologies or materials without switching any connection as well as prototyping directional feedback (left-right/ up-down) in helmets, gloves and many more.

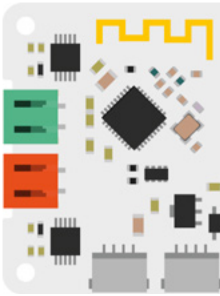
Allow for external trigger input
By including external input ports, the user can include sensors (capacitive/ gyroscopic/ force/..) or simply connect an external button to create a standalone application without adding an additional microcontroller. This way also the delay due to the wireless connection can be cut out.

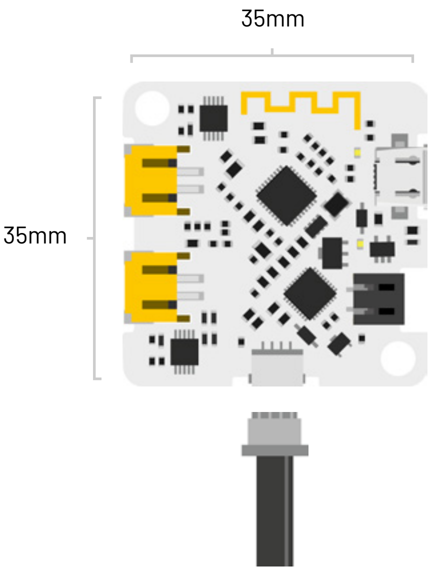
Save feedback files internally
Having an internal memory is also required to create a standalone prototype. This can be achieved by taking advantage of the internal flash memory of the ATmega328.

Intuitive usability
The in/ output ports are clearly labelled and colour-coded to prevent any user error by plugging components into the wrong place.



Microcontroller
ATmega328
Haptic driver
TDK DRV 2605 x2
Wireless communication
Bluetooth 4.0 Low Energy
Power management
Li-Po charging
Charging port
Micro USB
Battery input
JST ph, 2 wire
External trigger
JST Sh, 4 wire
Actuator output
WAGO clamp, 2 wire x2



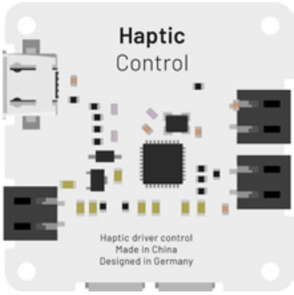


Component layout

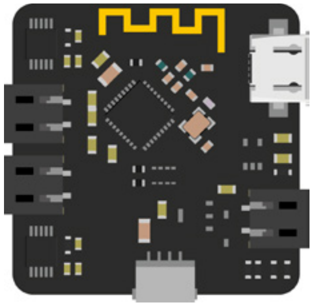
Designing a PCB on this detail level is challenging in a lot of aspects. Not being an electronics expert, I had to check for techniques and possibilities when it comes to layout components. The PCB also needs to be as small as possible, while still being easy to handle and work with. In the end, it also had to be aes-thetically appealing and approachable to people new to the field of electronics.

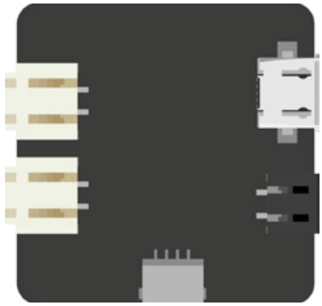
As for the colour of the solder mask (the top PCB layer) I chose white to express a bright and friendly character as well as to create a more sketchy rather than high-end feeling which is most often commu-nicated through the typical black-gold range.

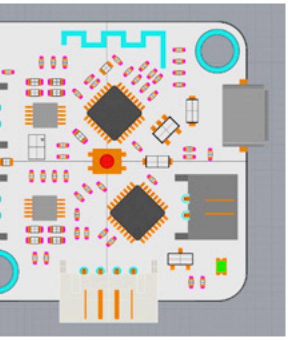
The PCB was also enhanced with the option to fasten it to the prototype through holes located in two corners.

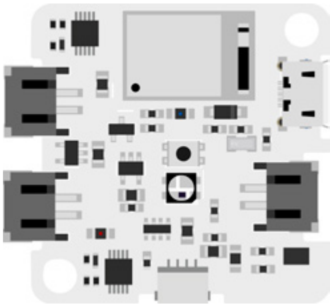


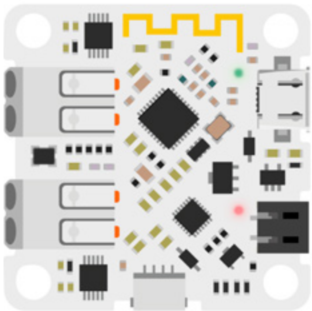
Haptic
Control
Haptic driver control
Made in China
Designed in Germany

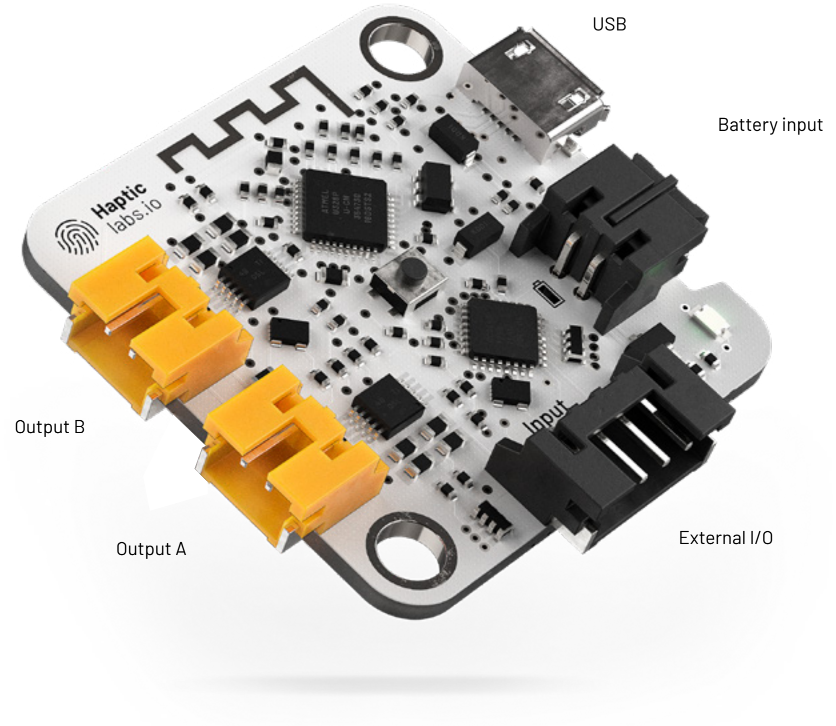












Final layout

All components and ports are placed on the front-side of the PCB. They are grouped based on their functionality (Input/ Output/ Power) and differentiate in form and colour to avoid user errors.
A QR-Code on the backside allows to easily connect a new satellite to the accompanying App.

Housing
Creating a suitable enclosure

Providing an enclosure for the PCB was important to not only protect the components, but to also ease the handling and conceal the complexity.

It needed to fit the following requirements:

› House the PCB and battery

› Allow in- and output-connections

› Protect the electric components

› Conceal the electronics to create a more approachable aesthetic

› Include an ON/ Off power switch

› Add further fastening possibilities.

A cloudy plastic material was chosen as to both show the insides and staying true to its functionality being an electronics prototyping tool, as well as to partially disguise its complexity.

The small size 450 mAh battery will last around 90 minutes with the actuator continuously vibrating. Which is more than enough for multiple user tests.

Li-Po battery: 450mAh @ 3,7V [26]
PD503133

LRA Coin actuator: 115 mA [25]
Microcontroller with BLE: 10 mA

0.405Ah / 0.27A x 60 = 90 Min.

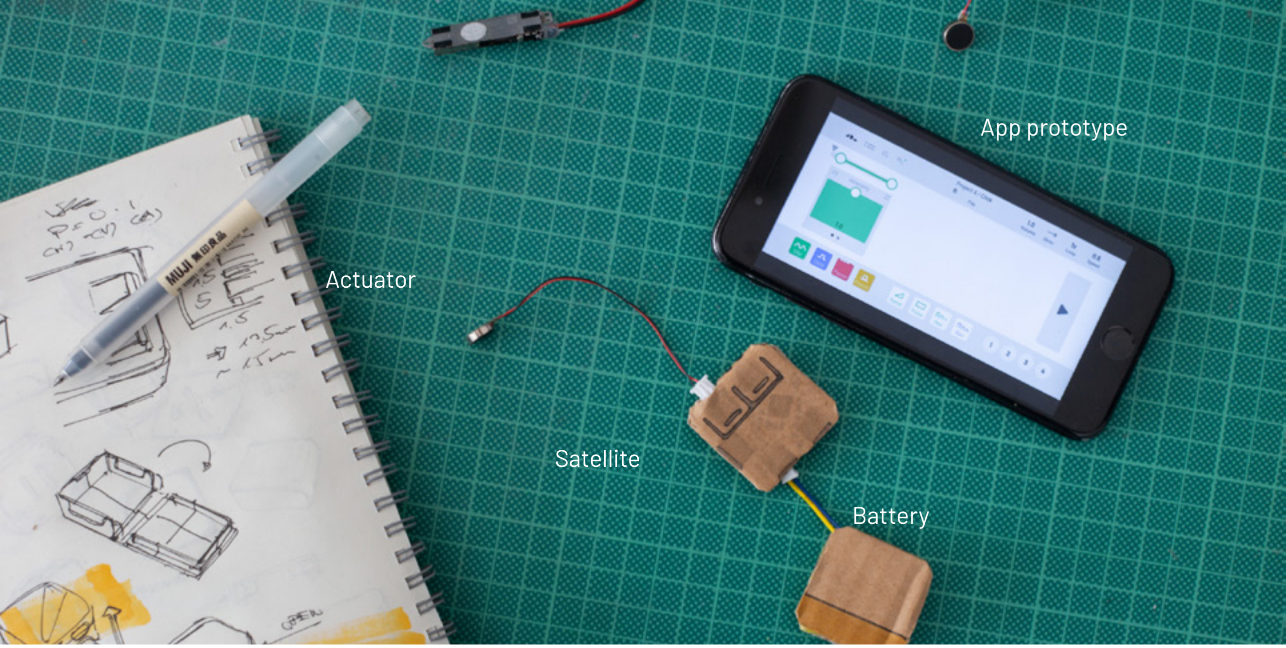

CH1
CH2
CHRG
BAT
I2C
TRGR
6SP 061225
450mAh 3.7V

Workflow evaluation
App - satellite - object

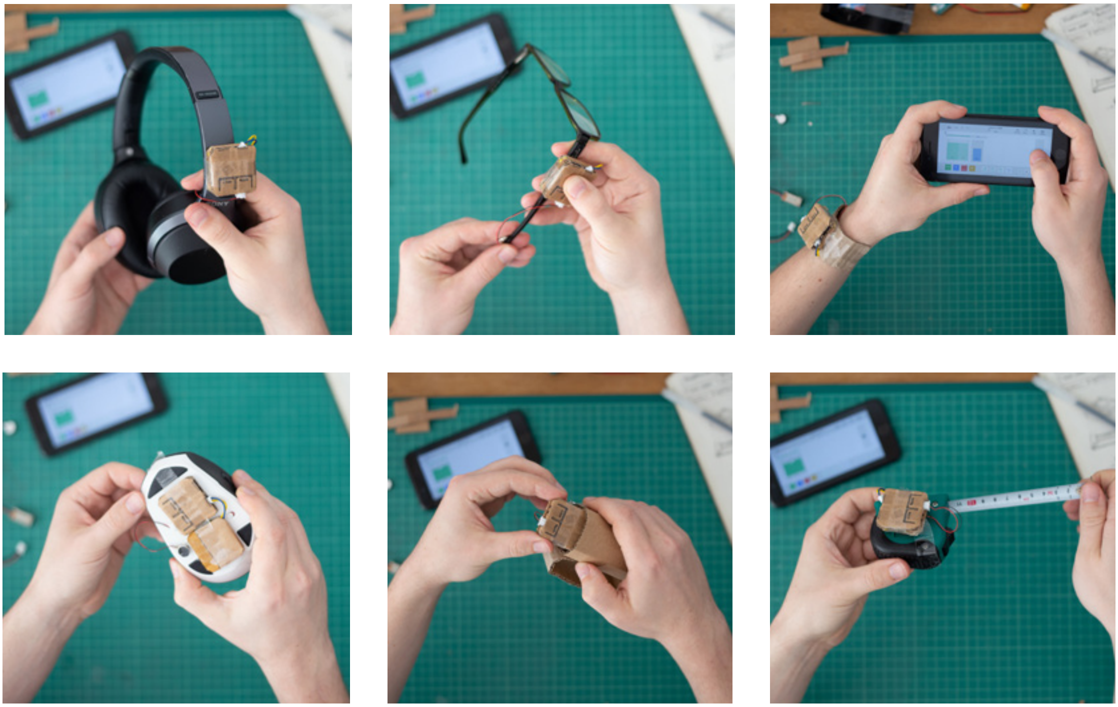
The form factor of the enclosure was evaluated in several low-fidelity case studies by using a 1:1 paper mockup in combination with an interactive app prototype to simulate a typical process.

While in some applications an elongated form factor might be preferable, in most cases a stacked arrangement of battery and satellite was more practical.

The squarish form also goes hand-in-hand with prominent UI elements and therefore creating a family feeling.



Evaluating the toolset in different product context

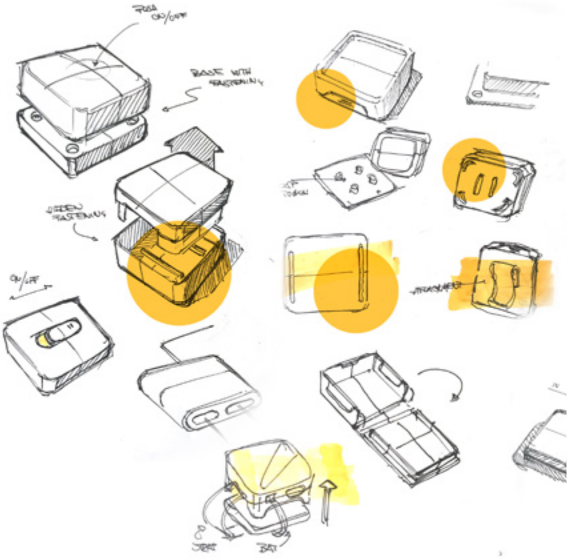


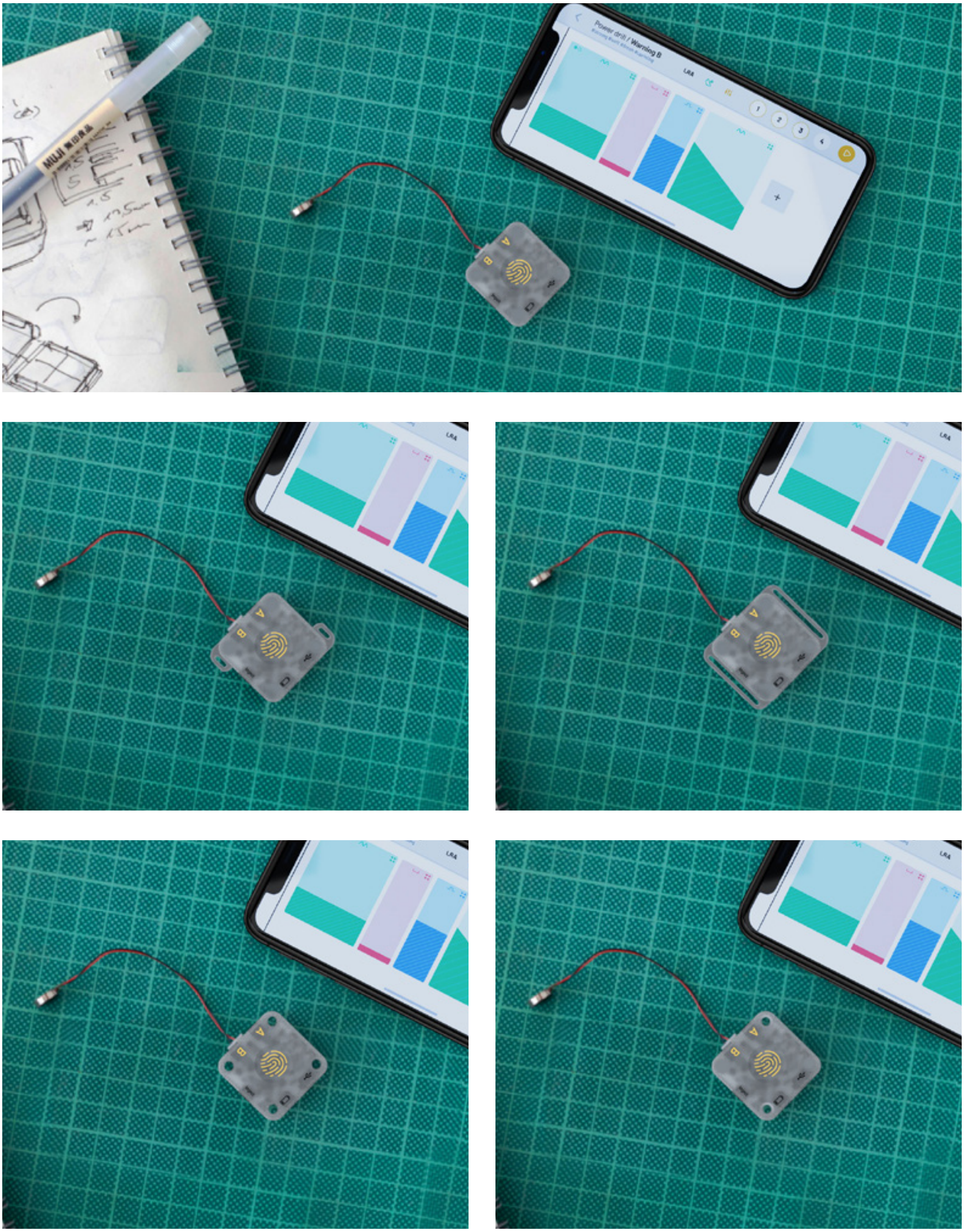
Evaluating the toolset in different product context

Housing
Concept

Another aspect of the housing was to provide the possibility to attach it to a variety of prototypes. The main challenge was again to keep it as small yet universal as possible.
In the end, I decided to stay away from any prominent flaps or similar, but make use of the already available through-holes of the PCB to attach a cable tie, screw or thread.

A next-generation could involve further modular accessories such as a belt clip or an integrated hook.

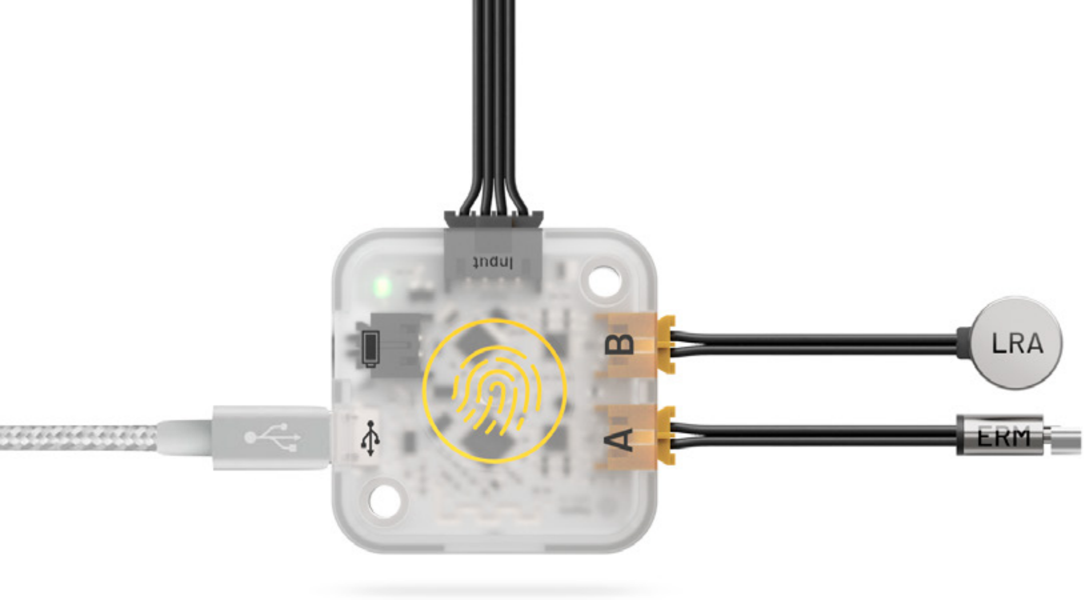




Photoshop exploration of attachment concepts

Satellite player housing
Final

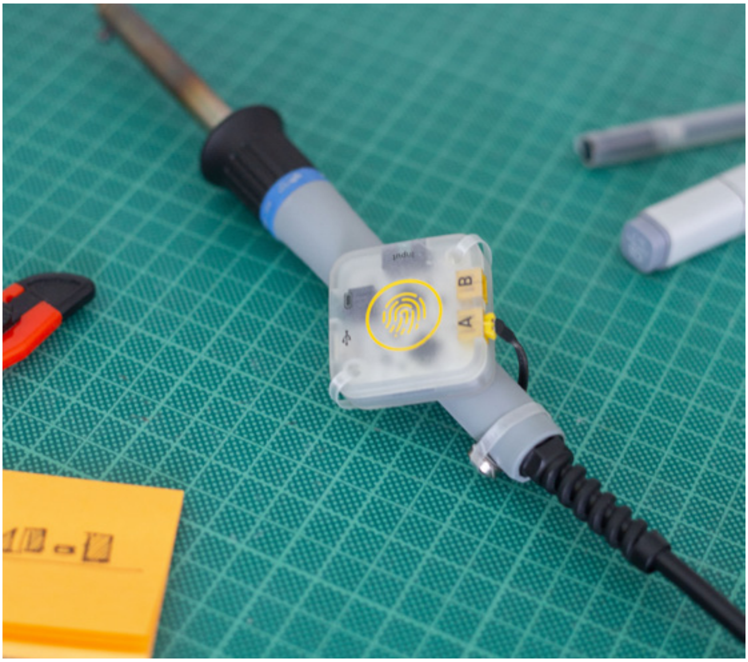
The final enclosure consists of a two part housing. The cloudy plastic partially hides the electronics but still showcases what the system is: an electronics prototyping toolkit. It also allows one to easily identify the coloured ports as well as the LED indicator from different angles.
Pad printed decals further indicate the functionality of each port.
Two holes allow for the attachment of the satellite to the prototype through screws, cable, ties, or other means.



USB charging, external input and two-channel actuators output.

The casing houses both the PCB as well as the battery.

Double-sided tape



Cable ties

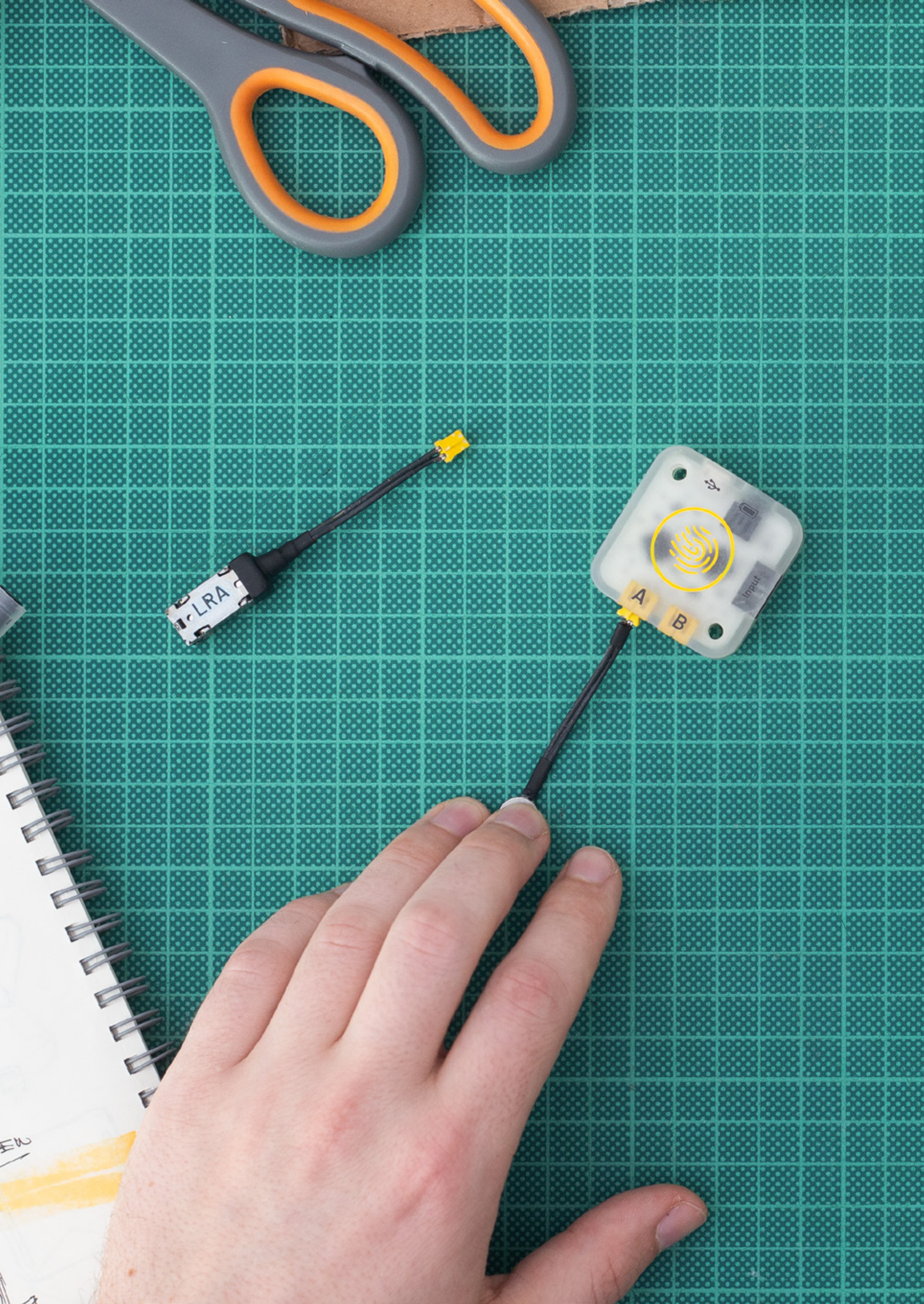
Bare PCB

Loose assembly

Evaluation
Test early and often

The combination of the satellite with the mobile App makes it especially easy to quickly create functional prototypes early on in the process, evaluate your design in the final context and create immersive user tests.


9:41
Current project
Vibrotactile feedback with different actuator types
1
Frequency test
23.01.20 #strong #soft
2
Double click
11.01.20 #strong #soft
3
Tripple click
19.01.20 #strong #soft
4
Notification
19.01.20 #strong #soft


LRA
A
B


New project / Feedback A
#strong #soft #fresh #uprising
1
2
3
4

The knowledge base

Putting it together
Collection of findings

At the same time, as it is essential to provide the right hardware toolset to experience haptic feedback, there is also a necessity for a theoretical toolset to provide guidance along the way.

Talking to designers who have worked with haptic feedback in a professional application, certain topics repeatedly came up, which I was also able to confirm during my own exploration.

While a theoretical guide can not replace the value of learning by doing, certain pitfalls can be avoided and hearing about other people's failure, and success helped me achieve better results much quicker.

To define the content of a knowledge base, I began by recapitulating and summarising the learnings I gathered throughout the thesis in different categories.

This was the basis of the final outcome, including an introductory tutorial, a collection of opportunity areas and a list of design principles.

Sense
Sound + hf
Attribute: There is always sound with every hf, the sound has a direct impact on the perceived character/ information of hf

Opportunity: Use sound to enhance and define hf

Sense
Multimodality
Attribute: In reality we never only experience hf

Opportunity: Include other modalities to make hf easier to interpret, create a seamless interaction

Design
Inspiration
Opportunity: Hf can be used to inspire product innovations

Example: BMW iDrive

Design
Form/ object design
Attribute: Digital hf can replace analogue hf

Opportunity: Non mechanic buttons allow for cheaper/ fully enclosed parts

Example: iPhone home button

Sense
Always on
Attribute: One can not turn off haptic perception

Opportunity: If in touch with the body, the user will always receive the information, not context sensitive

Sense
Obvious/ Immediate
Attribute: Notifications such as a single impulse do not require interpretation but can be acted on in a reflex

Opportunity: No/ only a small learning curve is necessary, reaction time is very low

Communication
Information
Attribute: Haptic feedback can be used to communicate information

Opportunity: Hf can be used as a communication channel enhancing or replacing other modalities

Communication
Branding
Haptic feedback can be used to communicate brand values/ brand specific characteristics

Opportunity: Create a seamless brand experience, recognize brand through hf

Sense
Perception distribution
Attribute: Haptic perception is no equally distributed across the human body

Opportunity: Create a body map to illustrate

Sense
Active contact
Attribute: hf requires body interaction, two directional interaction

Opportunity:

Communication
Subtle/ Safety feature
Opportunity: Hf can be used without disruptic the users' action thus resulting in incerased safety compared to other modalities

Example: In car interactions,

Communication
Tailored feedback
Opportunity: Digital hf allows to tailor hf to each action

Example: Large/ small steps in knobs based on application, iPhone home button

Communication
Invisible
Attribute: Hf is not visible and usually not audible

Opportunity: Use hf to reduce information clutter, in a silent environment

Communication
Private
Attribute: Hf is only felt by the user in contact with the object

Example: Smartphone vibration

Communication
Substitute modalities
Haptic feedback can be used to replace other modalities

Opportunity: Replace auditory or visual feedback to simplify and/ or de-clutter interactions

Communication
Enhance modalities
Haptic feedback can be used to enhance other modalities

Opportunity: Make interactions more prominent, add characteristics, more rich, perceived with less effort, incerasing comfort level

Communication
Low bandwidth
Attribute: The information bandwidth of hf is very limited

Opportunity: Make use of simple hf patterns or impulses which differentiate on multiple characteristics (eg. intensity + frequency)

Communication
Fine nuances
Attribute: We can recognise very fine nuances in hf

Opportunity: Design hf according to real world examples

Communication
Guidance
Fact: Haptic feedback can be used to guide the user

Opportunity: Hf can be used to create intuitive and non intrusive feedback to guide the user

Communication
USP
Opportunity: Hf is rarely used in physical objects and can create a USP

Example: Teenage Engineering OP-Z

Communication
Human interaction
Attribute: Human interactionsa rely on hf patterns

Opportunity: Object interactions can be based on human interaction patterns to reach a more seamless/ intuitive/ emotional experience

Communication
Intuitive
Attribute: Based on experience we can react intuitively to live-like hf

Opportunity: Create intuitive experiences, easy to learn

Example: Rising/ declining, spring/click

Application
Feed-forward
Opportunity: Use the same modality for in and output

Example: Use haptic as input and output modality

Communication
Value
Opportunity: Haptic feedback can be used to enhance the quality/ value of interactions

Example:

Communication
Enhance natural hf
Attribute: Natural hf can be hard to feel in certain contexts

Opportunity: Enforce natural hf by adding digital hf

Example: Working gloves

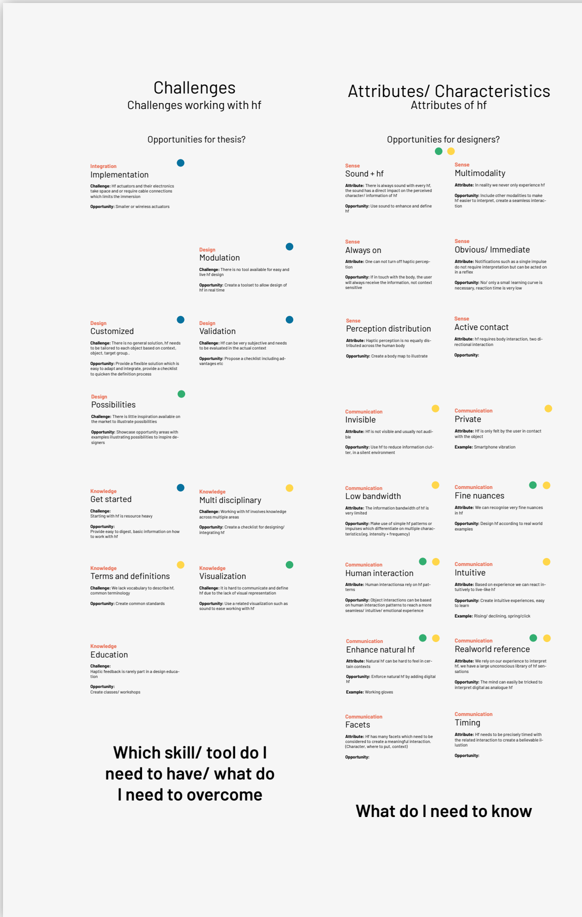
Communication
Realworld reference
Attribute: We rely on our experience to interpret hf, we have a large unconscious library of hf sensations

Opportunity: The mind can easily be tricked to interpret digital as analogue hf

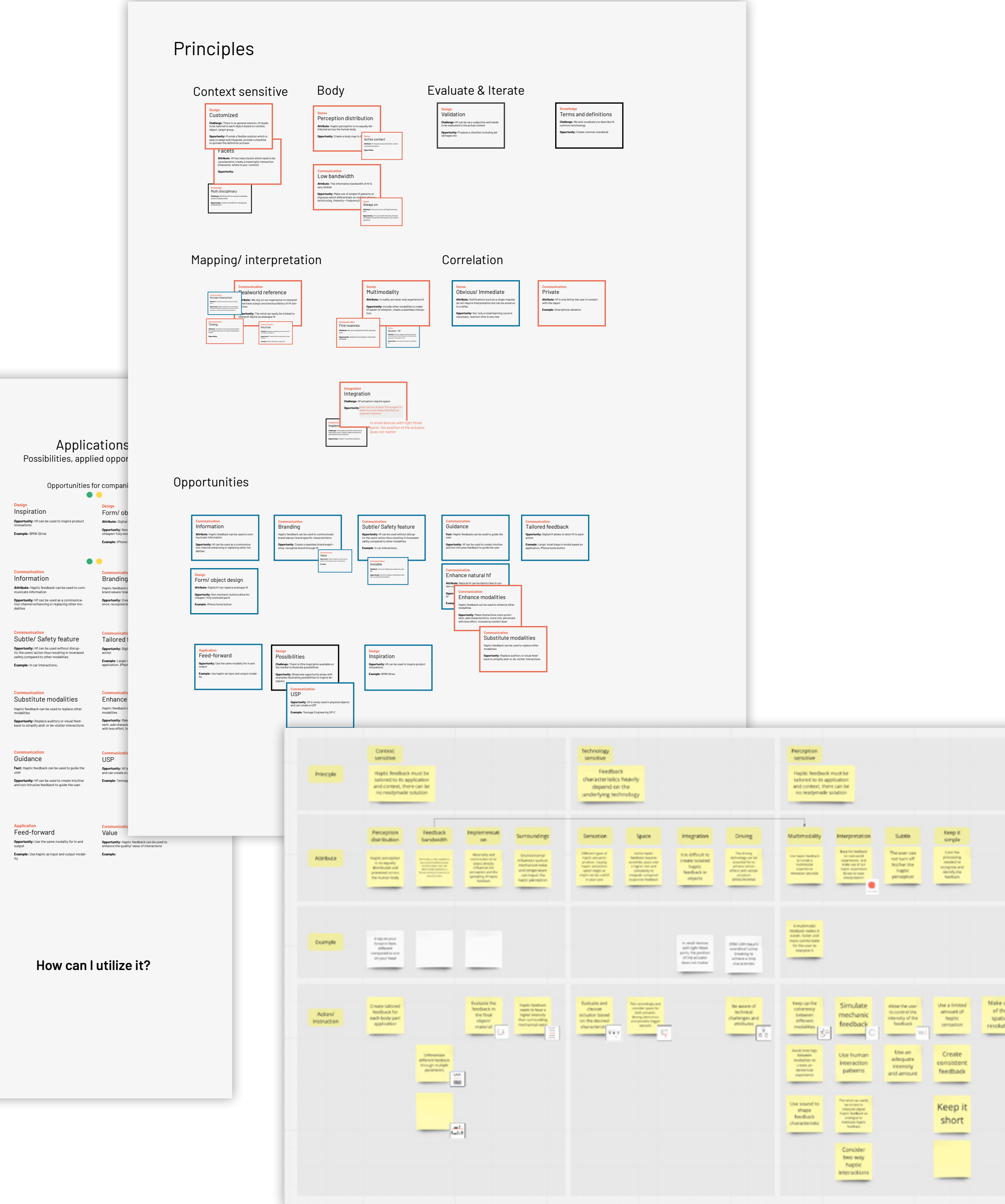
Once all findings were gathered and translated into the same format, I started rearranging and combining them into multiple subcategories.

This was done in multiple iterations to identify the optimal approach while continuing the physical exploration to evaluate the decisions.

Sorted by utilisation



Divided into opportunities / principles



Divided into area/ attribute/ example/ instruction

Design principles
A first sketch

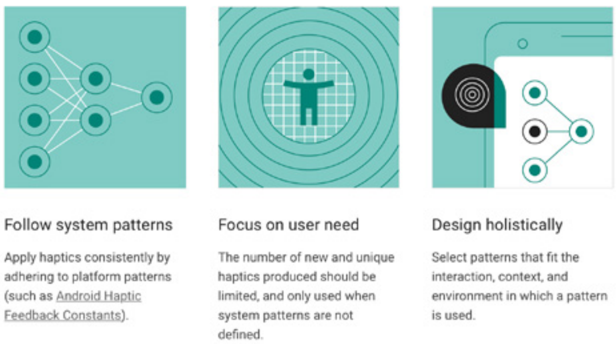
The risk of intimidating or limiting the user through guidelines or rules is very high, especially if they are too specific or come in a large number. In the opposite case, being too vague will lead to confusion or no help at all.

Instead of creating a rulebook, I narrowed the knowledge down to design principles. These are meant to be understood as friendly reminders to avoid pitfalls or do's, and dont's to succeed.

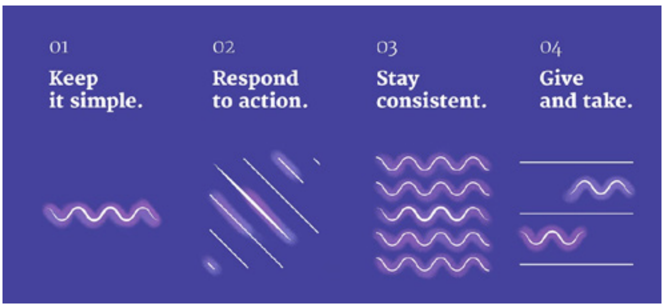
Again the hands-on exploration was essential for creating useful principles.
The biggest challenge was to condense the amount of information and filter out the essential topics and translate them into universal principles. At a certain level though, compressing information comes with a big drawback, as things become more abstract and harder to understand. Providing examples were essential to convey the message at that point.

To get a feeling for the right format and phrasing, I analysed similar approaches for different areas of design.

Very simplistic and friendly but highly abstract and general



Complex visualisations, helpful short description



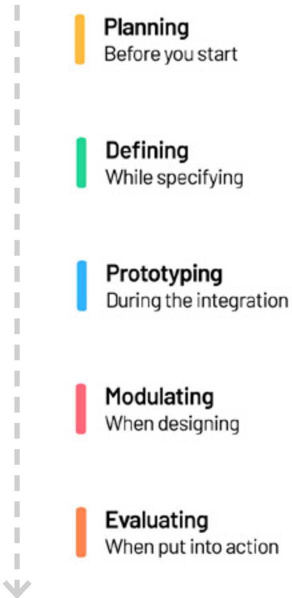
Visually interesting, but very abstract.

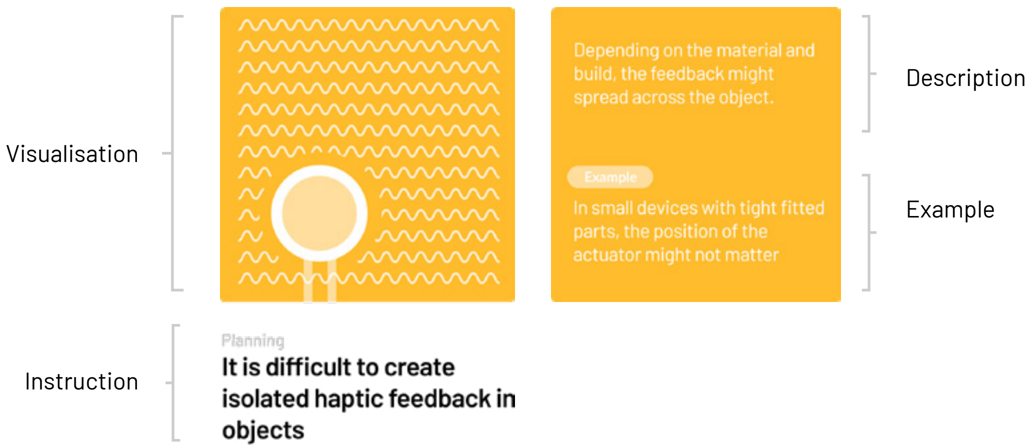
Design principles
Outcome

The final format includes a visualisation to illustrate the problem or goal, the guiding principle, phrased as a simple statement or instruction, a description of the principle and an example of a real-life scenario.

Especially the latter is extremely helpful to grasp the importance and application area of the principle.

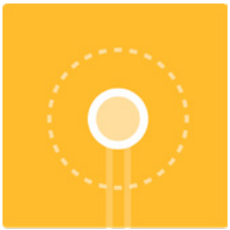
One of the feedback while talking to users was that principles could quickly become overwhelming. To reduce the complexity, I arranged them based on the design process in several stages, instead of listing them by category. This way, the user can put the focus only on the ones relatives at certain point in time.





Visualisation
Depending on the material and build, the feedback might spread across the object.
Description
Example
In small devices with tight fitted parts, the position of the actuator might not matter
Example
Instruction
Planning
It is difficult to create isolated haptic feedback in objects

Planning
Before you start



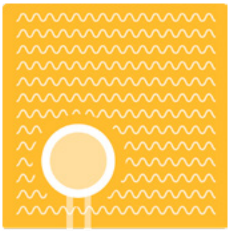
Active haptic feedback requires assembly space for both actuator, driving electronics and possible trigger sensors.

Example

A coin sized actuator might be the only option for a wearable object.

Planning

Be aware of the required assembly space



Depending on the material and build, the feedback might spread across the object.

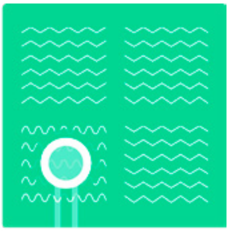
Example

In small devices with tight fitted parts, the position of the actuator might not matter.

Planning

It is difficult to create isolated haptic feedback in objects

Defining
While specifying



Environmental influences such as mechanical noise and temperature can impair the haptic perception.

Example

Holding a power tool will emit mechanical vibrations. Hands and feet are prone to receive environmental influences.

Defining

Differentiate from surrounding influences

Replicate feedback sensations we are already used to. This will make the feedback become less artificial and easier to recognise.

Example

Make use of characteristics and patterns from mechanics or human interactions.

Defining

Base the feedback on real world experiences

Prototyping
During the integration

Different types of actuators produce varying haptic sensations which might or might not be useful in your case.

Example

LRA's can produce a wide range of vibrations, but will never reach clicking sensations such as accelerated rams.

Prototyping

Choose the actuator based on the desired characteristic

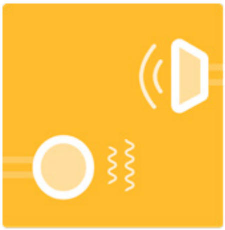
The driving electronics can have a big impact on the feedback.

Example

Using sound as input one can not reach a crisp feedback with ERM's or LRA's compared to a dedicated driver.

Prototyping

The driving electronics can be equally important



A multimodal feedback is easier, thus more comfortable to process and can also help shape the characteristics of the haptics.

Example

Receiving a notification on your phone in a muted vs. unmuted state.

Planning

Consider a multimodal experience whenever possible

Define the context, functionality, characteristics and content of the feedback before your start modulating.

Example

It is far easier to create, evaluate and reach the desired feedback if the goal is specified beforehand.

Defining

Define before design

Haptic perception is no equally distributed and preceived across the human body

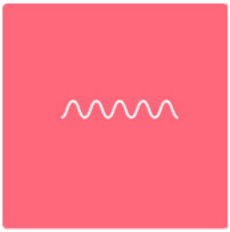
Example

High frequencies can work great on the fingertips, but are highly uncomfortable when used on the head.

Defining

Create tailored feedback for each body part application

Modulating
When designing



Haptic feedback is most powerful when one can intuitively react on it.

Example

The more complex the feedback, the less powerful it becomes and more repetitions are needed to learn it.

Modulating

Keep the feedback short, simple and consistent

To create an immersive experience, all modalities need to communicate the feedback coherently (characteristic/ intensity,...) and perfectly timed.

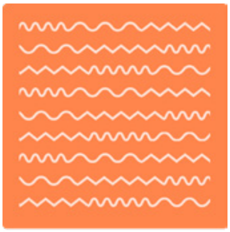
Example

Simulating a button click, we can sense a wrong timing down to microseconds.

Modulating

Keep up the coherency between different modalities

Evaluating
When put into action



Due to the complexity and sensitivity, the feedback needs to be validated and tested throughout the whole design process.

Example

Create tangible prototypes for each step in the process and provide a variety of cues to test.

Evaluating

Evaluate & iterate in multiple instances

The material and construction of an object directly influences the perception and spread of haptic feedback.

Example

Different materials and connections such as glue or screws will have an impact.

Evaluating

Put it into the final object or material

The user can not turn off his/her haptic perception.

Example

Be careful on the intensity level or let the user decide.

Modulating

Use an adequate intensity and amount of feedback

Our body can differentiate between a broad variety of nuances in characteristics [intensity, frequency, timing..] but has trouble identifying only slight differences.

Example

Make use of a high contrast in the parameter values when designing different cues.

Modulating

Clearly differentiate haptic sensations

The perception is highly influenced by the context it is perceived in.

Example

The users behavior and experience influences the perception, as well as the environment, clothing or other distractions.

Evaluating

Make it work in the final context

Opportunity areas
How to utilise it

Due to the availability of only a few products incorporating haptic feedback and its complex prototyping process, designers are often not aware of possible applications and opportunities.

Based on the summary of findings and takeaways during the thesis work, I defined a collection of opportunity areas which I consider to be the most essential ones.

As mentioned before, it is crucial to provide real-world examples when talking about haptic feedback. In this case, this was achieved by providing short Wizard-of-OZ like videos of concept studies which indicate the haptic feedback through sound and visual representations.

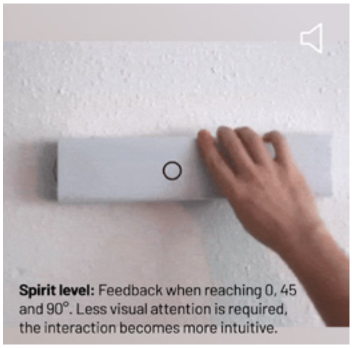
Visualisation

Description

Simplify/ de-clutter

Haptic feedback can be used to substitute or relief other modalities, simplifying the interaction, making it perceived with less effort or increase the comfort.

Example



Simplify/ de-clutter

Haptic feedback can be used to substitute or relief other modalities, simplifying the interaction, making it perceived with less effort or increase the comfort.

Humanize

Object interactions can be based on human interaction patterns to reach a more seamless, intuitive or emotional experience

Safety feature

Due to the seamless integration, haptic feedback can be used in critical situations without disrupting the users' perception.

Tailored feedback

Digital haptic feedback allows to tailor the feedback to each interaction.

Inclusive

Haptic feedback is great for inclusive interactions and support application for both visually or hearing impaired users.

Enhance

Haptic feedback can be utilised to make interactions more rich, prominent or to add a certain characteristic.

Object design

Haptic feedback can lead to different product designs by replacing mechanical interfaces with surface haptics.

Provide guidance

Haptic feedback can be used to create intuitive guiding systems by utilising multiple actuators or directional feedback.

Branding

Haptic feedback can be used to communicate brand values or brand specific characteristics.

Tutorial
Where to start

One of the main pain points when getting started working with haptic feedback besides the physical prototyping is acquiring theoretical knowledge. While one can go ahead without, it can be highly beneficial in creating successful and meaningful feedback.

The idea of the tutorial is to convey essential information on different topics to provide a general overview similar to the introduction of this thesis-report. It is the third part of the knowledge base, which is based on the research phase and its evaluation.

The biggest challenge in understanding haptic feedback is the lack of solutions where one can directly experience it in real life. By combining the tutorial with the prototyping toolkit, the user can experience an interactive showcase, for example, the effects of different parameters on the character.

The tutorial is made of three kinds of information blocks:

› Theory

› Live demo

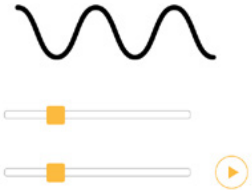
› Examples

Theory

A theory block provides easy to digest information on areas such as physiology, perception, technology or terminology.

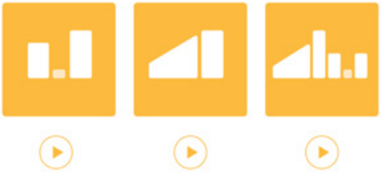
Live demo

If connected to the toolkit or when accessed via a smartphone, the user can explore haptics through interactive examples such as the influence of frequency and amplitude.



Examples

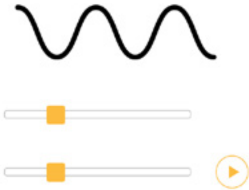
Through feedback examples, the user can experience how different approaches result in different characteristics, such as simple vs. complex patterns.



Tutorial
What you need to know

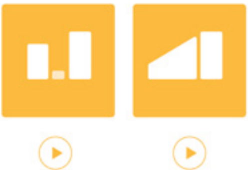
While access to theoretical information is not limited nowadays, acquiring an overview becomes more and more difficult.
In the tutorial section, a collection of relevant topics are broken down into simplified explanations such as the following:

Terminology

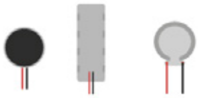


Haptic parameters

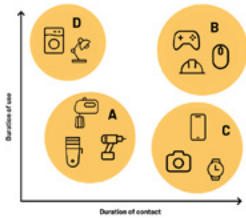
Perception



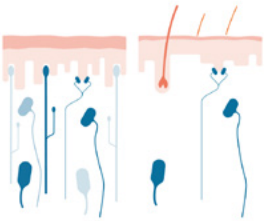
Feedback exam-ples



Technology



Categorisation



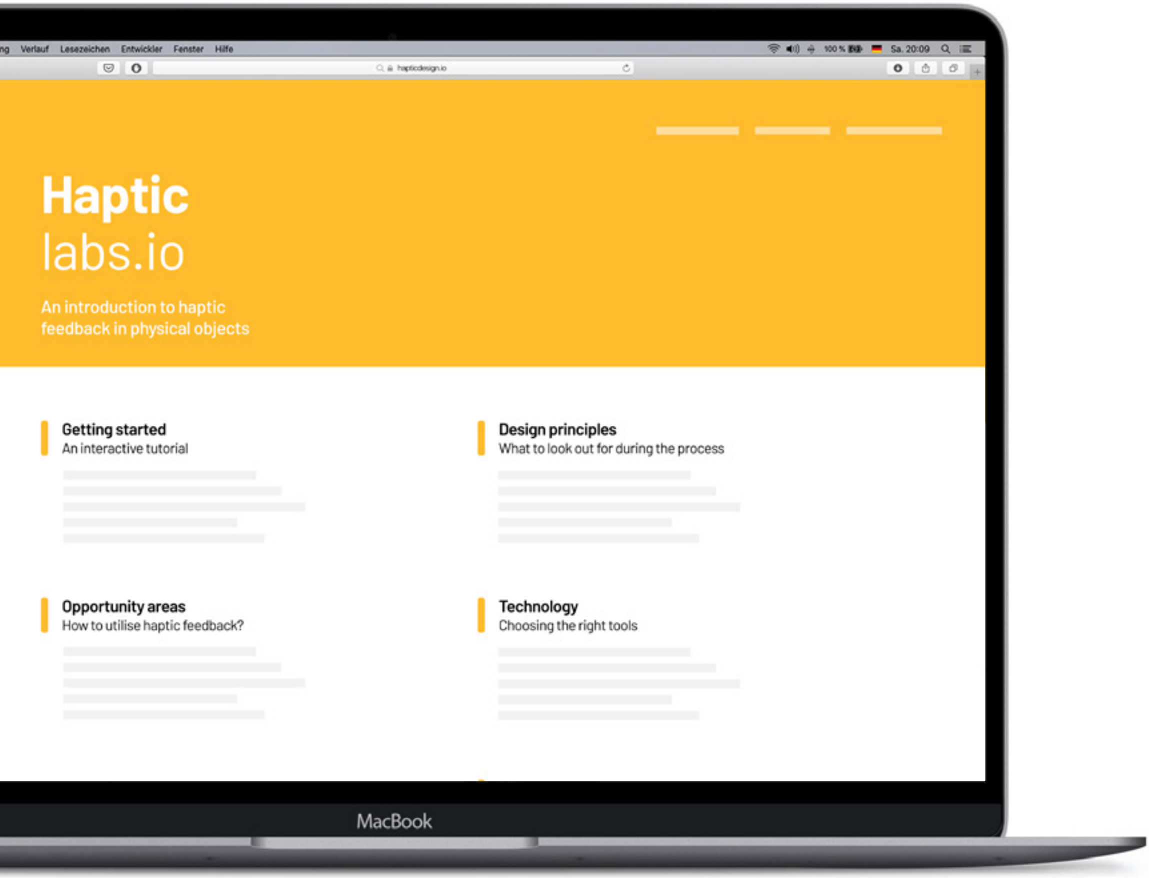
Physiology

Schemes

Online platform
Where it all comes together

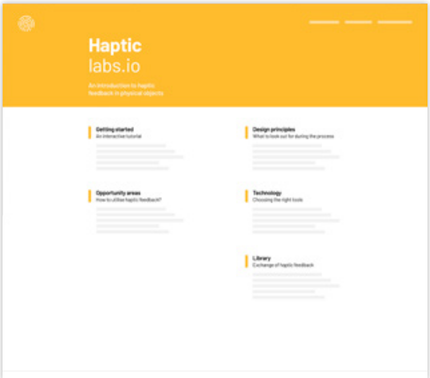
The knowledge base is a summary of my findings and takeaways during the project and also something I would have wished to have had in the beginning. It brings together the information needed to get started, supports during the process as well as inspires on how to utilise haptic feedback to its full potential.

The format of an online platform was chosen due to its ease of accessibility and the possibility to use sound and animations to translate haptic feedback in the best way possible.


Haptic
labs.io
An introduction to haptic feedback in physical objects
Getting started
An interactive tutorial
Design principles
What to look out for during the process
Opportunity areas
How to utilise haptic feedback?
Technology
Choosing the right tools
MacBook

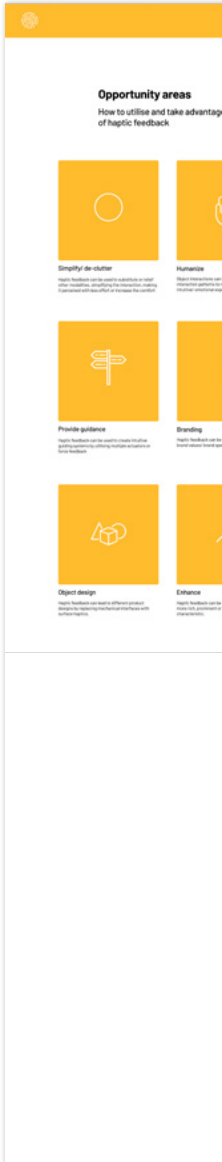
Platform overview
An interactive knowledge base

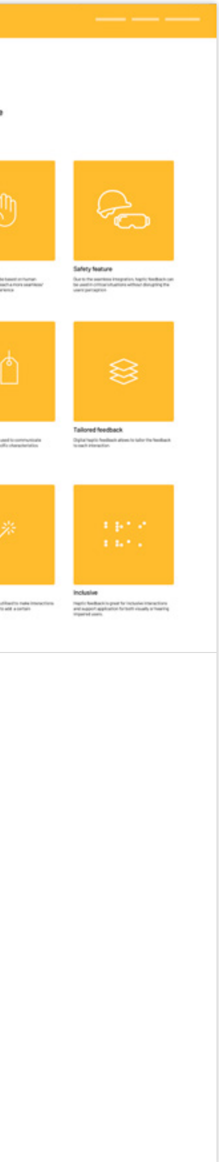
Home screen



The tutorial

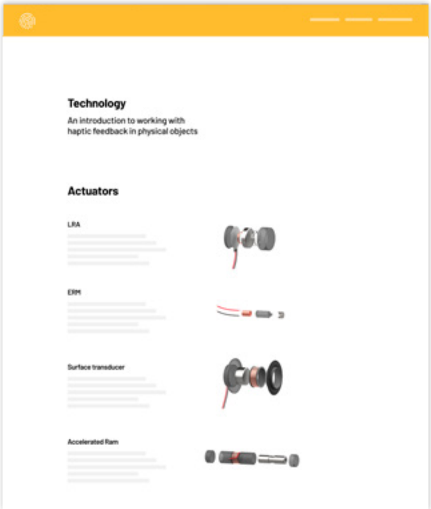
Opportunity areas





Design principles

Technology

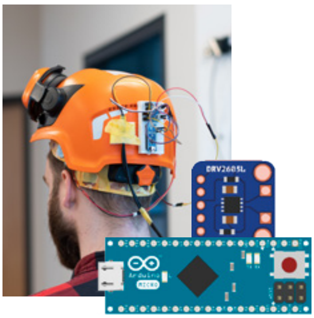


Exchange/Library

In summary
What it boils down to

Hapticlabs.io provides an ecosystem democratising haptic design. It simplifies the process of getting started, creating functional prototypes and taking full potential of the benefits.

Current design process

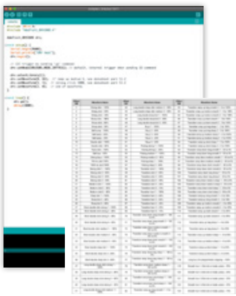


Prototyping

› Fragile and challenging prototyping

› Electronics put a lot of designers off

› A lot of pitfalls during the process



Modulating

› Complicated modulation process

› Requires coding knowledge

› Limited adjustment possibilities

Knowledge

› Extremely broad topic, difficult to get an overview

› Resource heavy process to get started

› Little inspiration available

Haptic
labs.io

Prototyping

› No electronics or coding skill required

› Mobile, compact and sturdy prototyping kit

Modulating

› Simple and intuitive design process

› Create highly tailored feedback

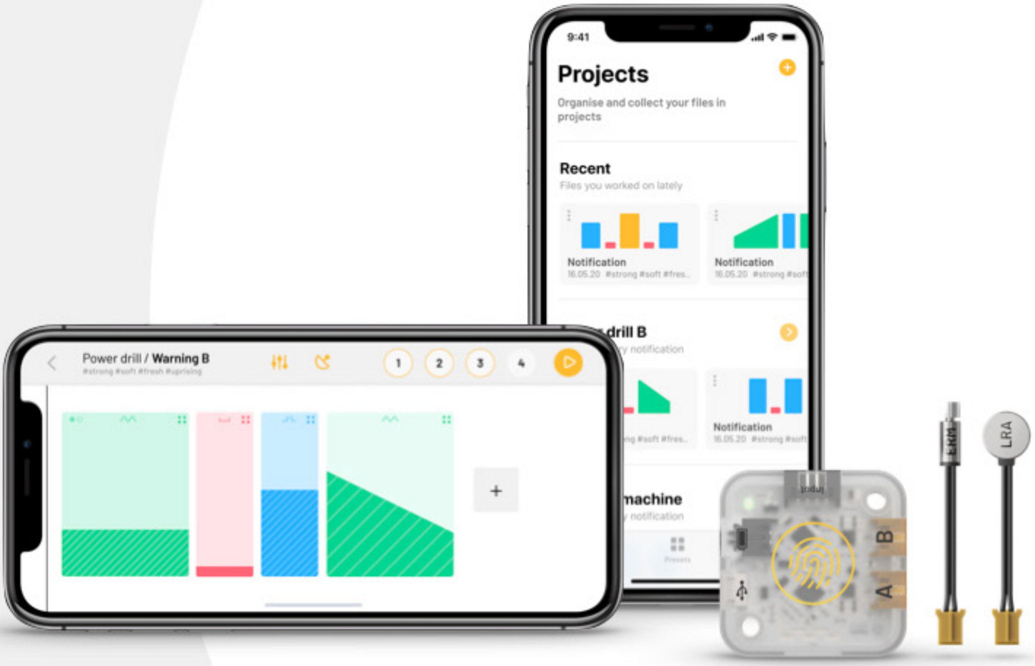
› Possibility to share and export the design

Knowledge

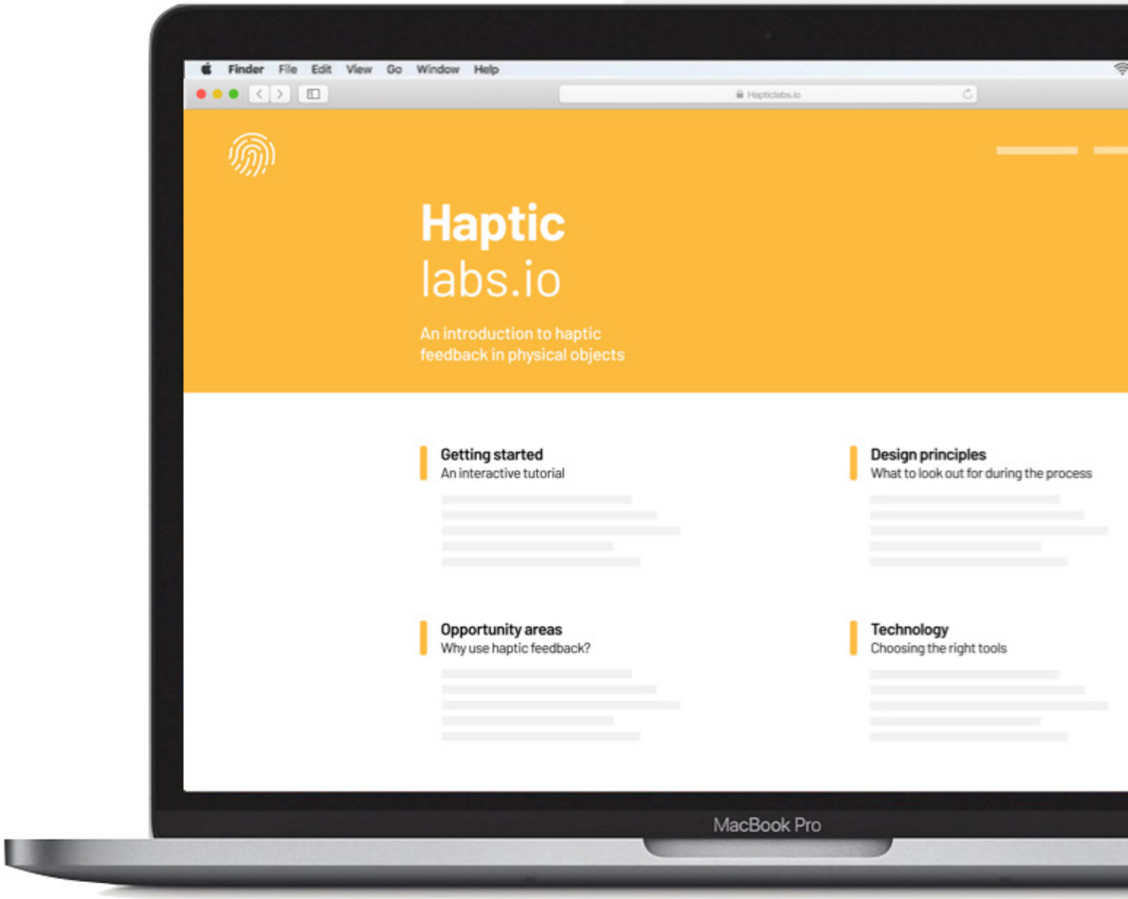
› Getting started in a breeze

› Discover opportunities and applications

› Design principles provide support in each stage



Prototyping kit



Knowledge base

Reflection and conclusions

Personal reflection
Is it already over?

When I decided to focus on haptic feedback for my thesis, I did not know what the outcome might be and where the project might lead me. What I knew was that the topic is highly intriguing, and it would allow me to push myself as a designer and APD student into new and uncertain areas.

Process

Starting without a problem, user group, or specific goal and keeping it open as long as possible was a conscious choice allowing the outcome to be based on applied experience as much as possible. One effect was that I had to highly rely on the process itself, working through dozens of iterations along the way, which lead to both dead ends, but also fascinating experiences. Staying at Intuity was highly beneficial to gain insights and kick-start the project. At the same time, it was also essential to take a step back and reflect on the findings and explorations. Haptic feedback is a highly complex topic with endless facets one can deep dive into and get lost in publications and details. It was crucial to limit myself in time and resources and re-evaluate the paths I took with people in- and outside of the project.
Working on the thesis during a world-wide pandemic certainly had an impact on the process. The initial plan on spending more time in the workshop, evaluating findings and concepts in more case studies was not possible. Also, the contact to users and the evaluation of concepts was only possible in a very limited manner. In addition, the work environment and the lack of exchange with colleagues took its toll.

Learning

Walking into an uncertain area came with a lot of challenges, but at the same time with a lot of learning opportunities. Although the topic was more focused on interaction design than traditional industrial design, I made good use of my skillset and enhanced it with new additions, which was very important to me.
I was able to strengthen my knowledge in coding and electronics, took my model building experience into action, integrated UX and UI design, created a product system with a common core and defined not only the hard- and software solutions, but also how I can communicate and educate other designers.

Looking back

It was a very ambitious approach to combine everything in a single project, and at times it seemed overwhelming. Even though I could have taken a lot of short-cuts and exclude parts, I am thrilled to end up with a solution that is beneficial for all stages of the haptic design process. Looking at my initial goals and wishes, I am proud of having achieved most of them.

Looking forward

One puzzle piece missing is making the result available for other designers to benefit from. While finishing up the satellite and smartphone application is out of my reach at this point, providing access to the knowledge base is already in the making.

Initial goals & wishes
On a project and personal level

Project goals

Synthesise knowledge to allow designers a headstart in working with haptics

Create simple principles on how to work with haptics as a designer

Use prototyping to discover and display opportunities

Through interviews get an insight into how experts work with haptics

Create an easy to use toolbox for creating haptics

Personal goals

Become an expert in the field of haptic feedback

Create functional prototypes

Create a final result which stands out of the mass

Project wishes

Identify how to create a haptic brand experiences

Illustrate the findings in the most simple and appealing way

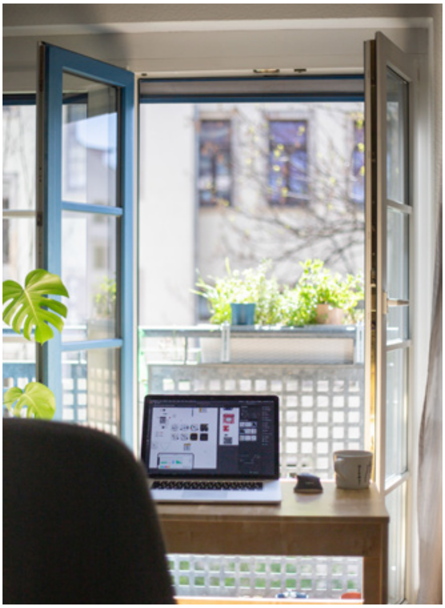
Discover what it takes to create great haptics

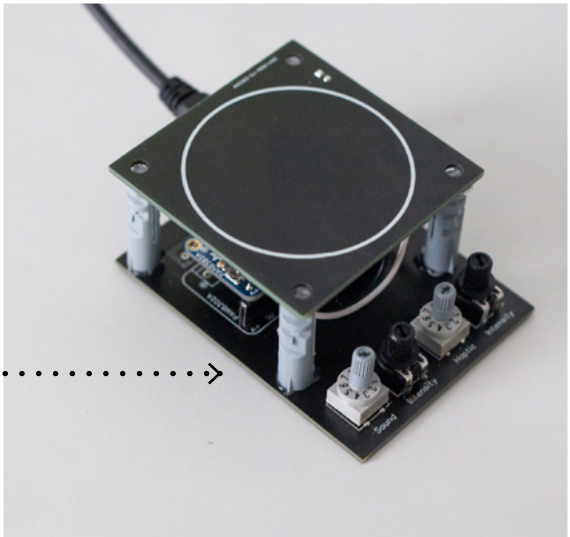
Apply my findings in real projects

Create an outcome which could potentially become an acknowledged solution

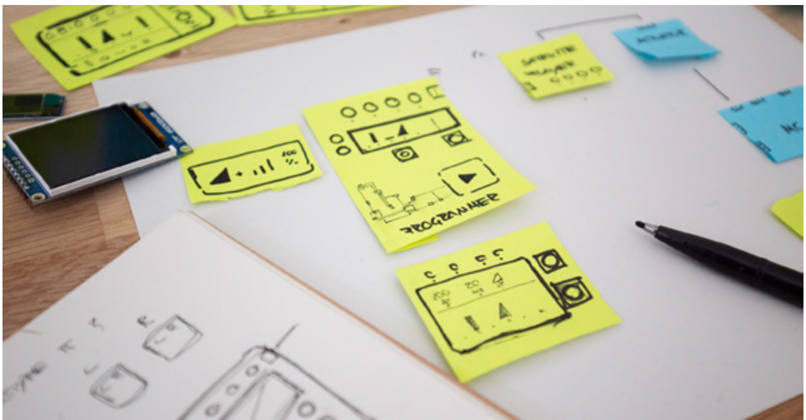
Behind the scenes
A COVID-19 workplace

The global pandemic most certainly had a big impact on the project and lead to some creative problem solving along the way.





Dowels



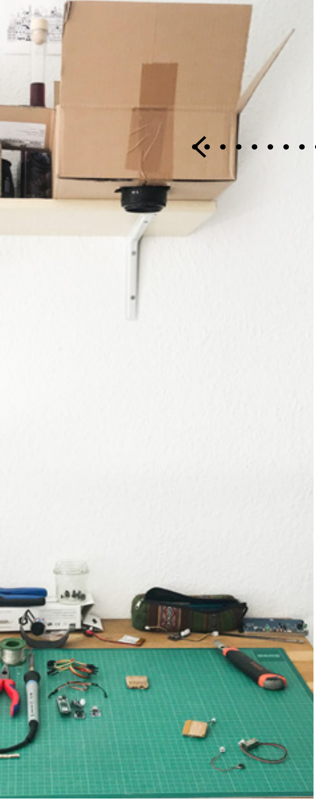
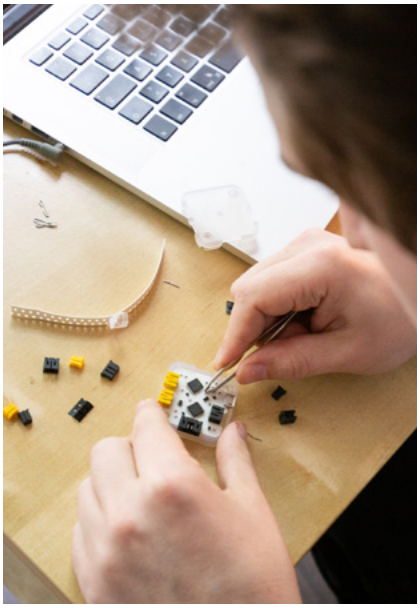
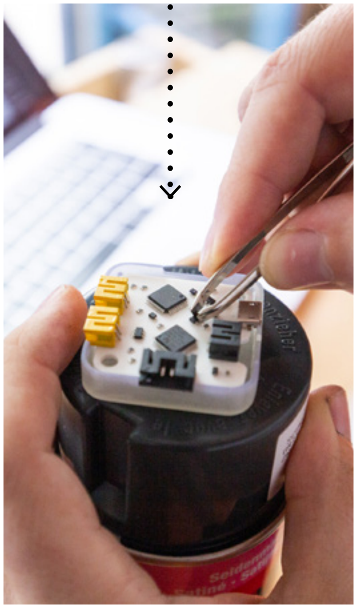


Photo booth

Bathroom equipment





Balcony
paint booth

Wood/ electronics/
paper workshop

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71 Navigation by shashank singh

71 Scale by Vectorstall

71 Chainsaw by lastspark

71 Screwdriver by Ben Davis

71 Hand Mixer by Graphic Tigers

71 Hard Hat by Grégory Montigny

71 Multimeter by Lars Meiertoberens

71 Chair by Drishya

71 Espresso Machine by Yorlmar Campos

71 Keys by Gregor Cresnar

71 Spirit Level by Srinivas Agra

71 Knob by Andrejs Kirma

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71 Scalpel by Berkah Icon

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73 Washing Machine by Tomas Knopp

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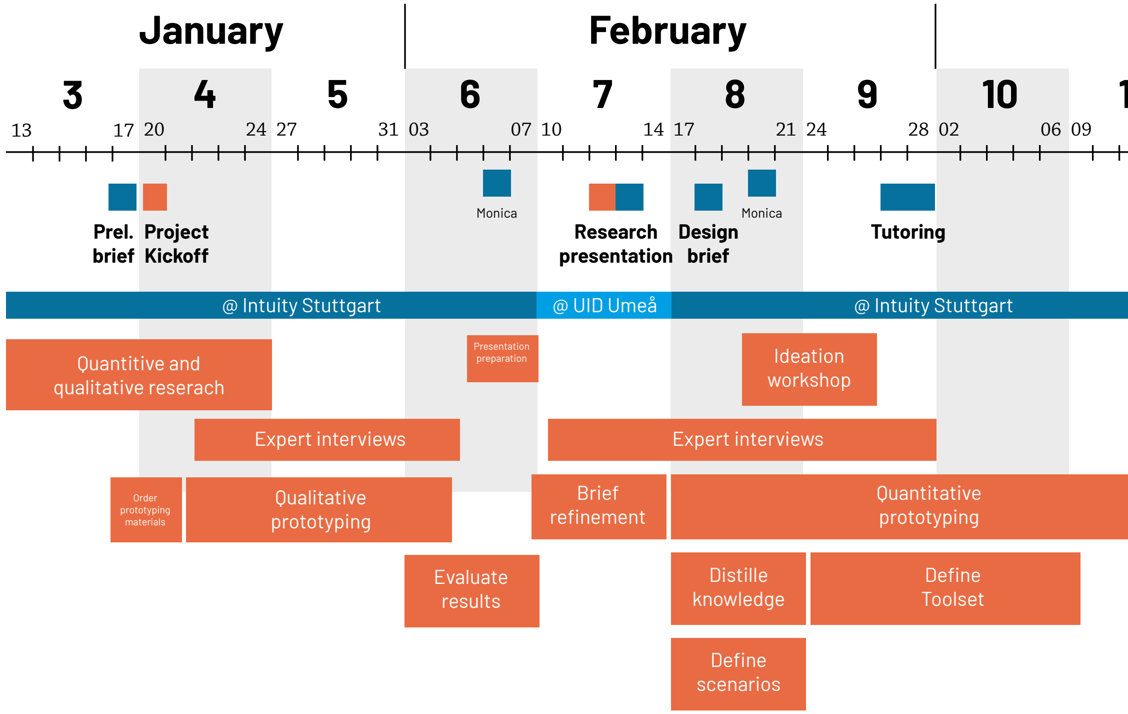
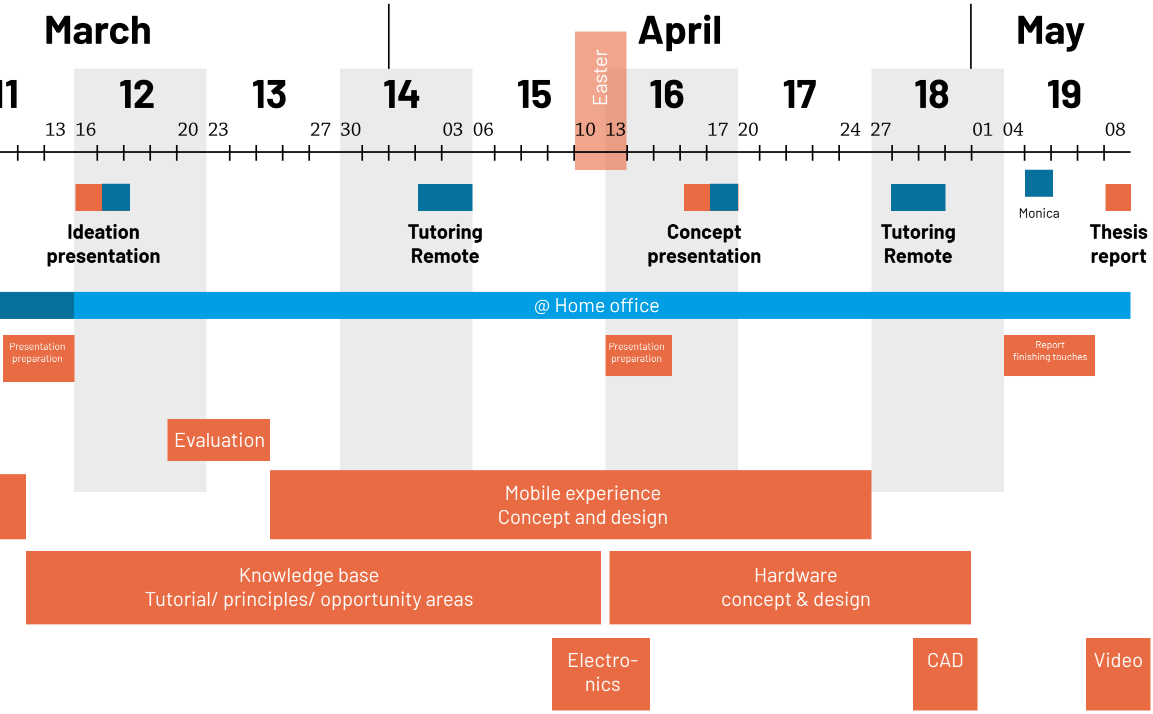
Appendices

Time schedule
Project planning





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Easter
Ideation presentation
Tutoring Remote
Concept presentation
Tutoring Remote
Monica
Thesis report
@ Home office
Presentation preparation
Presentation preparation
Report finishing touches
Evaluation
Mobile experience
Concept and design
Knowledge base
Tutorial/ principles/ opportunity areas
Hardware
concept & design
Electro-
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CAD
Video