Adriaan Bernstein

Metaphoric Interfaces

Msc Design for Interaction
Thesis

A case study for the digitally enabled luxury kitchen

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Metaphoric Interfaces:
A case study for the digitally enabled luxury kitchen

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INTRODUCTION

Food, and the practice of cooking in particular, is very rich in experiences. It challenges our perception and immerses us in a world of sensual impressions. Savoring the abundance of textures, flavors, and aromas – learning to understand and manipulate their various aspects - that is what makes the food experience so gratifying for many. This makes the kitchen a sanctuary for our senses.

And yet, as technological progress permeates further into more and more aspects of our lives, it is also entering our kitchens. And with it, screens, apps, and algorithms are threatening to replace many of those sensuous interactions with generic ones. But what if, instead of subjecting yet another domain to streamlined monotony, technology could be symbiotically woven into the sensuous nature of the experience?

It is the stated goal of the author to make a convincing argument for the thus far underexplored potential of technology to do just that. In particular, this thesis project argues for the creation of a scenario in which technology is used to complement and enrich, not supplant our sensory & intuitive decision-making capabilities.

BACKGROUND

Successful interfaces have often been the result of powerful metaphors. By likening an unfamiliar context to one we are more familiar and experienced with, it becomes relatable and easier to navigate *(Figure 1)*.

With its wealth of sensory stimuli, the kitchen space offers enormous opportunities for the creation of such metaphors. At the same time, the act of cooking is riddled with sensory "black boxes ": Moments in which little to no information is available to our senses *(Figure 2)*. In the kitchen, those are often caused by literal boxes: Ovens, microwaves, fridges, etc.

Whenever these moments occur, the process moves beyond our sensory reach. Being deprived of any direct means of probing food throughout the process presents a big challenge: Clues that would otherwise inform decisions and provide reassurance are no longer intuitively available.

This lack of tangible, practical information is therefore a core challenge future interfaces in the kitchen space will have to address. To some extent, the way these interfaces are shaped will define the nature of our future interactions with food. Considering the wealth of opportunities the kitchen space provides, it is our responsibility not to let them go to waste.

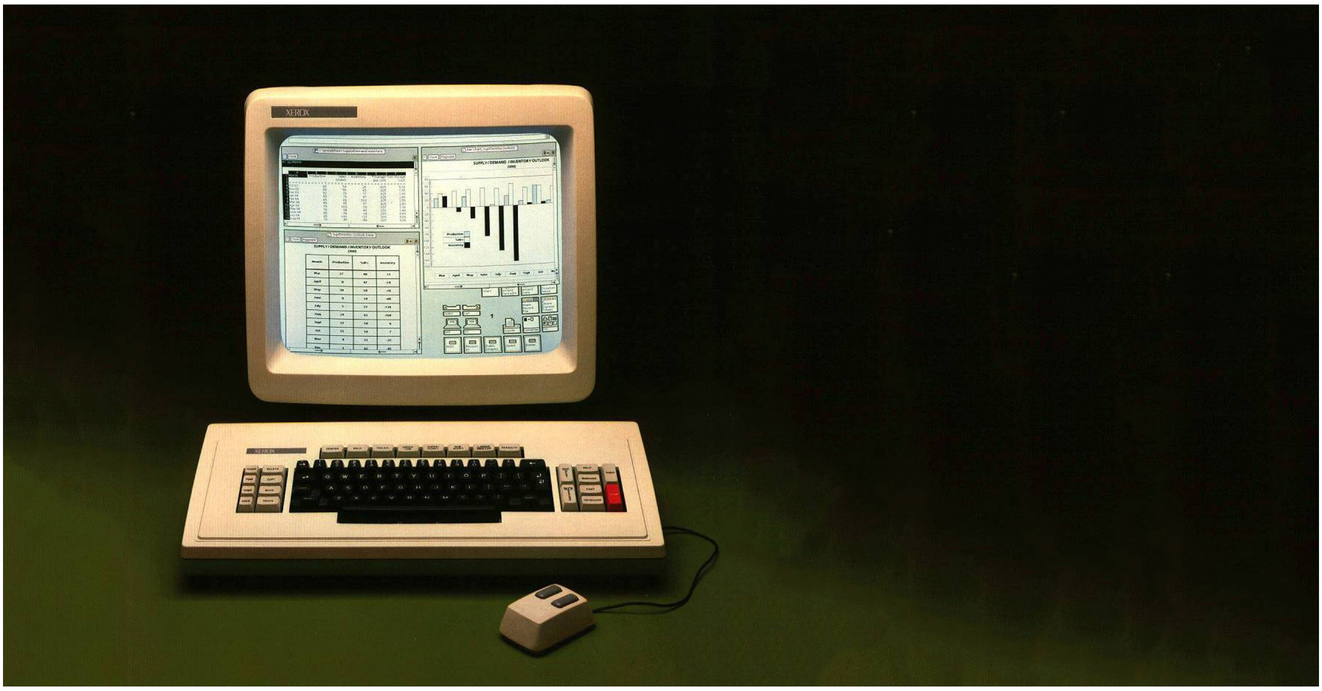


Figure 1: *The XEROX Star was the first commercially available product based on the desktop metaphor introduced by Alan Kay at Xerox PARC in 1970. It later was adopted by Apple and Microsoft and went on to revolutionize the way we interact with computers. It turned a complex, professional device into a powerful tool for everyone by making its functions relatable.*

Figure 2: *A situation limiting the cook's sensory perception of food. A physical box, the oven, represents a metaphorical black box where sensory access to the food being prepared is difficult. Baking thus is a clear example for a gap in the cooking process causing a reduction in sensory information value.*

GOAL

The end goal of this project is to preserve user engagement in the kitchen realm. This becomes apparent by observing the two most common ways used to navigate past the previously described sensory gaps *(Figure 2)*.

One possibility is not to confront users with challenges they are inexperienced with. To that end, automation can be a viable solution: Tasks and decisions that are beyond the expertise of a user are handled by the system *(Figure 3)*. This, however, happens at the expense of the user's autonomy. While this might be desired by some, more ambitious users may want or need to stay in control of the process *(Figure 4)*. In those cases, a conceptual understanding of the process is necessary.

Most commonly, gaining this understanding involves a process which requires some level of proactive work. This, amongst other things, can mean reading manuals, following tutorials, or undergoing a process of trial and error. All these measures require effort and are time-consuming in nature, giving them the potential to be major sources of frustration.

To prevent users from disengaging from the process, it is necessary to find alternative ways to make this knowledge accessible without diminishing the user experience. This objective raises the following questions:

- **How can interfaces be shaped to help effectively bridge sensory gaps?**
- **What kind of interaction strengthens user engagement?**

Both the increased usage of automation, as well as the exacerbation of complex knowledge required of enthusiast users, are direct results of how technologies are being incorporated into modern kitchens. This raises additional questions:

- **What role does technology currently play in driving complexity?**
- **How can technology enable interfaces that deliver information more intuitively?**

Figure 3: *Automation in scenarios with varying degrees of desirability for the user. While healthcare applications, such as the Apple Watch and the Kardia line-up by AliveCor, are using Artificial Intelligence to collect and interpret data to the user's advantage by detecting potential health hazards, other usages are more ambivalent. Smart Speakers and streaming services that use machine learning to choose agreeable music for the listener may be convenient, but may also lessen the emotional rapport to the music selection and decrease ownership over one's personal tastes.*

Figure 4: *Desired interaction qualities for users that are at least equally as invested in the process, as well as in the outcome of an activity. Especially in any context relating to personal enjoyment and self-realization (music, food, self-expression) the importance of autonomy becomes apparent.*

COMPANY

As the world's oldest kitchen appliance manufacturer and a renowned luxury brand, Gaggenau has a vested interest in finding answers to those questions. With its longstanding tradition of quality and functionalism, Gaggenau has built a reputation for bringing well designed, professional tools to the home user. Their products stand out by reconciling many seemingly contradictory concerns of their users: Delivering careful, intentional innovation that maintains simplicity, while helping customers accomplish individual ambitions and achieve professional results.

Such innovation must allow users to develop a complete understanding of the possible action space in the kitchen, while ensuring a pleasant, engaging and simple experience. Staying ahead of technological developments while finding the right ways to contextualize those in the kitchen space are key concerns for Gaggenau.

Being a company whose goals are uniquely aligned with the objectives of this thesis makes Gaggenau a great partner for this project.

A Gaggenau Showroom in Chicago

Margrave Ludwig Wilhelm von Baden founded the company in the eponymous Black Forest village of Gaggenau in the year 1683.

APPROACH

The challenges this work tries to address are not only rooted in the usability of existing products, but also in the way technology-driven visions are shaping the future of the kitchen *(Figure 5)*. With a focus on the interplay between humanistic and technological disciplines, this thesis therefore tries to find answers in the conceptual space at the intersection of these ideas:

- **Understanding usability challenges of present-day technologies by taking on a human-centered standpoint**
- **Developing technologies around human intuition using an innovation-driven design- & engineering process**

The first step will discuss the use of information by looking at different interaction models. The ways humans deal with information and the ways information should be directed are particularly interesting: What different kinds of information are there, what reactions do they evoke, and what is required to make them actionable? This knowledge will help create a more complete understanding of the solution space.

The subsequent exploration of possibilities within this space will begin with an ideation process centered around different technologies and interaction types. The usage of an iterative research through design process will be the basis for formulating and testing different assumptions. By building a range of prototypes, the technical feasibility of different ideas, as well as their validity in the context of interactions rich in sensory depth, will be evaluated.

These prototypes will provide the building blocks for the subsequent step: Insights gained through the examination of new interaction modalities, their usefulness and value, as well as the existing technological limitations, will allow for the creation of specific concepts for the kitchen. A selection of useful concepts will be defined in order to further explore their potential. Finally one concept is chosen to be elaborated in greater detail.

This elaboration will involve the creation of a demonstrator: A final prototype will be developed in order to provide a frame of reference allowing for the evaluation of the goals initially put forward by this thesis. It will also demonstrate the project's vision and make its findings tangible.

To conclude this project, the demonstrator will be put into practice, allowing users to experience it in context. These experiences will form the basis for the discussion of the aforementioned factors: How is it performing? To what extent does it fulfill the requirements set forth in the beginning of this project? The project will end with recommendations for future research and practice.

Figure 5: *A picture promoting Home Connect, Bosch's ecosystem for smart appliances. It illustrates the race towards the inclusion of new technologies in home appliances, but also typifies the industry's ongoing search for meaningful and coherent concepts.*

EXPLORATION

WHY MULTIMODALITY

As suggested in the introduction to this thesis, the approach from this point forward revolves around exploring multiple modalities in interface design . This chapter intends to provide some context as to what multimodality means, why it is important, and how it relates to the creation of enjoyable, enriching interactions.

The term “Multimodality” stems from the field of Human-Computer Interaction (HCI). In it, a “Modality” describes a distinct, independent channel for sensory input- and output information to be exchanged between a human and a computer (Karray, Alemzadeh, Saleh, & Arab, 2008). Typically, modalities are defined analogous to human senses and common input devices *(Figure 6)*: While computers often communicate with their users using visual, auditory or tactile modalities, users often use touch screens, pointing devices, or, more recently, speech recognition and computer vision as the modalities to enter information into a computer system.

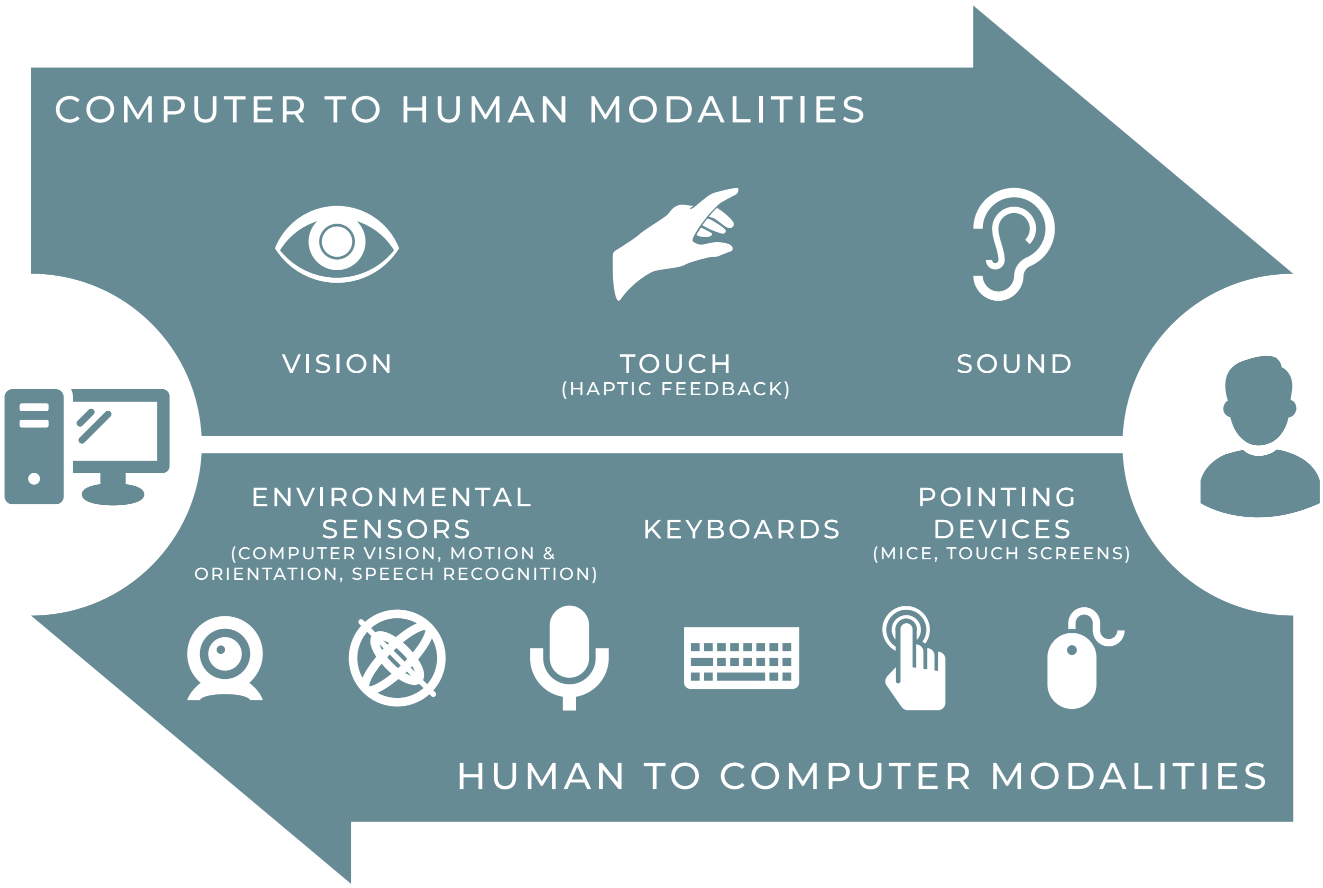


Figure 6: *Common human & computer modalities*

Why is a concept in Human-Computer Interaction relevant for a seemingly unrelated domain, such as the design of interfaces for high-end consumer kitchen appliances? The answer lies in current technology trends inherent to consumer products and electronics. Technological progress has forced designers to find new answers to create meaning for users before: A good example for that is the mass appearance of electric appliances at the turn of the 20th century. They introduced a breadth of new, unfamiliar capabilities into products *(Figure 7)*. By going beyond the utility provided by previously known mechanical devices, the design of these new products had to ensure users would be able to gain access to and derive meaning from these new capabilities (Müller, 2017). Currently, we are undergoing a different, but equally disruptive transformation: The advent of ubiquitous computing. Once more, a broad set of new functionalities are being integrated into consumer products. This time, these are emerging from computation, sensor data, and the analysis thereof *(Figure 8)*. As computers and consumer products are becoming more and more synonymous with one another, HCI research holds many important insights for contemporary design challenges.

There is, however, one significant caveat: Current research and literature often focuses on the application of multimodality in specialized, professional settings (medical technology, heavy machinery, etc.). It predominantly relates to the effectiveness and reliability of information transfer into and out of a computational system. These are logical priorities if multimodal interfaces are to solve issues in high-stakes situations where lives are potentially at risk in case the user misinterprets a piece of information. As the usage of multiple modalities allows for information to be presented in a redundant way, it should come as no surprise that multimodal interfaces are of great interest to anyone trying to increase the robustness of an interaction.

This is not the only valuable quality of multimodality however: Even though it has been less thoroughly researched, there is a persuasive argument to be made for the utilization of multimodality to offer complementary instead of redundant information across multiple modalities. That way, richer and more wholesome interactions can be created. It stands to reason that many positive implications for user satisfaction, aesthetics and ease-of-use are there to be explored.

In other words, this describes the exploration of sensory stimuli and the human senses responding to them as a designing material, just as much as the technologies needed to do so themselves.

The remainder of this chapter will explore different senses and stimuli, as well as the technologies needed to cater to them.


Source: Smithsonian Institution


Source: Science Museum London


Source: MoMA


Source: Smithsonian Institution

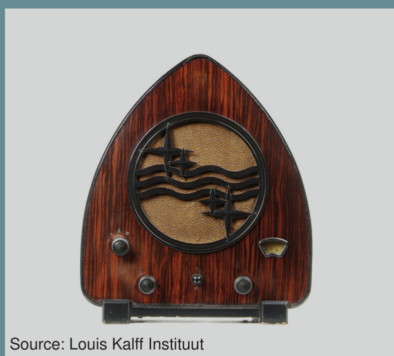

Source: MoMA


Source: Wiel Arets

First row:
Kerosene lamp, 19th century
Early electric light, T. Edison, 1879
Bauhaus Lamp, W. Wangenfeld, 1924

Second row:
Tea pot, early 19th century
AEG Electric Kettle, P. Behrens,1909
Alessi Electric Kettle, W. Arets, 2009

Third row:
Philips “Chapel” radio, L. Kalff, 1931
Telefunken FE-III television, 1934


Source: Louis Kalff Instituut


Source: Early Television Museum

Figure 7: *A selection of products common before and after the technological revolution. Early electric appliances often improved on and resembled known products (Edison’s electric lamp and the AEG electric kettle designed by Peter Behrens draw heavily on the appearance of previous products). With the increasingly fast emergence of radically new product groups that had no precedents to rely on, electric appliances had to find a new visual language to communicate their purpose to users. The Philips 930A radio and early TV sets by Telefunken (the first company to manufacture electric televisions) show a transition to an increasingly functional design language. This is later also reflected in the design of more conventional products (see Wilhelm Wangenfeld’s WG24 table lamp and Wiel Arets’s electric kettle).*

Figure 8: *A range of smart products representative of new abilities and usage scenarios enabled by computation. From top left to bottom right: Nest Thermostat, a smart thermostat capable of learning, predicting and controlling temperature settings for its user while maximizing energy-efficiency and comfort; Roomba, an autonomous vacuum cleaner capable of unsupervised vacuum cleaning and maintenance (recharging, emptying); Amazon Echo Show, a smart assistant and display capable of conversationally supporting users in various ways, for example by controlling other smart devices (shown in this case with the Philips Hue intelligent lighting system and its companion app); Tile, a Bluetooth-enabled tracker allowing users to tag and monitor the location of objects such as keys, wallets, etc.*

THE SCOPE OF MULTIMODALITY

Unlike what some might expect at first glance, there are a plethora of technologies capable of enriching interactions with new, sensory qualities. While some technologies are already being applied in mainstream interface development and design, others are not. They may be seen as being too complicated or inaccessible to Designers, or not as worth exploring due to a supposed lack of technological maturity. Approaching innovation without these preconceptions may reveal a wealth of opportunities. In order to limit these opportunities to ones relevant for this project, the following questions come to mind:

Which senses have the most potential?

Conventional wisdom states that the human senses are those linked to the five sensory organs: The nose (olfaction), the tongue (gustation), the eyes (sight), the ears (audition), and the skin (touch). In reality, many more senses play important roles in human perception. Some examples include the perception of pain (nociception), the passage of time (chronoception), temperature (thermoception), and the kinesthetic sense (proprioception), which describes the perception of one's body's position and movement in space. Which of these senses should actually be targeted by interface designs is strongly context-dependent. The kitchen space involves many activities involving an understanding of temporal and spatial processes, which may present a good starting point.

Figure 9 provides an overview of different sensory modalities and their respective roles.

In which direction should information flow?

This question is especially important to answer. A touch screen interface, for instance, can be seen as a multimodal interface: It involves both visual, and haptic elements. For the purposes of this project however, this definition alone is not sufficient: While the (visual) display allows the computer to convey information to the user, it does not allow the user to input information into the computer system. Conversely, the digitizer (the part of a touch screen that recognizes touch) allows the user to input information into the system but does not display any information to the user *(Figure 10)*. So, while the overall interaction takes place across multiple modalities, the communication from user to computer (or vice-versa) does not. To resolve this ambiguity, an additional qualifier is needed. While there certainly is great potential for designing bi-directional interfaces, this endeavor is outside the scope of this graduation. The main goal of this thesis is to make abstract information more easily accessible and contextually meaningful. Multimodally conveying information from the system to the user should therefore be the priority.

Consequently, it is important to realize that any kind of innovation will not diminish the importance of already existing interfaces. As an example, many existing interfaces rely heavily on visual elements, such as screens. These will retain their importance for rich interactions: In fact, if vision is the first step towards a more intuitive, human interaction, touch can be seen as a next logical step towards build expand the repertoire of an interface. As Bill Buxton, a pioneer in HCI and multi-touch interfaces, points out, a core challenge for interfaces is to find elements that work together well, or that support and complement one another (Buxton, 2007).

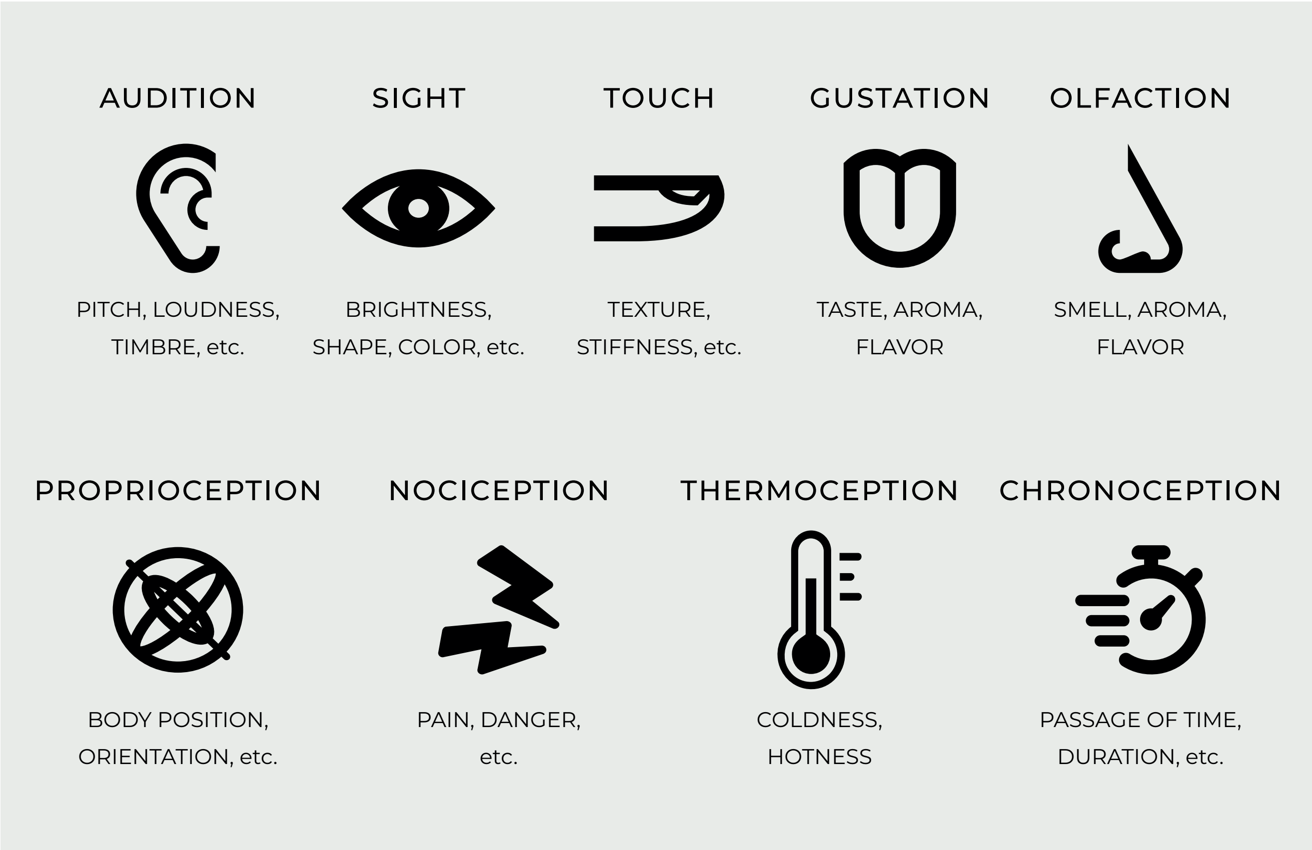


Figure 9: *An overview of common sensory modalities and their roles*

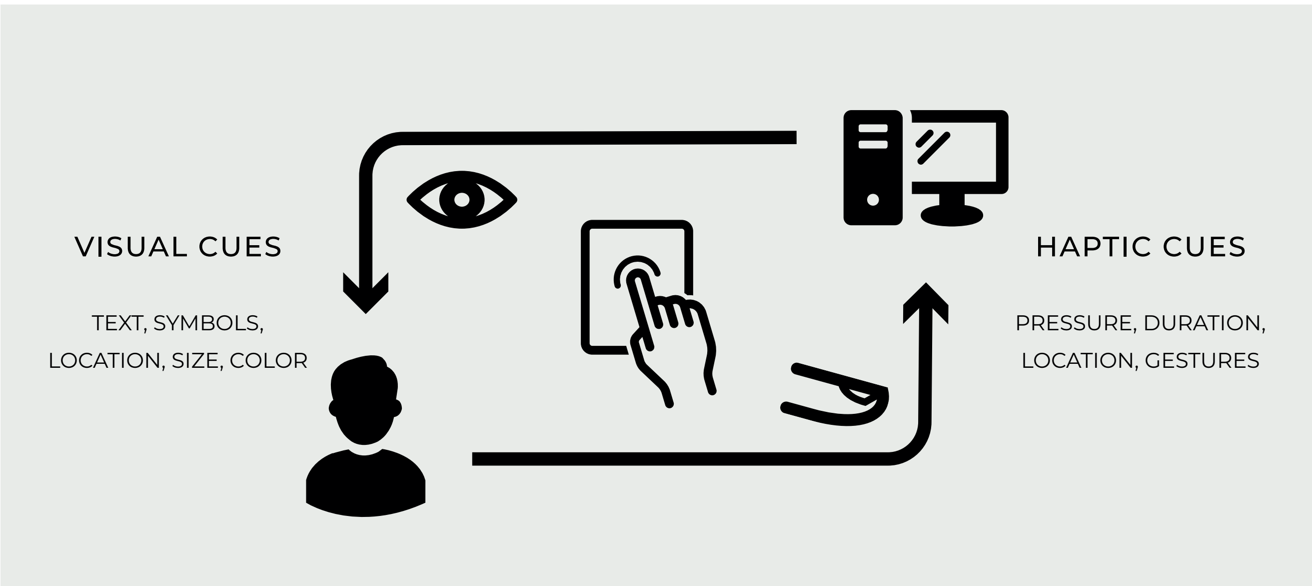


Figure 10: *Schematic representation of the information flow common for an interaction with touch screen interfaces*

INITIAL IDEATION

With these guidelines in mind, a range of initial ideas were explored *(Figure 11)*. The following pages provide an overview of prototypes investigating different conceptual directions. These will be accompanied by background information about different aspects that influenced that prototype, such as the motivation behind it, its working principle and the sensory effect it was meant to evoke.

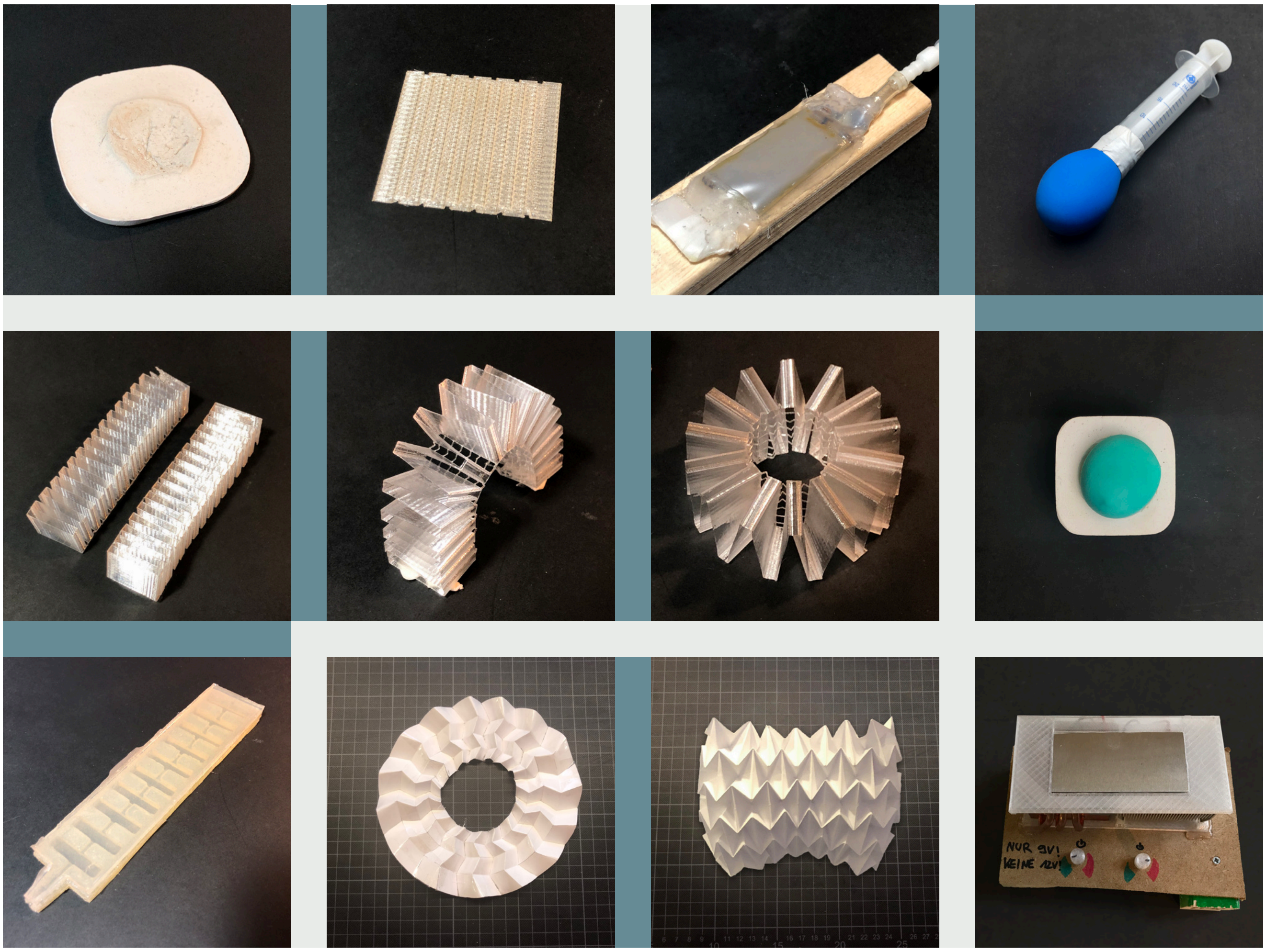
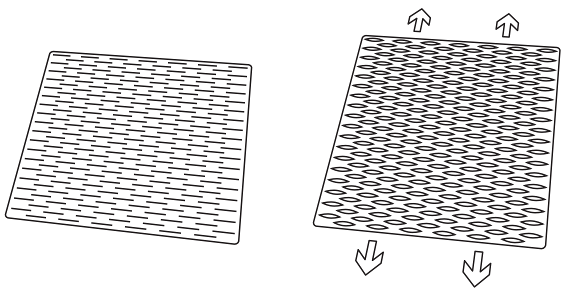


Figure 11: *Prototypes investigated in this chapter, grouped by topic. From top left to bottom right: Texture renderings (p. 25), Stiffness Renderings (p. 26), Shape Renderings (p. 30), Shape & Texture Renderings (p. 33), Temperature Rendering (p. 35)*

TEXTURE

This first exploration began with a rudimentary experiment into ways of rendering different textures. For that purpose, a slotted pattern similar to patterns found in living hinges was created and applied to a 3D printed membrane *(Figure 12)*. The membrane was manufactured by depositing a thermoplastic elastomer (TPE) onto a glass plate. This allowed the resulting membrane to have a smooth and seamless texture when relaxed and an increasingly rough texture equivalent to the amount of tension applied to its edges.



Aside from this experiment, an initial test was designed to look into the information value of texture. To ascertain how well texture carries information, the coconut was chosen as an object that unified many aspects of sensory experience: Weight, balance, texture, size and smell all play a role in how the coconut is perceived.

To single out the texture and ascertain how much information it carries, a section of the textured shell of the coconut was molded in gypsum *(Figure 13)*. This test turned out to be a quick way of confirming that texture can hold significant amounts of information: After exposing just a handful of people to the texture sample, it became clear that its fibrous qualities evoked associations to natural materials, such as linen or wood. At the same time, it served to affirm that without the perception of the coconut's other properties, many synergetic aspects of experiencing the texture are lost.

Figure 12: *A 3D-printed TPE membrane with expanding and contracting patterns, depending on the tension being applied. That way, a range of textures from smooth to rough can be created.*

Figure 13: *A gypsum mold of fibrous material, in this case of a coconut. It served to test how much information about the original object was retained just by its surface texture.*

STIFFNESS

As the exploration of texture reaffirmed, experiencing information in one modality alone is often not sufficient to make important information inherently available through the properties of a sensory interface. Texture alone maps onto a rigid, unyielding surface, much in the same way visual information does on a screen. By interfacing with our sense of touch in this way, it leaves out one aspect that is often experienced in conjunction with touch: an object's stiffness.

Finding ways to render stiffness in an interface may tie into some interesting capabilities: Aside from being an evident companion to texture, it may also allow for the involvement of our kinesthetic sense. Stiffness and the way it relates to the deformation of an object can help create new use cues. These can be based on our ability to memorize different manipulations according to how they behave spatially, rather than visually. This might prove advantageous in certain contexts, especially when it comes to the preparation of food. Freshness, ripeness, doneness, and many other qualities are often gauged by the perception of stiffness.

With this in mind, different ways of creating objects and materials capable of rendering varying degrees of stiffness were researched. There are a number of potential avenues: Purely mechanical solutions revolving around spring mechanisms, thermo-chemical solutions involving low-melting-point elastomers or alloys *(Figure 14)*, or physical-mechanical solutions, such as laminar jamming structures *(Figure 15)* or particle jamming devices *(Figure 16)*. Due to relevant safety advantages as well as its easily accessible nature, this latter working principle was chosen as a basis for the creation of prototypes.

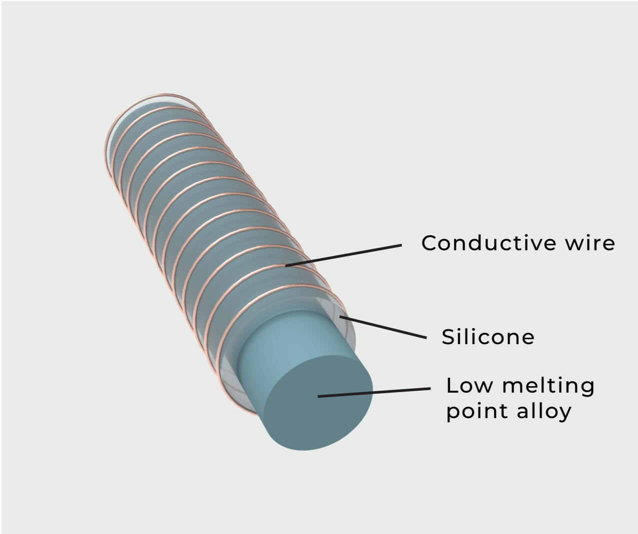


Figure 14: *Schematic representation of a variable stiffness fiber developed at the École Polytechnique Fédérale de Lausanne and the Istituto Italiano di Tecnologia (Tonazzini et al., 2016). Running current through the conductive wire coil heats up the low melting point alloy, thereby reducing the fiber's stiffness. Letting it cool reverses the effect.*

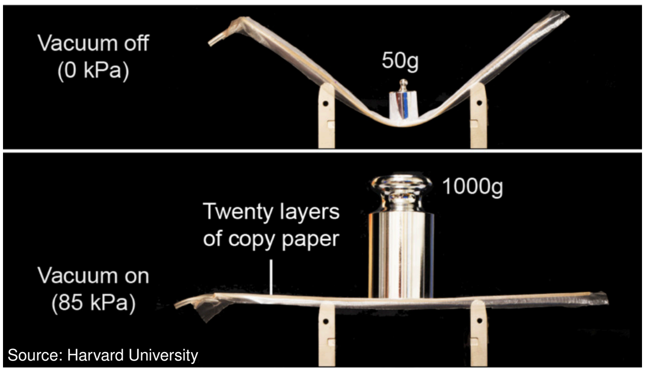


Figure 15: *Demonstration of the working principle of laminar jamming structures developed at Harvard University (Narang, Vlassak & Howe, 2018)*

Based on the working principle shown in *Figure 17*, first ways of creating prototypes were explored. In an initial attempt, ground coffee was placed in between two thin sheets of silicone, which were heat welded together *(Figure 18)*. Thanks to the inclusion of a pneumatic tube, a syringe could be used in order to apply negative pressure to the resulting chamber. While this device served to confirm the working principle, the range it was able to produce was very limited. Due to its shallow form directly mounted onto a wooden carrier, the resulting states ranged from stiff to very stiff.

To achieve a broader spectrum, a different shape was needed. This was accomplished by using a balloon. Once filled with ground coffee and fused with the body of a modified syringe, the round shape allowed for manipulations in greater depth, with more spatial dimension, and with a broader spectrum *(Figure 19)*.

As this prototype yielded promising results, yet was limited in terms of experimental applicability, a modified version was created. It retained the balloon and ground coffee structure, but instead of being directly mounted to a syringe, the device was embedded in a gypsum base *(Figure 20)*. The goal was to create the semblance of a button or dial, allowing for an easier way to test the device in the context of a kitchen and enabling easier associations in that direction at a later stage.

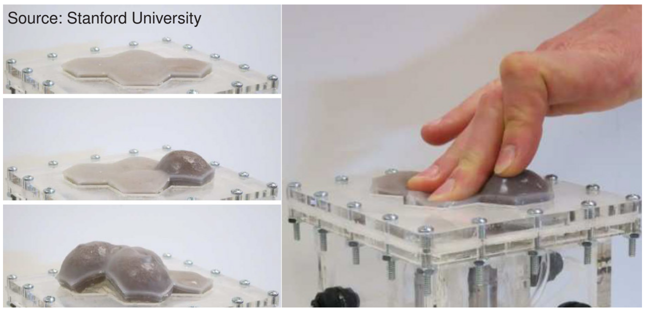


Figure 16: *A particle jamming display with deformable hexagon shells that render different levels of stiffness depending on the strength of a vacuum applied. This device was developed at Stanford University (Stanley, Gwilliam, Okamura, 2013)*

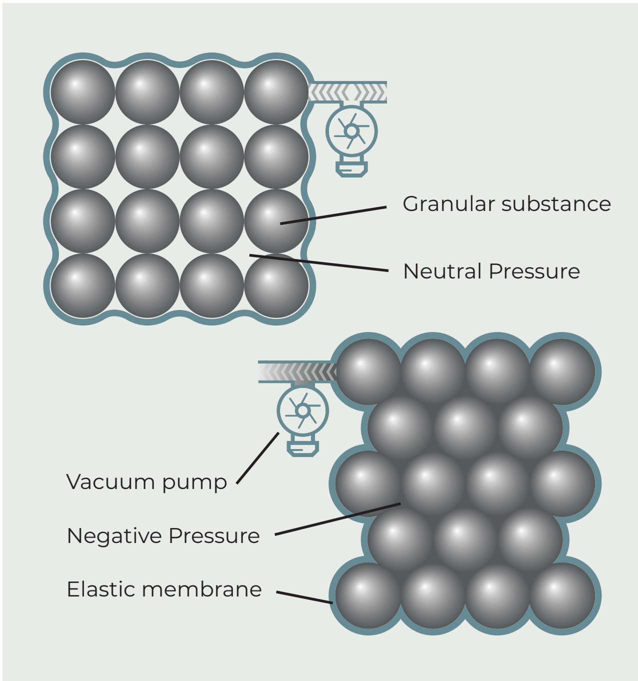


Figure 17: *Schematic representation of the particle jamming working principle: A fine, granular substance (e.g. sand, ground coffee) is enclosed in a flexible, airtight shell. While under normal pressure, the particles can move past one another, making the device malleable. With increasing negative pressure, particles begin to mechanically jam against one another, resulting in stiffness.*

The base was designed around a centrally mounted pneumatic connector, allowing for the device to be connected to a vacuum pump. First actuation attempts using widely available electric vacuum pumps, such as the ones found in blood pressure meters, were unsuccessful: Not only was the high noise level a nuisance during the testing of interaction qualities, but the pump needed to be perpetually enabled in order to maintain the negative pressure. Furthermore, regulating the stiffness of such a construction would have required data from a digital pressure gauge to be precisely applied to regulate the voltage to the pump.

As this would go beyond the scope of an early prototype, a different solution was explored.

Based on the design of syringe drivers for medical and laboratory use, a simple syringe pump was constructed *(Figure 21)*. This had many advantages over the electric pump: Due to the airtight nature the syringe, negative pressure can be maintained even with the device turned off, drastically reducing noise. This solution also allows for the relative position of the plunger to reliably control the amount of negative pressure applied to the particle jamming device. The device is controlled by an Arduino Microcontroller, allowing for the device to be easily controlled. It may also be interfaced with other prototypes at a later stage.

Rendering stiffness based on particle jamming proved itself to be a very promising technique to be further explored.

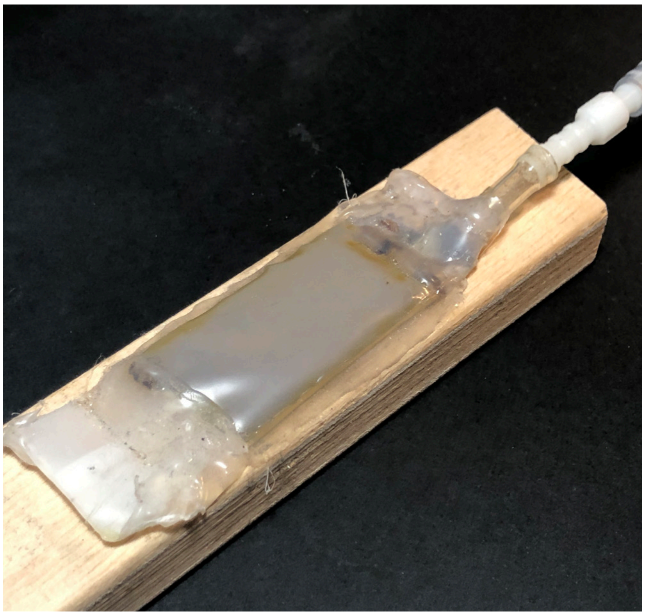


Figure 18: *Two silicone sheets heat welded together, filled with ground coffee.*

Figure 19: *Syringe with severed nozzle and an added filter mesh, a balloon filled with ground coffee attached to its base.*

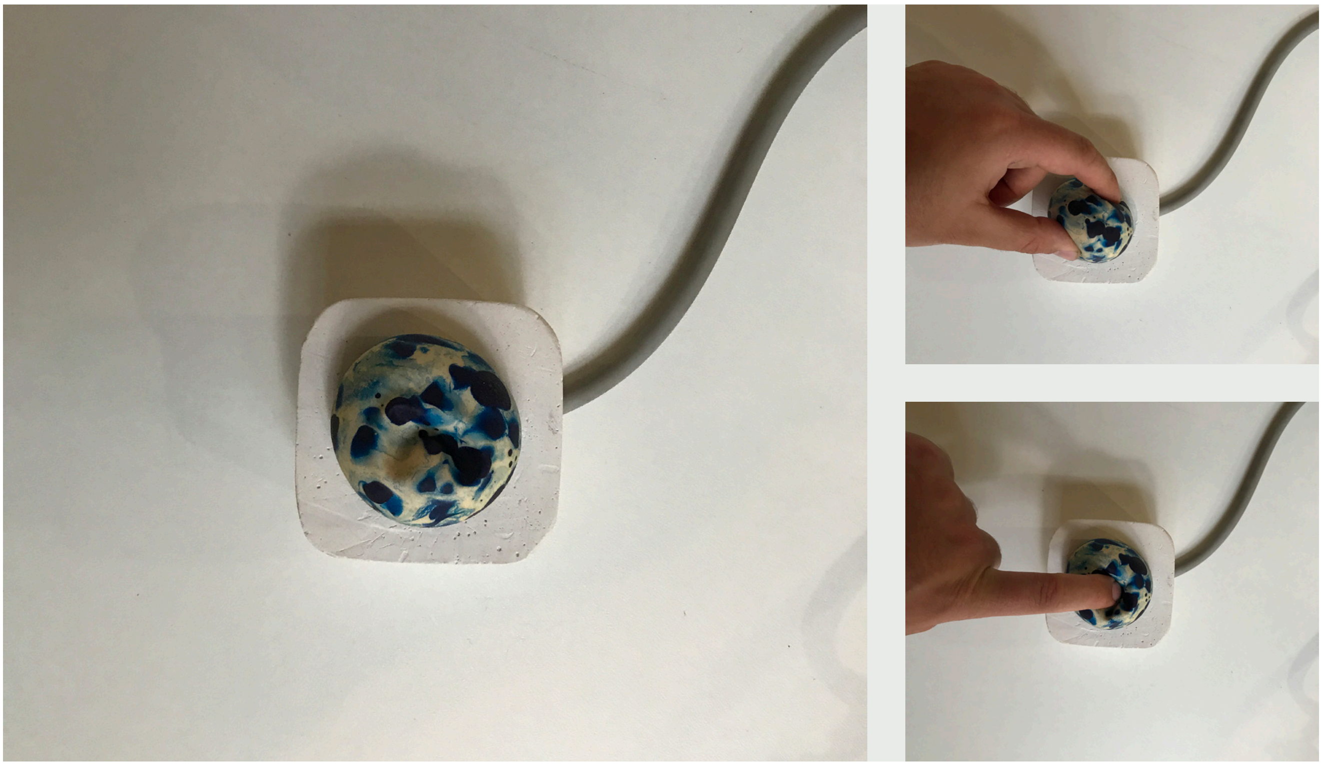


Figure 20: *Particle jamming device embedded in gypsum base*

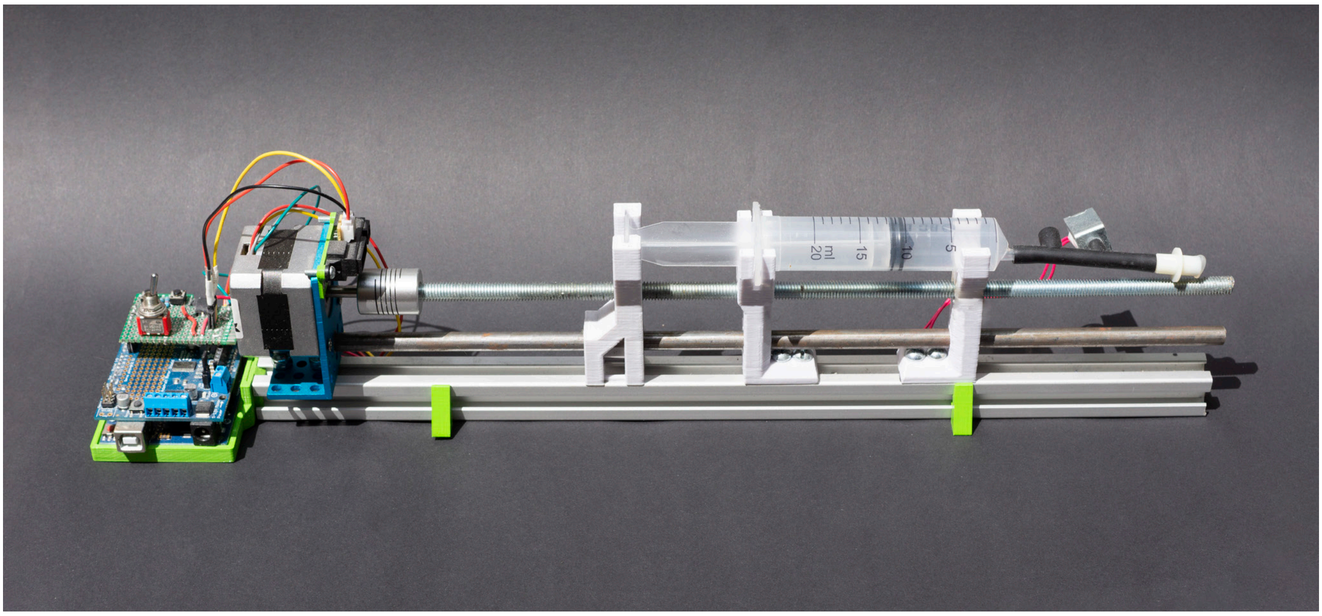


Figure 21: *Syringe pump for the actuation of the particle jamming device. An Arduino Microcontroller at the base of the construction controls a stepper motor that is used to turn a threaded rod. The base of the syringe is fixed, while the plunger is attached to a nut sitting on the threaded rod. This allows the rotation of the rod to increase or diminish the distance between the plunger and the syringe base.*

SHAPE

Another evident approach for creating interactions based on kinesthetic abilities is the exploration of shape. An object's shape is commonly a static property, yet is often its most expressive attribute. Aside from its capability to guide actions and manipulations in space, an object's geometry is also an effective guide for other senses to evoke complementary information: It accentuates features that should be looked at, touched, or otherwise explored.

When animated, shape communicates a great deal of information about evolving processes. There are numerous examples that demonstrate the power of animated shape: Changes in a plant's size reveal its maturity, changes in the volume of a sponge reveal if it is drying out or absorbing moisture, etc. Knowledge and insight emerging from animated shape is often a result of an innate understanding of natural processes, making it a desirable quality to work with. As Pixar's ground-breaking 1986 animated short film "Luxo Jr." and Gertie, a robotic desk lamp developed at the Technical University of Munich (Gerlinghaus et al., 2012) impressively demonstrated, animating shape can go as far as implying intent and emotions on an object's part, such as reluctance, happiness or timidness *(Figure 22)*.

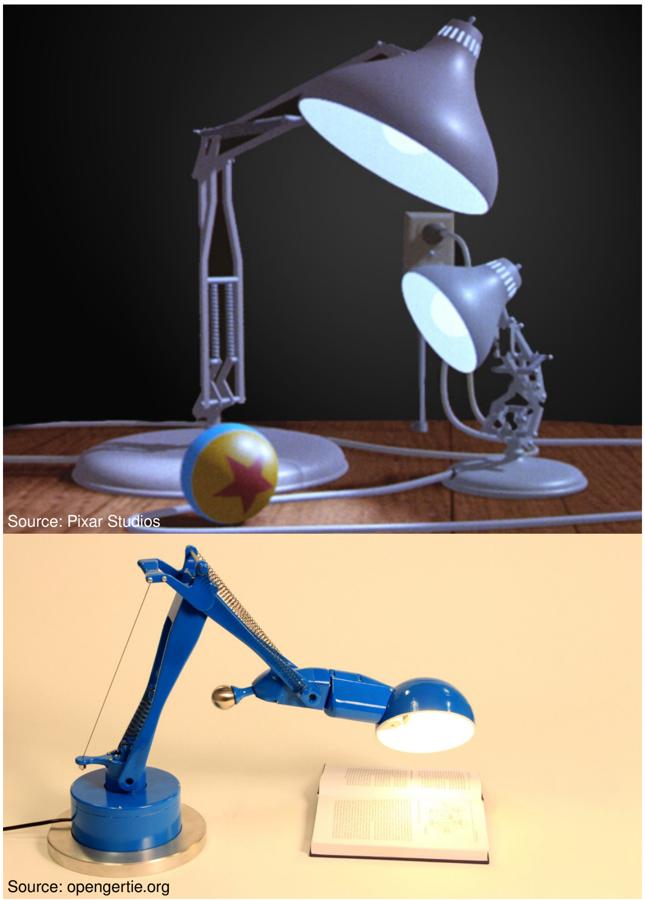


Figure 22: *A still image from Pixar's 1986 animated short film "Luxo Jr." (top) and Gertie, the robotic desk lamp (bottom).*

These insights were a big influence for the first explorations into shape: How can growth be simulated? Can deformation be animated in a way that evokes emotional responses in an observer?

In order not to be limited by mechanical attributes and to achieve a more seamless experience, the focus was placed on methods to animate the entirety of an object's shape. For that purpose, prototypes were based on promising research in the areas of soft robotics and metamaterials.

Soft robotics is a field of robotics that, instead of articulating rigid components using joints, uses flexible and elastic materials. Patterns are created in those materials that are meant to encode specific behaviors. These are often inspired by the way invertebrate animals (e.g. octopuses, snails, worms) move. Often, these materials are actuated via inflation or deflation: The distribution of material will determine in which direction an object will yield, thereby defining the quality of its motion *(Figure 23)*.

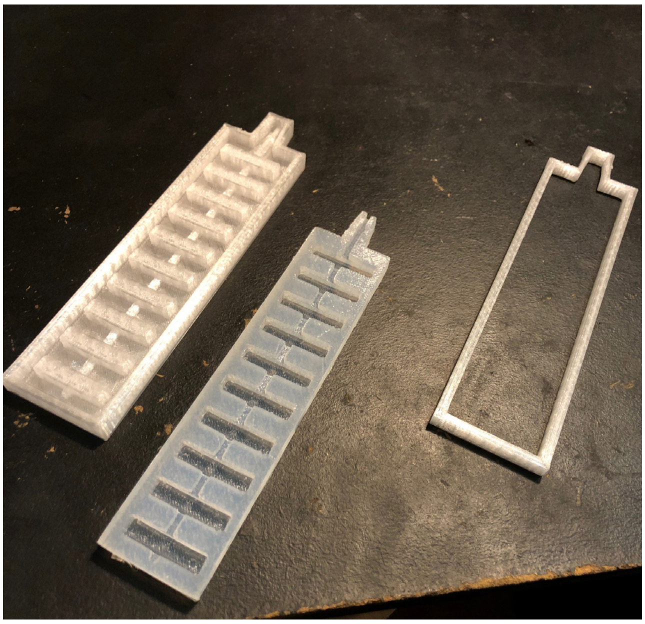


Figure 23: *Silicone soft actuator and its 3D printed molds. Its behavior when inflated can be determined by making the underside of the actuator thicker than the upper membrane.*

Figure 24: *Soft actuator when inflated. As the cavities fill with air, the thin, upper membrane yields allowing the inflating actuator to deform in a predictable and controllable fashion.*

Based largely on resources made available through the Soft Robotics Toolkit (softroboticstoolkit.com), initial experiments into soft robotic actuators were conducted *(Figure 24)*. While these prototypes quickly yielded intriguing results, they also had a number of shortcomings. While many of them failed after a short amount of time, the main concerns were related to their aesthetic qualities: Being reminiscent of motions found in the animal kingdom, they sometimes evoked unappetizing associations. Additionally, they easily accumulated dirt, reducing the appeal of using them in a kitchen setting.

Metamaterials were also explored as a promising method for the animation of shape. Such materials posses properties that are not primarily emerging from their chemical composition, but rather are the result of the structure they are given. While these structures are usually created on a nanoscale, there are some macroscopic examples as well. An example of such a macroscopic metamaterial would be a sheet of paper with origami folds *(Figure 25)*: The folds program a physical properties into the sheet, which are not a result of paper as its base material, but rather its spatial arrangement.

An early idea for the application for such a metamaterial was the augmentation of a dial. By modulating the shape or the radius of a dial, its appearance could be used to provide feedback to the user. Initial attempts at creating such a behavior using 3D printed structures *(Figure 26)* did not perform as expected, as they provided no clear method for their integration into a dial or button.

Even though these initial attempts at animating shape fell short of existing expectations, the potential benefits provided enough incentives to possibly explore this further at a later stage. As working out many of the issues identified would have been beyond the scope of this initial exploration, the focus was shifted towards the next series of experiments.

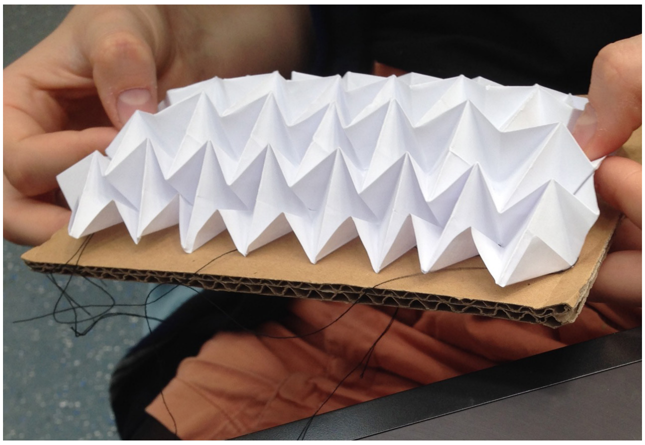


Figure 25: *Origami folding pattern*

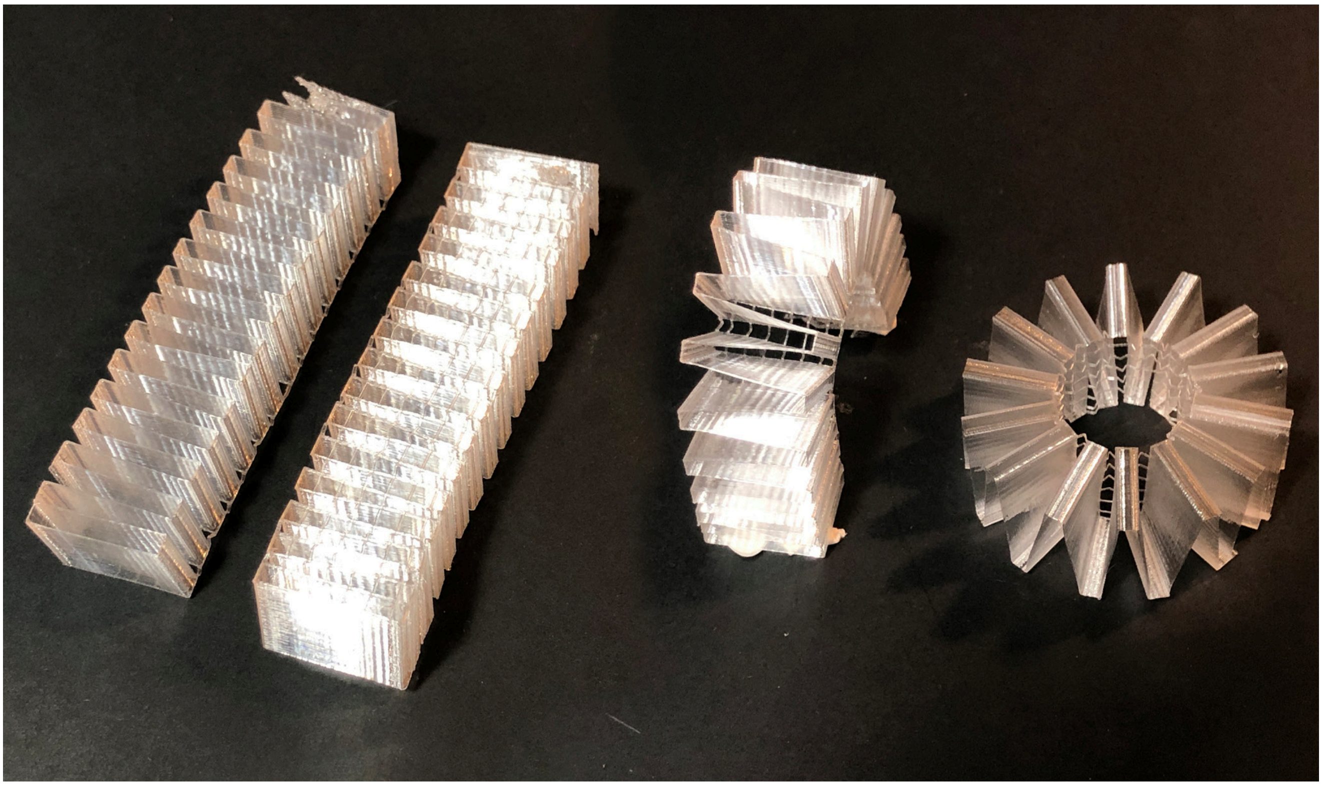


Figure 26: *3D printed pattern with macroscopic structures intended to encode specific behaviors into the object. The zigzag pattern is locked in place on one of its sides while the other side is free to expand and contract. This results in an object that arches when force is applied.*

SHAPE & TEXTURE

This series of experiments was partially based on the outcome of a previous project conducted at TU Delft. Having resulted from a group effort in the context of a course called Interactive Technology Design, the prototype used animated origami patterns as a sculptural & textural information display *(Figure 27)*. The goal was to create textural representations of energy consumption. High levels of power usage were associated with tense and rough textures, while lover levels were represented by softer and smoother textures. The device was reasonably effective at evoking associations between the tension represented by the texture and the amount of work (in the form of electricity consumption) being delivered. By singling out the origami display, the prototype was able to serve as an effective platform to expand on the ideas discussed in the section "Shape".

As these explorations began to combine insights gained by evaluating properties of texture as well as of shape, they helped reframe findings from previous explorations. Research efforts into mechanical properties of origami as a metamaterial led by Itai Cohen at Cornell University revealed promising new opportunities to implementing earlier ideas: By applying a structure based on the miura-ori origami fold to a paper washer, a ring is created that has a stable inner diameter and a flexible outer diameter (Liu et al., 2017) *(Figure 28)*. While this property gives it the potential to be a spring or a damper, it also provides the required mechanical properties to attach a central shaft to a dial that would be capable of varying in volume and size. The surface of such a device could be augmented by applying a membrane such as the one proposed in the section "Texture" (*Figure 12)* on page 25.

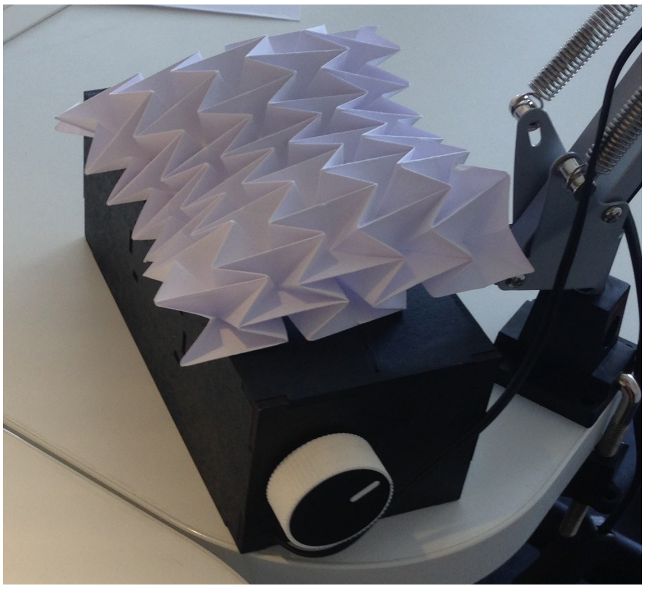


Figure 27: *Animated origami pattern used for dynamically representing the energy consumption of a desk lamp.*

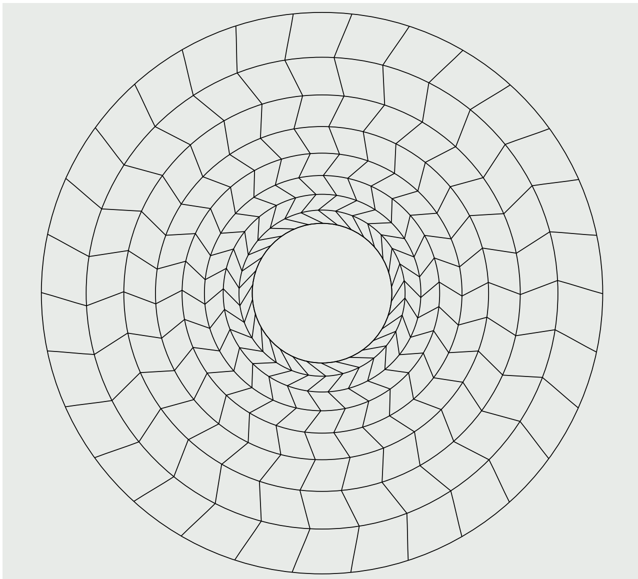


Figure 28: *Scoring pattern needed to apply a miura-ori fold to a washer shape. This particular pattern allows the outer diameter to be collapsed while the inner diameter retains its size.*

To explore the feasibility of such a device, several strategies were used to attempt the creation of such a miura-ori washer on a scale usable for a dial. A CNC cutter was used to score and perforate 0.5 mm PMMA sheets to allow to fold them into the required pattern. Unfortunately, this process proved to be ineffective. Using available tools, the score lines created were too inaccurate and the perforations were too wide to achieve a functioning end result. A larger paper prototype was successfully created, that helped to visualize the working principle and provided the ability to further test the interaction *(Figure 29)*.

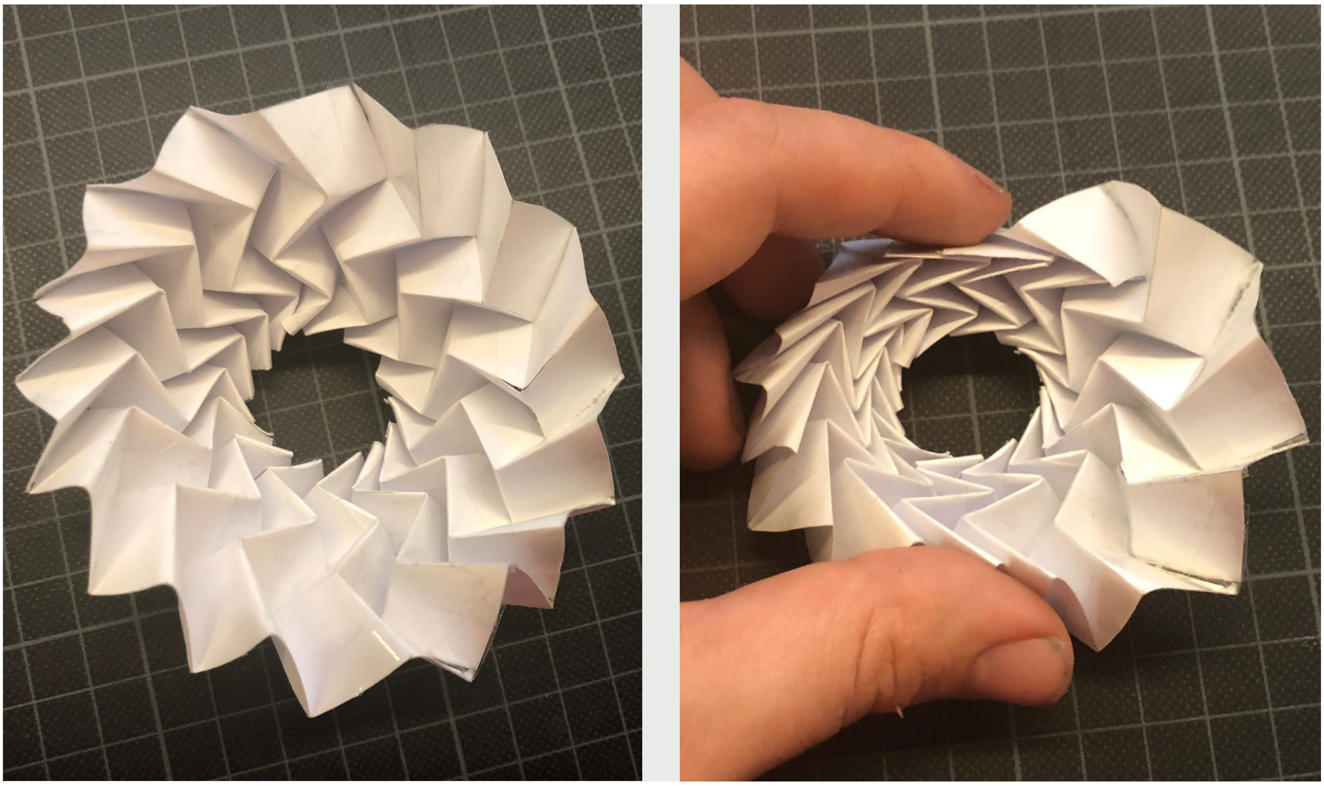


Figure 29: *A paper washer programmed with the miura-ori folding pattern as seen in Figure 28. This prototype shows the object in a relaxed state as well as in a collapsed state. The radius of the inner diameter remains static as the varying density of the folds allows for flexibility in the outer diameter of the object.*

TEMPERATURE

After having explored many of the other modalities discussed leading into this chapter, this last set of explorations was dedicated to the perception of temperature. Temperature is at the core of the cooking process and is a crucial aspect for any interface to effectively communicate. Currently, the representation of temperature varies greatly from kitchen to kitchen, and even from interface to interface *(Figure 30)*. This can in part be explained by existing conventions, but also by the fact that it was (and still is) not always possible to provide a sufficiently accurate temperature reading. Different combinations of kitchen utensils, for instance, already introduce a lot of uncertainties: Even if the heat a stove puts out can be accurately measured, a shallow pan will heat up faster than a ticker pan. It will also lose more heat to the environment and spread the heat more unevenly than a ticker pan will. Therefore, numerical scales are commonly used to represent the relative energy output. This usually works as long as the user is already familiar with the equipment in a kitchen. Nonetheless, numerical scales have the potential to introduce many uncertainties. Most importantly, they can make the causal relationship between temperature and its effect on food less clear.

The desire to highlight this relationship between cause and effect inspired the idea of using temperature perception itself as part of an interface. This opens up interesting opportunities, as temperature perception is both very accurate

Figure 30: *A range of interfaces commonly found on kitchen appliances. This selection showcases the diversity of different approaches that can be found even within narrowly defined product groups. This lack of coherence might contribute to a sense of confusion and makes experience with that particular appliance indispensable.*

and very subjective. The thermoreceptors in the skin for instance can, under the right circumstances, resolve relative changes in temperature down to 0.2°C (Van Someren, Raymann, Scherder, Daanen, & Swaab, 2002). At the same time, it is very difficult to determine an absolute temperature, and the perception of something being hot or cold often depends more on the temperature level previously experienced than the actual temperature currently being experienced. Under certain circumstances, temperature transitions can also trigger nociceptive (pain) responses. Especially beyond the boundaries of what both cold receptors and warm receptors can resolve *(Figure 31),* temperature perception transitions into nociception.

This means that a modest range of temperatures can potentially be used to create a vast spectrum of different sensory responses. These responses may include the perception of more extreme temperatures, that are actually created by using moderate temperatures.

To put this knowledge into action and test important assumptions, a prototype was required. Investigating different ways of controlling temperature quickly led to the conclusion that the thermoelectric effect (also known as the Peltier effect) would likely yield the best results. Since it allows for the direct conversion of electric voltages into temperature differentials *(Figure 32)*, it provides a much faster, repeatable and more

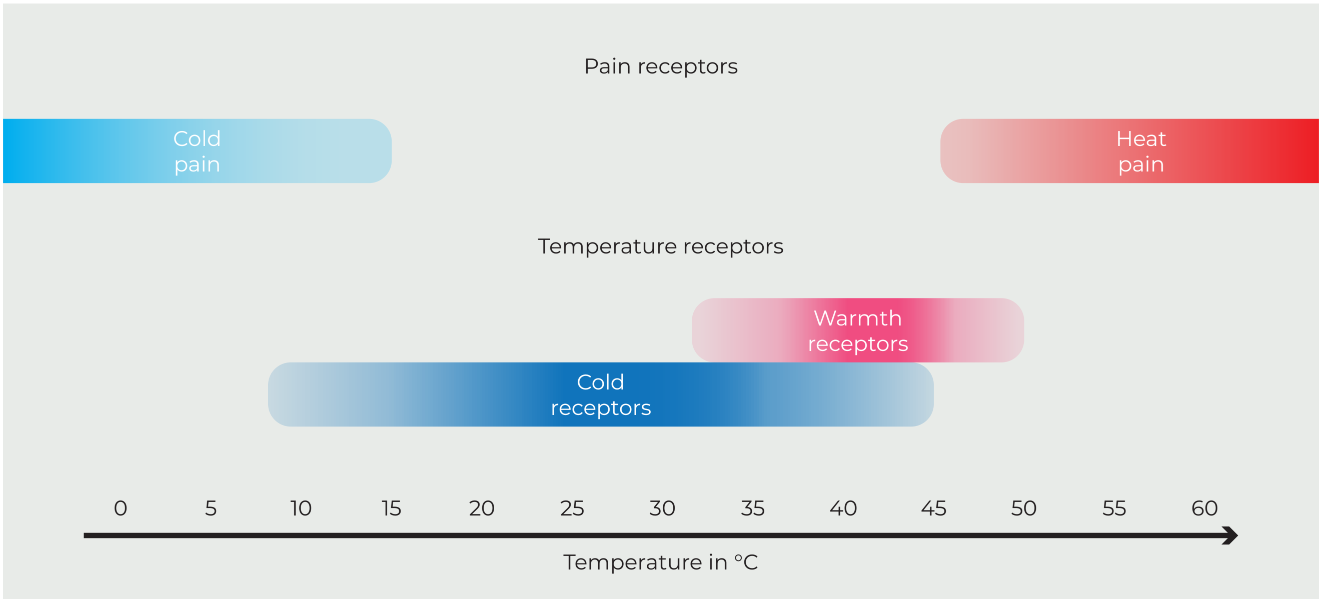


Figure 31: *The range of human temperature perception. The blue section represents the perceptive scope of the cold receptors, the red section depicts the scope of the warmth receptors. The color intensity indicates the strength of the stimulus. In the range of temperatures where both stimuli overlap the subjectivity of the temperature perception increases. This means that under the right circumstances very small temperature differences can be felt, while different circumstances can make it hard to distinguish even large temperature differences. (Data: Van Someren et. al., 2002)*

direct way of creating a desired temperature than most other solutions would. What's more, Peltier elements do not rely on any potentially hazardous components and are very light, compact and reliable. Due to their widespread use in science and consumer applications, they are also relatively cheap and accessible.

Peltier elements allow for the creation of temperature differentials: If a voltage is applied, one side of the element heats up, while the other side cools down. Which side turns hot and which one turns cold depends on the polarity of the voltage. In order to enable not only quick rendering of different temperatures but also

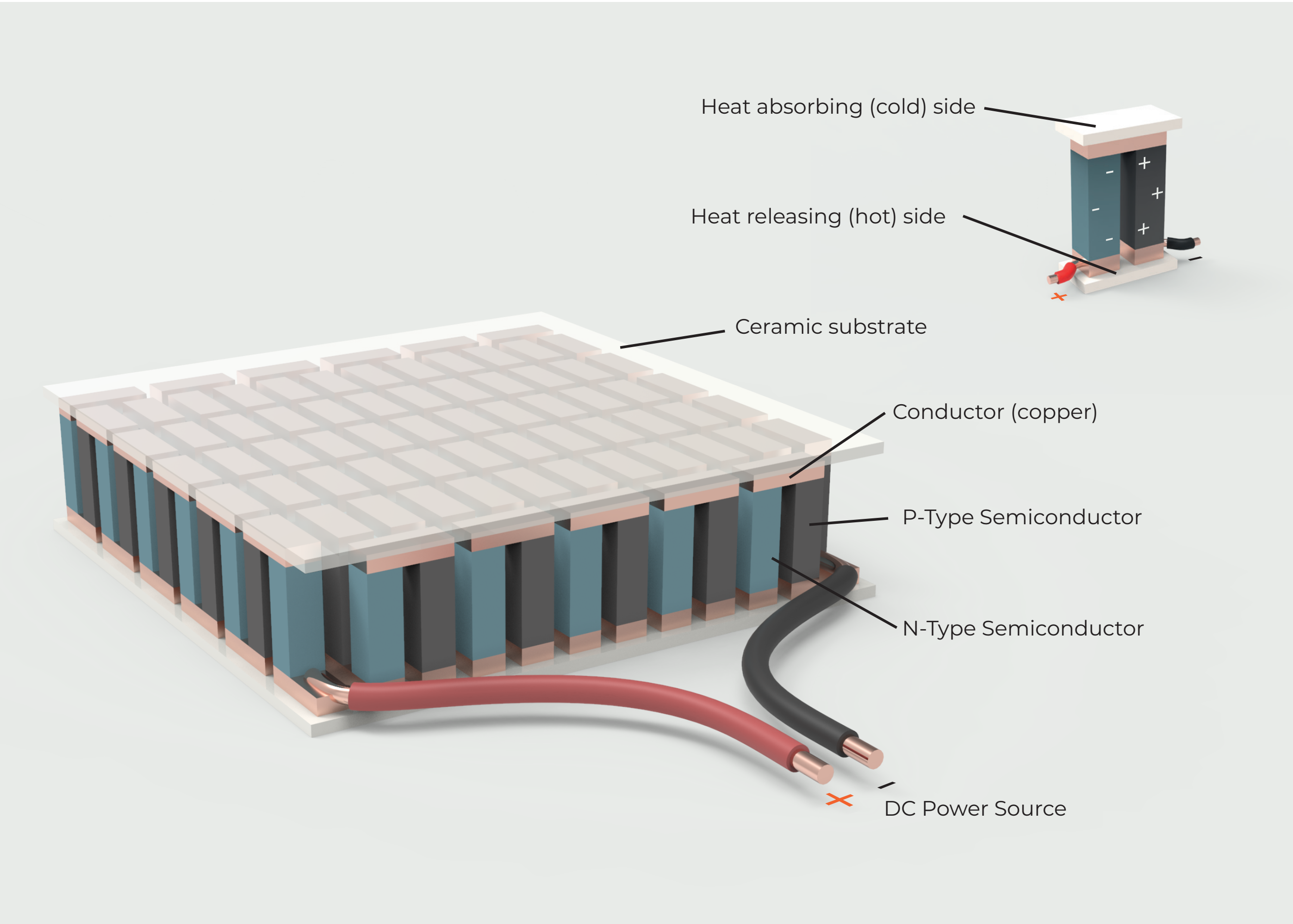


Figure 32: *A schematic representation of a peltier element. Conductive metal bridges serve as interfaces between pairs of semiconductors that have negative (n-type) and positive (p-type) energy levels respectively. N-type materials have excess electrons while p-type materials have an electron deficit. In order for electricity to be conducted though these interfaces, energy needs to either be absorbed from (cooling effect) or released to (heating effect) the environment, depending on the polarity of the electric current applied. Reversing the current also reverses the heating & cooling effects.*

the rendering of temperature differentials, the prototype *(Figure 33)* was conceived using two 40x40mm Peltier elements mounted side by side. Both elements were mounted on a heat sink intended to dissipate temperatures generated on the unused side of the elements. On the other side, a 1 mm aluminum sheet would serve as the interface for users to interact with, and ensure more a even temperature distribution. The Peltier elements were actuated using an Arduino microcontroller and two H bridges to control the voltage and the polarity.

Despite performing poorly in the beginning, a few minor adjustments to the prototype quickly went on to create some of the most visceral emotional responses yet. By validating most of the relevant assumptions, the prototype revealed many opportunities for temperature renderings later in the process.

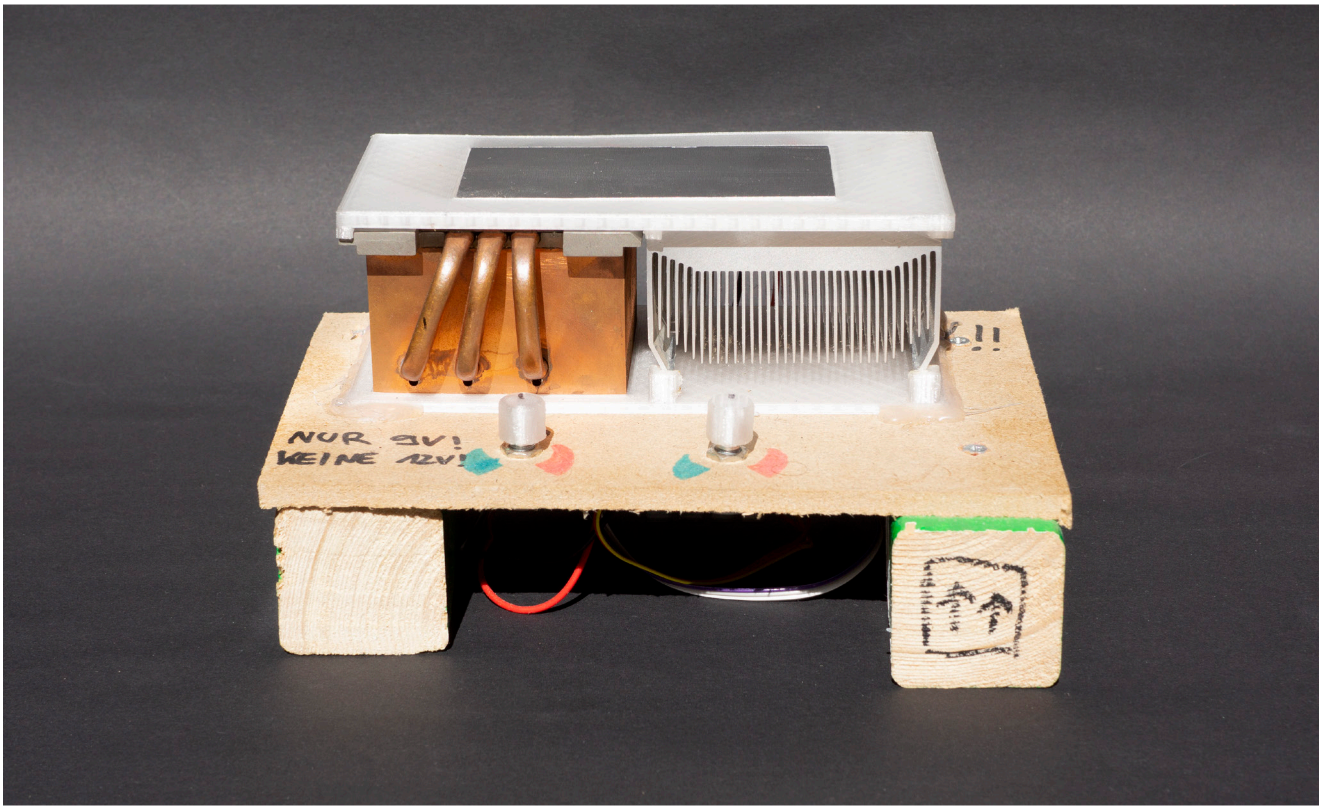


Figure 33: *The prototype of a temperature display unit capable of rendering temperatures and temperature differentials between -5°C and 50°C.*

LAB VISIT: CHARM LAB STANFORD

Charm Lab, which is situated at Stanford's Department of Mechanical Engineering in California, is involved in haptics research. Furthermore, they are actively researching several technologies with a clear potential to enable multimodal interfaces. One notable example is particle jamming, which is the technology behind the prototypes built and explored in the section "Stiffness" on pages 26-29.

Their research focus lies predominantly on creating haptic and mechanical innovations for applications in the medical field. Many of these innovations may however also be useful outside this narrow context.

To initiate an exchange of ideas on how such applications could take shape, contact with the lab was established. To kickstart this dialogue and to get a better understanding of ongoing research activities, a lab visit was scheduled as soon as the opportunity arose.

The visit was facilitated by Melisa Orta Martinez, a PhD student at the lab focusing on the applications of "Haptics for Education". She is also a principal developer of the lab's Hapkit project (http://hapkit.stanford.edu), a simple, one degree of freedom (DOF) haptic paddle meant for educational purposes *(Figure 34)*.

Source: Stanford University

Figure 34: *Charm Lab's Melisa Orta Martinez holding the "Hapkit", a one degree of freedom haptic paddle developed by the lab for educational purposes.*

Topics discussed during the exchange yielded a variety of new insights. The lab's work researching particle jamming devices for instance may hold answers to challenges faced by medical professionals: Many remote-controllable surgical devices, such as those used during minimally invasive procedures, force doctors to surrender their sense of touch. Without it, the procedure has to succeed only using the feedback provided by an endoscopic image on a screen. And while seeing the orientation and motion of the surgical tool are important, so is the sense of touch while exerting control over such a delicate situation. To that end, the lab employs particle jamming principles to design tools that provide a remote sense of touch. By enabling surgical tools to convey the stiffness of a tissue and the force the surgeon is applying to it, these technologies demonstrably increase the chances of success for delicate procedures such as stitching fragile blood vessels.

This example underscores the importance of multimodality in the way humans perceive information: Partial feedback through a screen combined with practice and experience can guarantee success. But it is when different, complementary aspects of information are delivered through their respective sensory modalities that a complete picture emerges that can be acted upon with confidence.

Another field of research at Charm Lab is Soft Robotics. Similar to the principle exploited by the soft actuator prototype described in the section "Shape" on page 31, this field uses compliant materials to create mechanisms that are capable of accomplishing tasks conventional robotics are unsuitable for. Typical applications for soft robots explored by the lab include situations that require a high level of safety when working with and around humans, as well as situations that require tools with highly flexible means of locomotion and control to access dangerous or confined spaces. Medical applications, reconnaissance, as well as search and rescue missions are therefore obvious use-cases for these highly flexible and nimble devices.

As these mechanisms often mimic nature, the motion they generate often evoke associations to natural phenomena. Being able to observe a breadth of soft robotics mechanisms, beyond the principle employed by the aforementioned prototype, shed some further light on the communicative potential of soft robotics. Using soft robotics not only to perform functional tasks, but also for communicative purposes, is arguably and underexplored use-case.

One particularly interesting aspect of the lab's research is their work utilizing haptics for educational purposes. One of the purposes of the aforementioned "Hapkit" *(Figure 34)* is to teach mechanical engineering students fundamentals of haptic technologies. This ranges from the manufacturing process and mechanical assembly to the electrical engineering and programming knowledge required to make them work. Beyond that, the lab also uses the tool for broader science education purposes. The most relevant example for the goal of this thesis that comes to mind is its application in teaching math to middle school children. In this context, the haptic paddle was used to allow students to gain an understanding of different science, engineering and math principles by interacting with them. This direct interaction in conjunction with human kinesthetic intuition allows students to create a context and to explore the meaning of the information contained therein. This experience can ultimately help create a more personal, exploratory way of understanding information. By contrast, a graph in a school book requires a previously agreed upon, common understanding of a conceptual visual language to represent this kind of information. This is not only very static, but also a highly impersonal way to convey information. As the ability to directly engage with something can help creating a sense of curiosity, it is unsurprising that trials using the haptic paddle in classrooms created promising and highly engaging learning experiences (Martinez et al., 2016).

All in all, the lab meeting proved to be an invaluable source of new insights and inspirations. It validated many of the explorations undertaken so far and gave them a broader context. It also served to reaffirm some of the beliefs and motivations that gave the impetus for this graduation project.

ITERATION

NEXT STEPS

Many of the explorations in the previous chapter yielded promising results. In some cases however, the outcome was more ambiguous. While these following pages are dedicated in part to resolving lingering questions, their center of attention is placed on building on important insights resulting from the process so far.

Some prototypes created interesting interactions, but were too unspecific to develop ideas giving them a clear role in a kitchen environment. In other cases this connection to the desired context was more clear, but technical questions or questions of scalability remained. This chapter's purpose is to refine ideas and visions, as well as to clarify questions to feasibility and scale.

Figure 35 provides a quick overview and reference guide for the exploration and research activities described in the following.

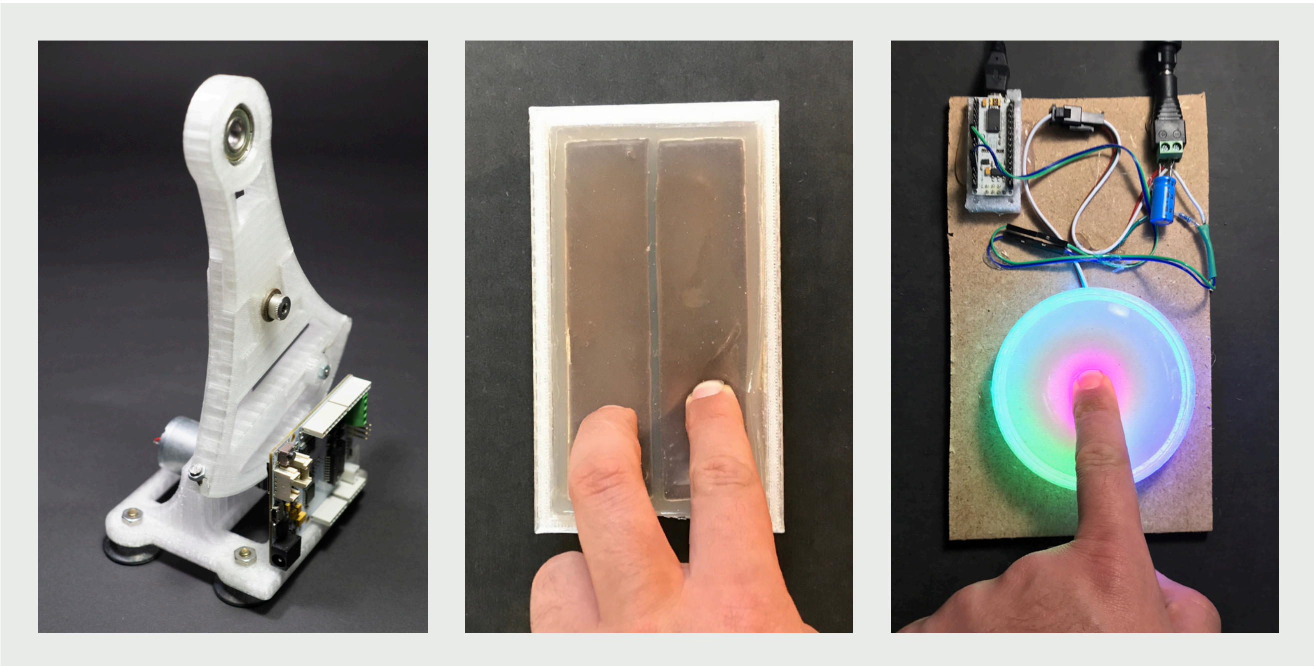


Figure 35: *The three prototypes described in this chapter. Each one was conceived to expand the knowledge gained from previous prototypes. From left to right: The haptic paddle (p. 45) revisits position and shape as a communicative tool, the Haptic Display (p. 47) builds on the capabilities of particle jamming for haptic interactions, and the Visual Haptic Display (p. 50) envisions new modalities as part of haptic interactions.*

HAPTIC PADDLE

Intrigued by learning more about the haptic paddle's capabilities and potential during the Lab Visit at Charm Lab, a reprisal of ideas explored in the previous chapter's section discussing "Shape" (pages 30-32) was attempted. Previously, the focus lay on using soft robotics and metamaterial properties to create deformations in shape. These deformations were meant to evoke responses in the user that go beyond basic interactions with interfaces such as buttons, dials, or similarly static interface elements. Despite enabling promising interactions, these early attempts seemed likely to fail. Their physical and mechanical properties as well as their fragility presented no clear path towards productively integrating them into a kitchen environment.

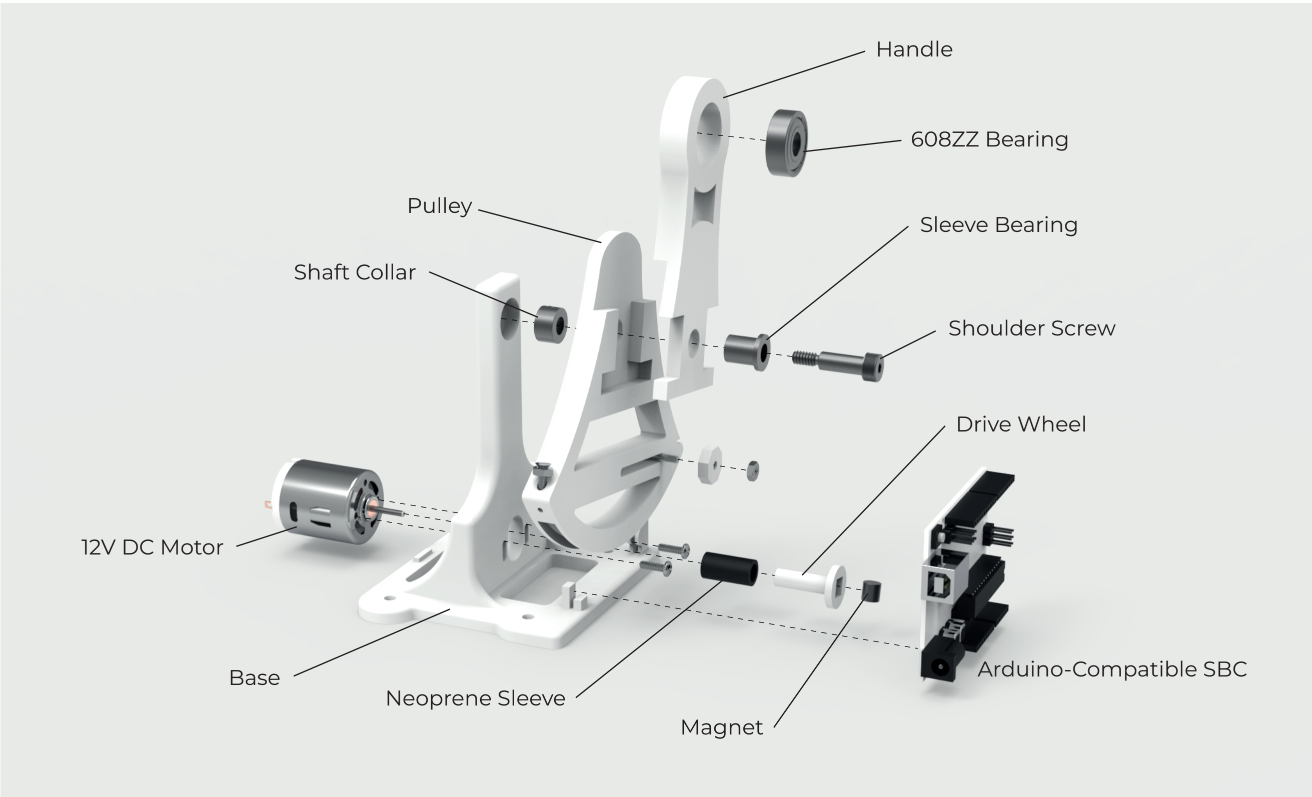


Figure 36: *Exploding view of a customized Hapkit device. The paddle (consisting of a handle and a pulley) is fastened to the assembly's base using a sleeve bearing and a shoulder screw. This allows the paddle to rotate around the shaft of the shoulder screw. A single board computer (SBC) is used to determine the position of the paddle. This is done by using a magnetoresistive sensor mounted to the back of the SBC. It determines the position of the motor by measuring the magnetic field orientation of a magnet embedded in a neoprene-clad drive wheel on the motor shaft. The motion of motor and pulley are locket together using a flexible steel wire that is fastened to either side of the pulley and wrapped around the neoprene sleeve. The Arduino-Compatible SBC reads the sensor value, enabling it to not only determine the paddle's position, but also govern its behavior by controlling the current to the motor.*

As a device relying on classical mechanics, yet able facilitate a similarly dynamic range of interactions, the haptic paddle might be able to enable very similar experiences to the ones created previously. At the same time, the device would be a much more resilient and reliable way to do so, that due to its mechanical structure would also allow for an easier integration into more elaborate concepts and usage scenarios down the line.

Using the resources made available through the website of the Hapkit project (http://hapkit.stanford.edu/), a slightly modified version of the paddle was developed *(Figure 36)*. These modifications included the conversion of the build assembly from US customary units to metric units, in order to be able to construct it using parts and tools available in Europe. Furthermore, the material distribution was altered to reduce the time and costs involved in manufacturing. To allow for easier integration of the haptic paddle into future prototype concepts, a number of additional mounting options were designed, such as the inclusion of a slot for a 608ZZ ball bearing in the handle.

After completing the haptic paddle *(Figure 37)*, code resources made available through the Hapkit website were used as a starting point to exploring its potential. Different physical behaviors were programmed, allowing the device to act as a virtual spring or damper, but also prompting it to move and dynamically change its behavior in accordance with external triggers.

These promising explorations opened up many perspectives for the creation of interactions that would include properties such as force and position. Experiencing and interacting with different physical behaviors enabled by the haptic paddle triggered a number of early ideas: Handles that would allow users to remotely feel the consistency of dough or represent the passage of time via their position, as well as buttons capable of "pushing back" under certain circumstances were among the directions that seemed promising for later exploration.

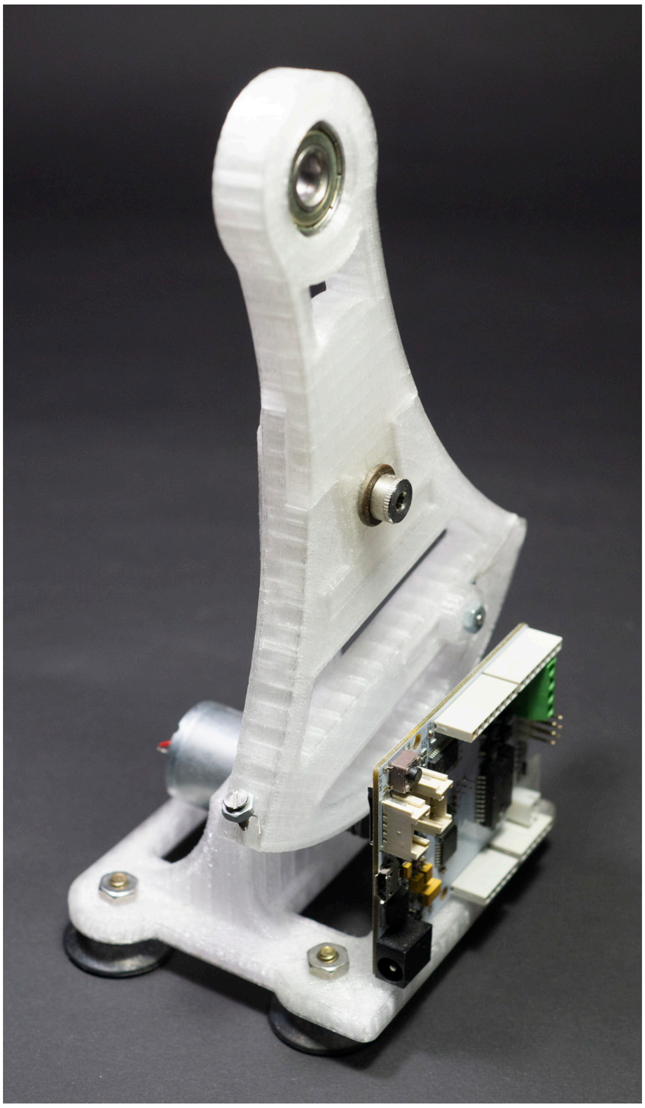


Figure 37: *The fully assembled, customized "Hapkit" haptic paddle.*

HAPTIC DISPLAY

The visit of Charm Lab also contributed to the iteration on another prototype. The earlier explorations on “Stiffness” (see pages 26-29) concluded that particle jamming technology had a wealth of interactive potential to be explored. As researching this technology played a role in the decision to reach out to Charm Lab, it is not surprising that the exchange led to new inspirations and insights.

A lot of parallels can for example be drawn between challenges faced by medical professionals using remote controllable surgical tools (described on page 39) and challenges faced by cooks in a kitchen environment. In both cases actions and decisions could be made easier if sensory information that is unavailable under normal circumstances can be made accessible. In one case, this may be the sense of force applied to a blood vessel while stitching it. In the other case, it may be the stiffness of a bread baking in the oven that is made available to the user in a similar way.

To make particle jamming useful for representing the biggest possible spectrum of information, its capabilities had to be expanded in several ways. Firstly, the haptic display should be enabled to render more than just one stiffness at a time. That way, it would be able to spatially represent data, such as the cross-section of a roast reflecting its stiffness in multiple locations. Secondly, the pump operating the haptic (particle jamming) display should allow for the integration of multiple data & information sources for later prototyping purposes. To achieve that in a relatively resource- and time efficient way, a bluetooth 4.0 module was to be integrated into the design.

In order to test the feasibility of rendering stiffness gradients and other three dimensional properties, a simple actuator was conceived that would be capable to render 2 haptic states simultaneously, much like a display capable of rendering two pixels. The actuator was designed to consist out of two directly adjacent silicone chambers filled with the same granular substrate (ground coffee) as the one used in the previous prototype *(Figure 38)*.

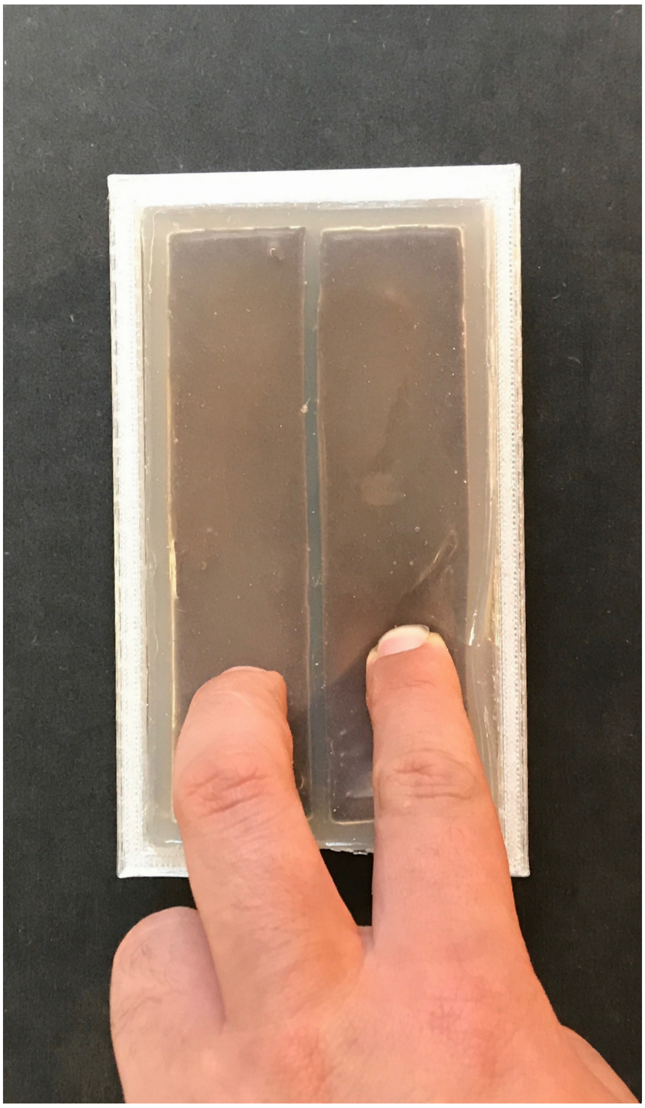


Figure 38: *The soft actuator assembly consists of two chambers separated by a silicone membrane.*

The underlying idea was that the stiffness of one chamber would decrease towards the edge as long as the other chamber would be in a less stiff state. That way, a gradual transition was to be achieved.

The choice to use silicone rubber was made for its chemical inertness, easy handling, and its wide availability as a food safe material. Furthermore, it was already used for the soft robotics actuators previously explored, making the design and manufacturing process easier.

The mechanical design expanded on the syringe pump built for the first prototype was built using 20 x 20 mm V-Slot profiles and aluminum brackets, as these are readily available off-the-shelf components. The electronic components necessary to control the assembly were soldered by hand onto a perforated prototyping board and plugged onto an Arduino development board *(Figure 39)*. All other structural components were 3D printed using different methods: Small sensor mounts as well as the connectors used to

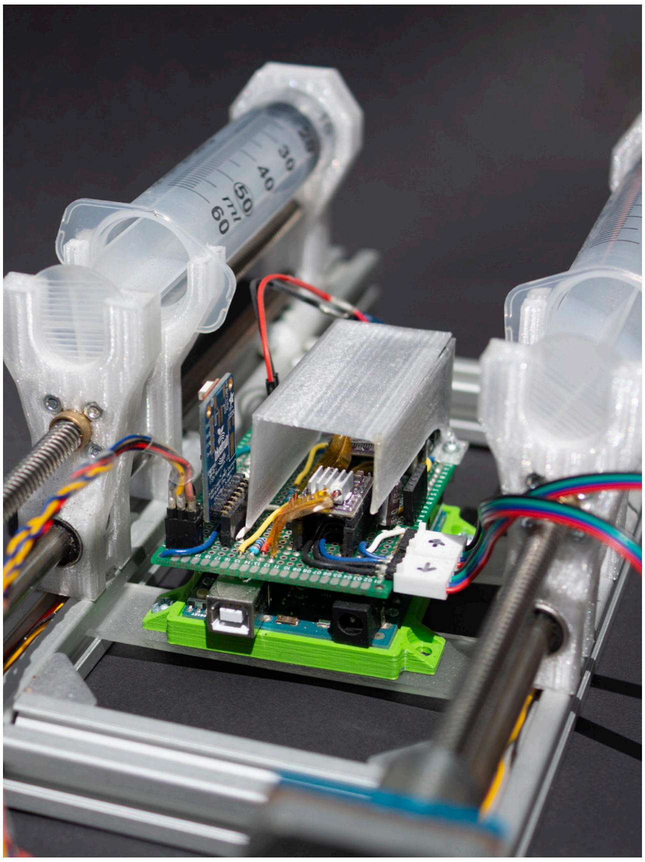


Figure 39: *The assembled circuit board. It features two temperature controlled motor drivers (under the fan shroud), four position control sensor inputs (bottom left), as well as a bluetooth module (left).*

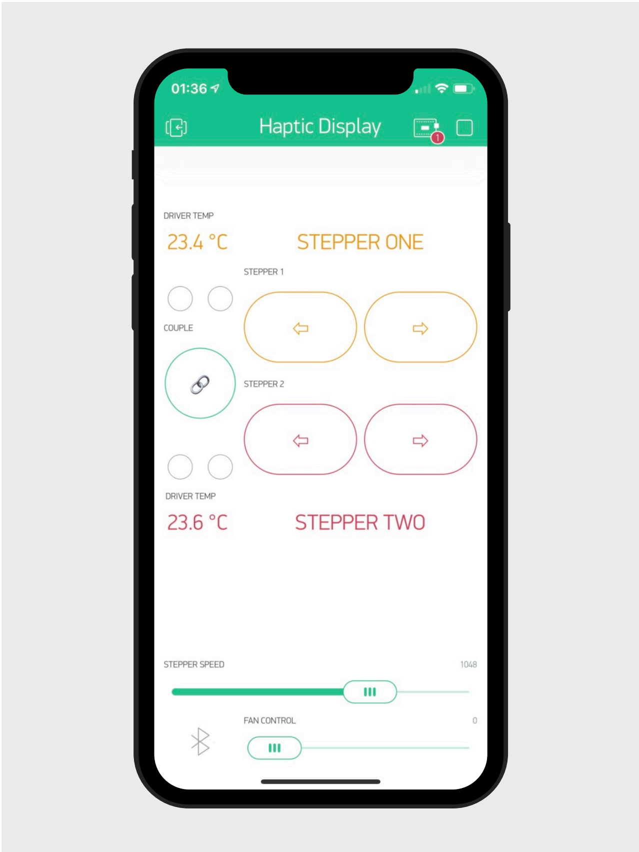


Figure 40: *iPhone app used to control the haptic display. This first version can control the pressure as well as the speed at which the pressure change occurs for either chamber.*

interface the soft actuator, the silicone tubing and the syringe pump were manufactured using Direct Light Processing (DLP). This photopolymerization technique was the easiest and best option available to achieve a high enough level of accuracy for these components.
The remaining parts were printed using conventional Fused Deposition Modelling (FDM). The Blynk framework (https://blynk.io/) was used to create a platform-independent app capable of controlling the haptic display *(Figure 40)*.

These design improvements resulted in a haptic display prototype *(Figure 41)* that later would serve as a reliable basis for usability testing, ideation sessions, as well as the validation of earlier assumptions.

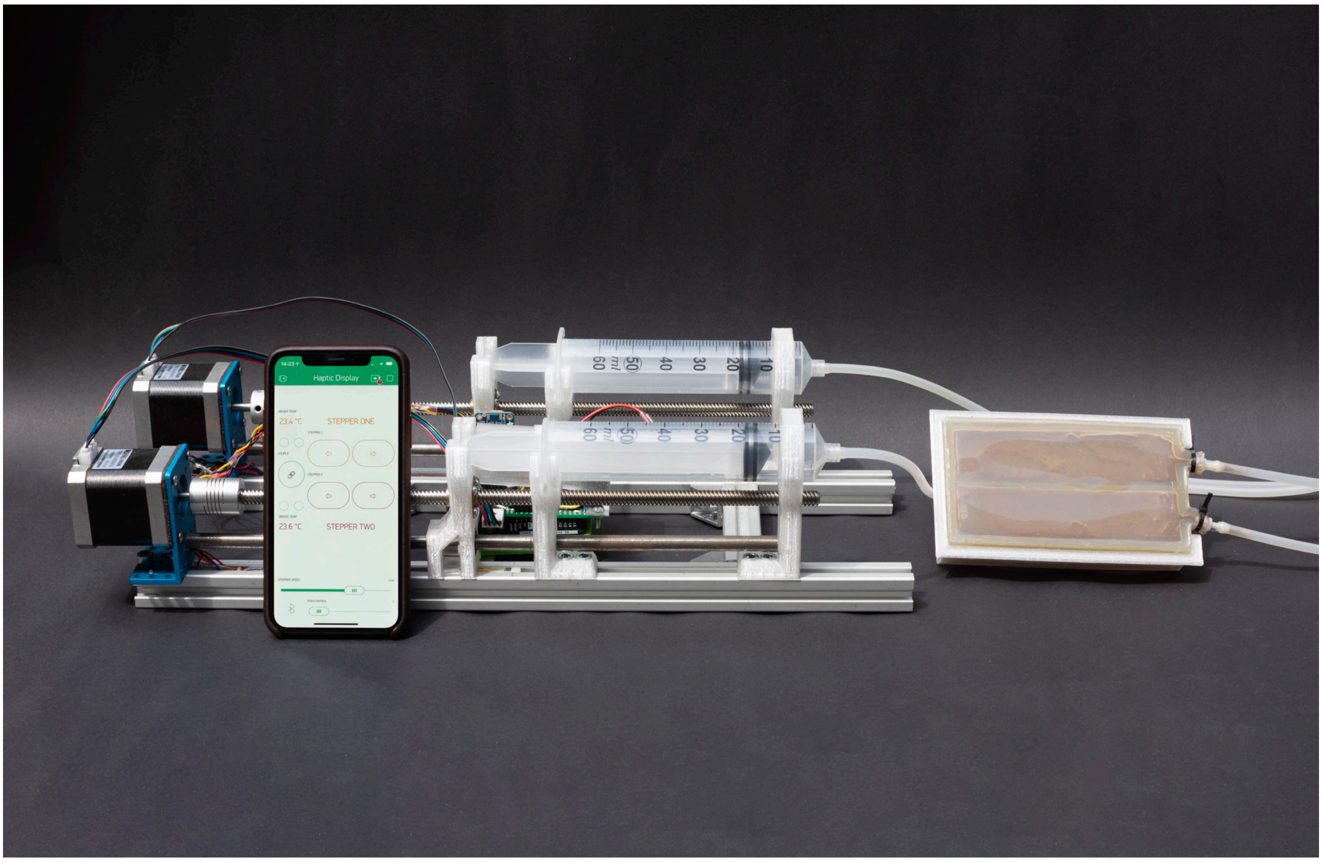


Figure 41: *The complete assembly of version two of the haptic display. The phone app serves as a proof of concept and demonstrates the prototype's capability to be actuated by any system capable of wireless bluetooth communication.*

VISUAL-HAPTIC DISPLAY

In an attempt to shift the focus more towards multimodal applications for haptic devices, another evolution of the haptic display was conceived. To that end, several aspects of the existing prototypes were put into question. Arguably the most influential aspect of the particle jamming actuator is the granular substrate used for its assembly. And while coffee grounds as a substrate for particle jamming displays had been working reasonably well thus far, its color, structure and opacity has unfavorable optical properties.

This realization prompted a series of investigations into the advantages of different substrates. Aside from coffee grounds, three other substrates were explored: White sugar crystals, silica sand, and fine grit glass beads commonly used for abrasive sand blasting. Additionally, the granule size of different substrates was considered. The purpose of these explorations was to determine the effect of different material properties on the overall surface texture, stiffness rendering capabilities, and visual properties of the particle jamming display. The hope was that the outcome would lead to new ways of incorporating new modalities into the prototype, with an emphasis on texture and visual information.

To determine the influence on texture and stiffness, the different substrates were filled into balloons attached to 20 ml syringes, equivalent to the assembly shown in *figure 19* on page 28. That way, negative pressure could be applied to all substrates in a comparable way. While it would have been possible to measure the deflection of each substrate at different levels of negative pressure, it was decided to perform a more subjective test. The ultimate goal being an application as part of an interface using its user's subjective perception, this seemed to be the most reasonable approach.

Each equally sized balloon was filled with 3 cm^3 of substrate. Subsequently, the influence

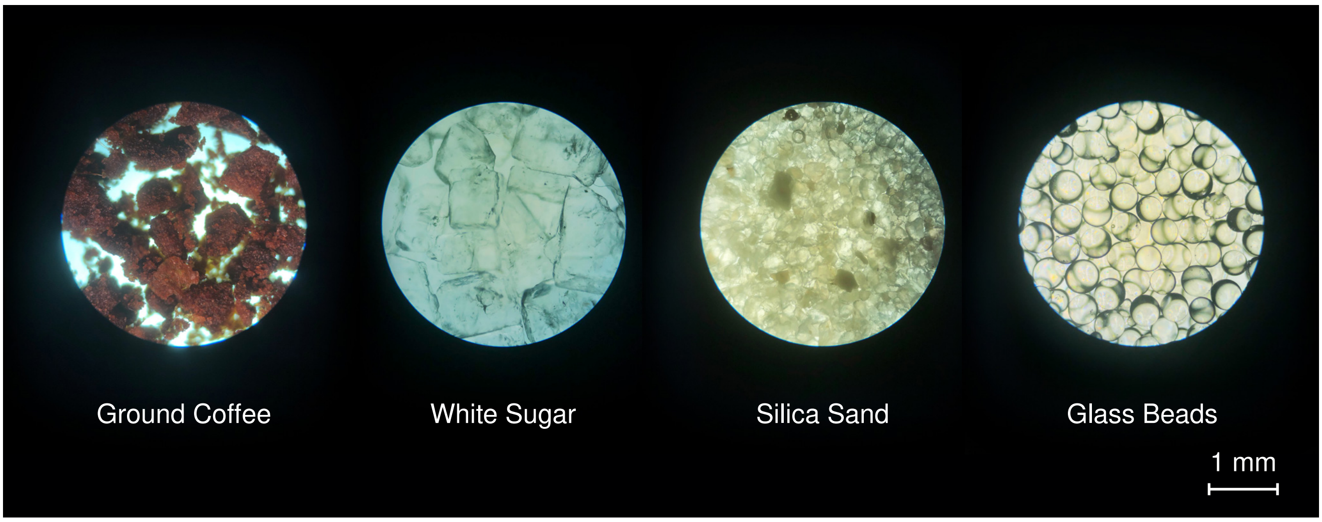


Figure 42: *Magnifications (50x) of the different substrates used. They feature different shapes, levels of irregularity, and optical properties. These substrates were chosen to evaluate the effect each of those properties would have on the overall performance of particle jamming actuators.*

of increasing the level of negative pressure was evaluated. *Figure 42* provides an overview of the different substrates used.

The comparatively rough and square sugar crystals resulted in an overall stiffer actuator, even at neutral pressure. The actuator would get substantially harder than its ground coffee counterpart, even at lower levels of negative pressure. It also created a “crunchier” sensation when deforming it, presumably because the shape of the sugar crystals would cause them to jam against one another more thoroughly, requiring a higher activation energy to allow them to move past one other. Hence, the actuator would initially appear stiff, but, once a high enough level of pressure was applied to it, would yield almost instantaneously.

Silica sand was a substance chosen for its neutral, aesthetically pleasing appearance. The hope was that, if used in conjunction with a clear membrane, it would present a suitable basis for projecting information onto the actuator. Despite its significantly smaller granules, its behavior in the actuator strongly resembled that of ground coffee. This indicated that the shape of the granules have a more significant impact on the overall behavior than the observed differences in size.

Comparing the behavior of sugar crystals to the observations made with coffee and silica sand led to the conclusion that sharper, edgier granules resulted in stiffer, coarser behavior. Conversely, more consistent, smooth, and spherical granules might result in a more nuanced and fluid behavior. Fine grit glass beads were used to verify this assumption. This material, normally used for abrasive sand blasting, was chosen for its almost perfectly spherical granules. The comparatively low amount of internal friction in this material indeed yielded a highly compliant actuator at neutral pressure, almost comparable to the flexibility of a liquid. Even though the negative pressure created by a 20 ml syringe was insufficient to fully solidify the actuator, the range of textures it allowed for was far superior to the actuators created using other substrates. This shortcoming could however easily be mitigated by the use of a larger syringe. As this material also allowed for the approximation of the behaviors enabled by the other materials by controlling the speed of pressure changes, it was chosen as the most promising option for the prototype.

The fine glass beads also have a number of optical advantages. Their light-scattering properties are aesthetically pleasing and create a translucent appearance that evenly diffuses light. These properties could potentially allow for a back-lit actuator. This is important, as in multimodal research, visual perception is divided into separate modalities: Focal and ambient vision (Wickens, 2002). Focal vision describes the central 5° of the human view field. It is necessary to distinguish fine details, for instance to recognize text or symbols. The remaining view field corresponds to the peripheral or ambient vision. According to Wickens, it constitutes a separate modality from focal vision. One is used to consciously perceive literal information (focal), while the other is used to sense more general properties, such as color, motion, and orientation (ambient). The light-scattering properties of the glass beads might therefore be used to cater to this modality of ambient vision.

As opposed to the Haptic Display explored in the previous section, this prototype retained the single chamber design of the first prototype. This decision was made in part to simplify engineering challenges caused by the increased complexity of the overall assembly. Additionally, this would allow for the exploration of different shapes that might open up new contexts.

After deciding on the shape and diameter of the actuator, its thickness was determined by measuring how deep the light produced by a 5V RGB LED would penetrate into the substrate. The particle jamming actuator was cast from silicone rubber according to the dimensions determined that way. To compensate for the reduced depth of the actuator, a hollow bracket holding it was designed. The hollow space below the actuator would allow it to arch downward, resulting in an increased perception of depth. An LED matrix incorporated into that same hollow space would serve as the backlight. *Figure 43* provides an illustration of the assembly. A hand-actuated syringe or a syringe pump developed for a previous prototype could be used to control the actuator itself. To control the LED matrix, a small Arduino Nano SBC was sufficient.

The resulting prototype successfully embodied the potential of its multimodal approach *(Figure 44).*

Figure 43: *Exploding view of the Visual-Haptic Display's assembly. A round 12V RGB LED matrix sits at the bottom of a hollow retainer, which in turn allows the soft actuator sitting on top to deform.*

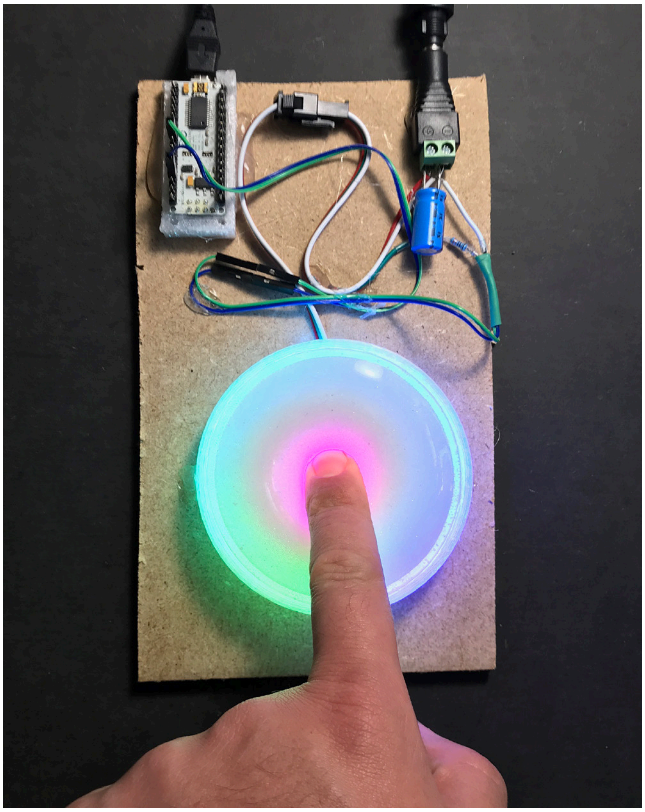


Figure 44: *The Visual-Haptic Display prototype is able to represent information three-dimensionally: Pressing a finger into the actuator reveals information buried in deeper layers.*

VALIDATION

RECAP

The prototypes explored in the previous two chapters covered many of the modalities discussed going into the evaluation phase *(Figure 9, page 23)*. This process of researching sensory modalities and the technologies required to cater to them created a deeper understanding for the situations each modality or technology might best be suited for. It may therefore be helpful to call those aspects back into memory in order to proceed to the evaluation. For that purpose, *figure 46* provides an overview of different prototypes as well as the modalities addressed by each one of them.

Before any further steps towards the concrete implementation of any prior ideas were taken, a more thorough validation & evaluation process was needed. To that end, potential users as well as professionals were involved in a range of evaluatory activities. User tests, brainstorming sessions, as well as validation sessions with an expert from Gaggenau and Charm Lab's Melisa Orta Martinez were part of the process.

The activities performed fell into one of three main categories: In a first step, activities were focused at quickly gaining a broader overview of available insights. A second step was then meant to solidify and build on those results in a more thorough manner. Two separate aspects were evaluated: The performance of different prototypes by themselves, as well as their suitability for addressing challenges in the kitchen space.

All validation and research activities conducted are referenced in *Figure 45*.

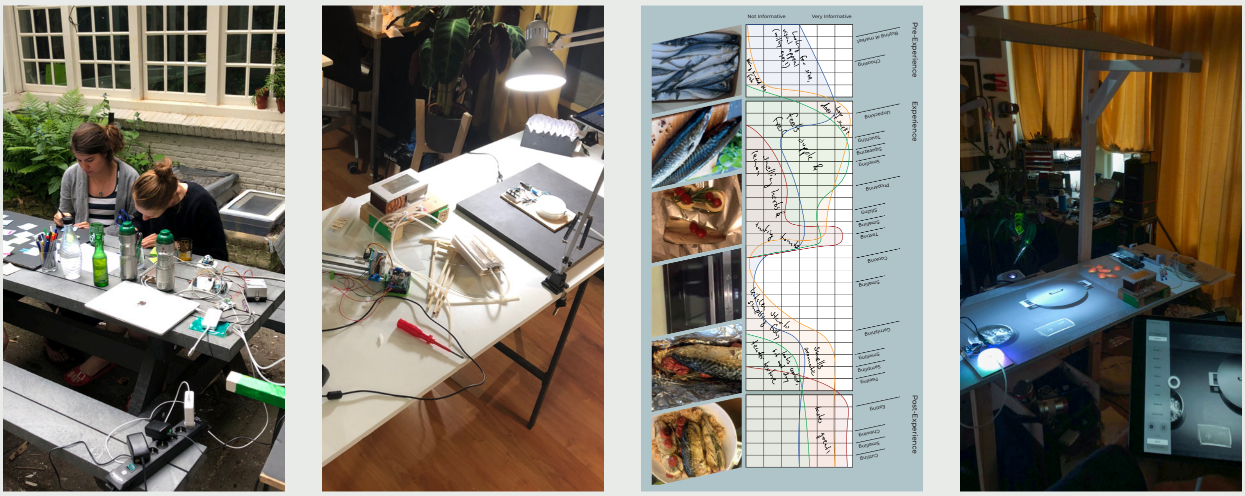


Figure 45: *The validation activities described in this chapter. From left to right these include creative sessions (p. 58), user testing sessions (p. 62), the mapping of cooking journeys (p. 66), and a deeper immersion in the kitchen context, including further user test (p. 69).*

Figure 46: *The prototypes chosen for broader evaluation with users. They cover behaviors and modalities that have either performed well in prior explorations or that raised questions that needed answering in a more user-centric context. The icons on the left indicate which modalities play central roles in the interactions with either device.*

CREATIVE SESSION

The process thus far focused mainly on formulating interaction visions and building prototypes based on theoretical knowledge and intuition. While this yielded promising results, a better understanding of the design opportunities created by the modalities explored was needed. To that end, a creative session was organized. Participants included design students as well as young professionals of various fields between the ages of 24 and 32. The field of participants was chosen to feature an even gender distribution, as well as to include usability experts (UX Designers & Students) and potential users (young professionals, CEO of a start-up company). The group consisted of six people (excluding the facilitator).

The process was divided up into three stages. For the first part, participants were asked to consciously take note of their experiences while preparing food in the days leading up to the creative session. Special attention was to be placed on the obstacles faced during that time. During the session itself participants were then asked to recount and discuss the challenges they faced and distill them into a number of major "pains". It became evident that these pains fit into one of three categories: Struggles relating to a lack of understanding of appliance settings ("How did I burn this cake before it was even fully cooked?"), the inaccessibility of information during certain activities ("It's hard to predict how cooked the egg actually is"), and difficulties understanding how different decisions affect the end result ("there is such a wide range of cooking vegetables the right way, but I don't know which one creates the taste I want").

In a subsequent step, participants were encouraged to interact with the selection of prototypes highlighted in *figure 46*. This happened without sharing previous insights into the potential applications of individual prototypes. That way, participants were free to make associations in an unbiased way, providing an independent source of validation *(Figure 47)*. The associations and insights generated that way were noted down and used for the third step.

Based on the pains identified and the associations triggered by interacting with the different prototypes, the participants were encouraged to ideate and identify solution spaces *(Figure 48)*. By mapping out activities commonly encountered in the kitchen space as well as the challenges associated with them *(Figure 49)*, helpful interaction ideas could be applied to them. This was done with the help of a method called Braindrawing.

Braindrawing is a visual brainstorming approach somewhat similar to mind mapping and provides an effective way to quickly generate a broad pool of new ideas. Different goals are written onto individual sheets of paper. These goals were defined in a common effort. Each participant begins with one objective and uses the piece of paper to sketch and note down ideas on how to reach it. After a fixed amount of time, participants exchange the sheets of paper, continuing the ideation process on one of the other topics. That way, participants are enabled to ideate in rapid increments, building off of one another's ideas.

For this process, four questions were chosen. They were partly based on the pain categories identified in the first stage, but also pertained to the different way different interactions could be applied.

Figure 47: *Participants of the creative session seen writing down their thoughts after having experienced a number of different interactions with prototypes.*

The questions were as follows:

- **How can the state of a dish be represented using new sensory modalities?**
- **How can new sensory modalities be used to control appliances?**
- **How can tactile interfaces interact with other sensory modalities?**
- **In what shape would different multimodal experiences be most helpful?**

Many of the session's results seemed to reflect earlier intuition. The challenges participants encountered reaffirmed that indeed many problems in the kitchen space arise from sensory blind spots (or sensory "black boxes" as discussed in the introduction to this report). Participants easily understood the qualities represented by most of the prototypes and readily associated them to various food behaviors or reals of information. Results of the brain-drawing session also strengthened the research focus: While many promising ideas for controlling appliances using new modalities

Figure 48: *The creative session in progress. Participants can be seen sharing and structuring individual thoughts and engaging with ideas triggered through that process.*

emerged, they were far more abstract and conceptual than ideas meant to bridge sensory blind spots. This confirmed that this bridging of sensory blind spots is not only the more imminent and relatable objective for improving usability, but also the better path towards achieving more meaningful results within the scope of this work.

The process however also had some pitfalls: The way prototypes were presented occasionally led to a fixation on their immediate aesthetic qualities rather than the potential of their functionality.

Furthermore, group activities such as the ones described here bear the risk of participants introducing and reinforcing one another's biases. Nevertheless, many valuable insights were generated, especially since later activities were able to mitigate many of these factors.

The detailed results of the brain-drawing session as well as other materials produced during the different steps of this creative session can be found in *Appendix I*.

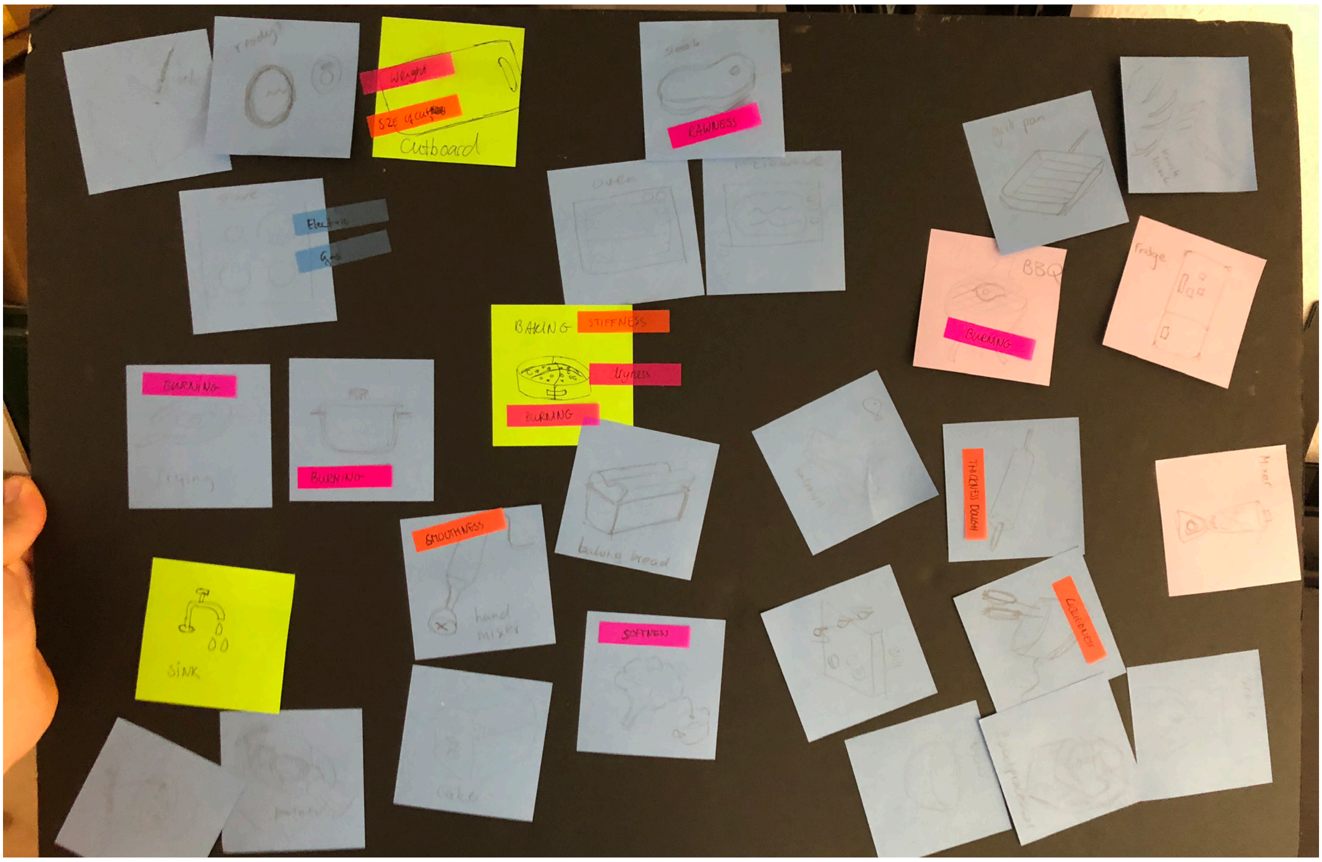


Figure 49: *A selection of items identified by participants to have been related with frustrations during recent cooking activities. Types of information users at the time wished they had access to are mapped to individual items.*

USER TESTS

The Creative Session discussed in the previous section proved to be an effective tool at validating broader design directions and strengthening insights. As this was done with a limited number of participants over the course of half a day, the process was well suited for quickly gaining a broader overview. In order to strengthen those insights and determine to what extent prior results can be reproduced, a number of user tests was performed.

As with the approach during the Creative Session itself, the reactions and associations evoked by the prototypes themselves were to be analyzed first outside of the kitchen context. That way, a baseline for the affordances created by each modality and prototype could be established. Affordances describe the properties of an object that communicate possible action spaces to the user.

Over the course of ten days a number of user testing and feedback sessions were organized with a total of fourteen participants. The group was composed of 6 male students of various engineering disciplines between the ages of 20 and 26, three couples, two of which in their mid 20s and one in their 60s. Furthermore, one session was conducted with a design strategist from Gaggenau, and a remote validation session was scheduled with Charm Lab's Melisa Orta Martinez via Skype *(Figure 50)*. This selection of people was

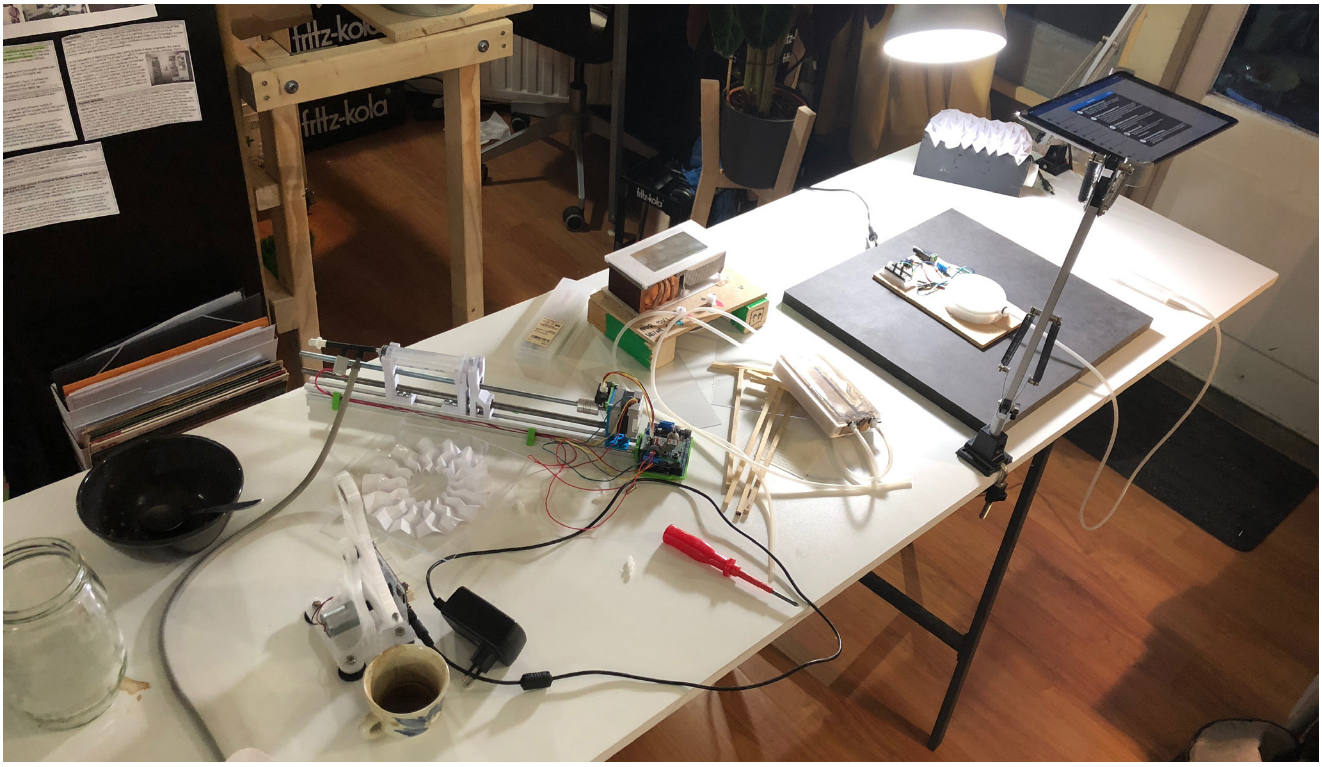


Figure 50: *The set-up used for the user test with Gaggenau as well as for the remote validation session with Charm Lab's Melisa Orta Marinez.*

meant to reflect groups of people in different living arrangements and from different backgrounds. While younger students were more likely to cook for themselves, couples were more likely to commonly utilize a kitchen space. That way, a variety of different interests could be reflected in the results. The two experts were included to generate insights from a point of view that includes a more general knowledge of the kitchen industry as well as eventual technological hurdles.

The user testing sessions conducted with more than one person were recorded for later in-depth evaluation, provided the consent of the participants was given *(Figure 51)*. Insights of individual sessions were collected in writing. Furthermore, most participants agreed to answering a questionnaire about their experiences with the different prototypes.

The questionnaire consisted of 25 questions, five questions relating to the vision put fourth by each of the five prototypes participants interacted with *(Figure 52)*. On the last two pages, respondents were encouraged to freely associate their insights to situations encountered in the kitchen, as well as to visually ideate. For that purpose, a list of different kitchen appliances as well as a neutral line-drawing of a kitchen were provided as a starting point *(Figure 53)*. The full questionnaire can be found in *Appendix II*.

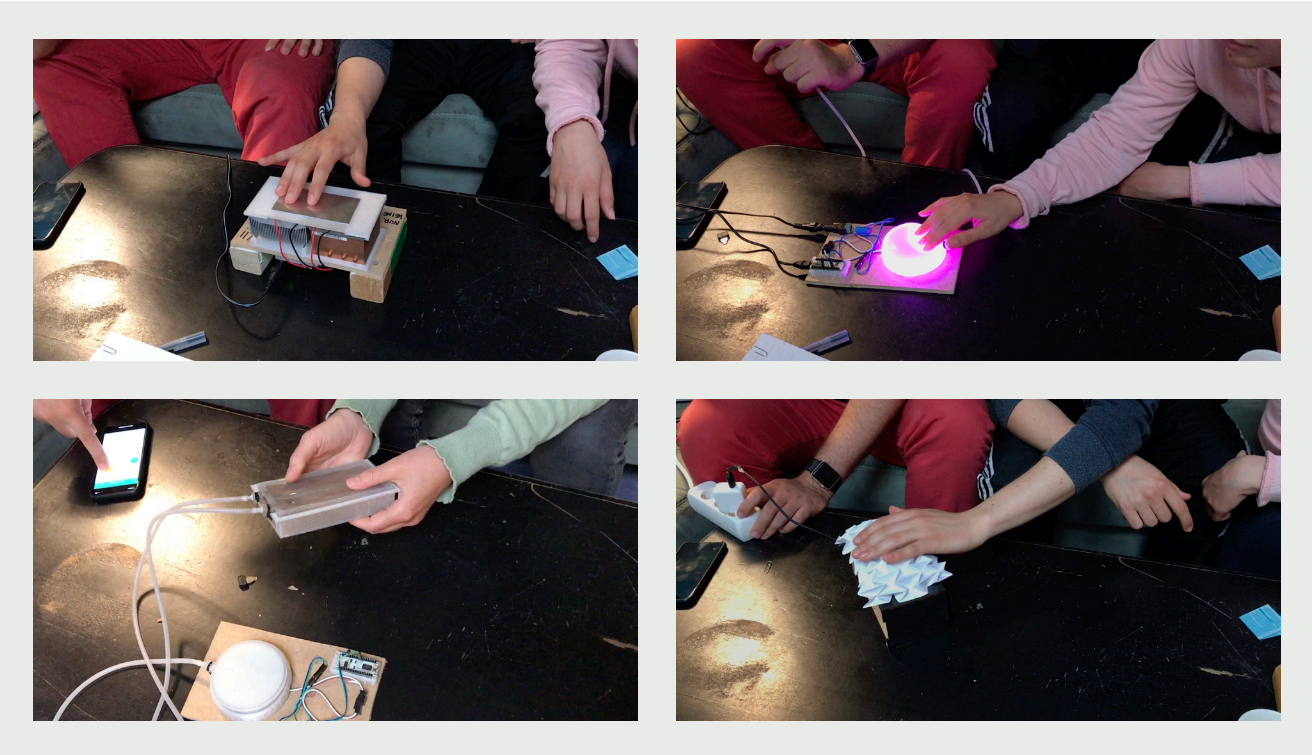


Figure 51: *Screenshots taken from the recording of a user test. Participants can be seen interacting with a variety of prototypes during one of the group sessions.*

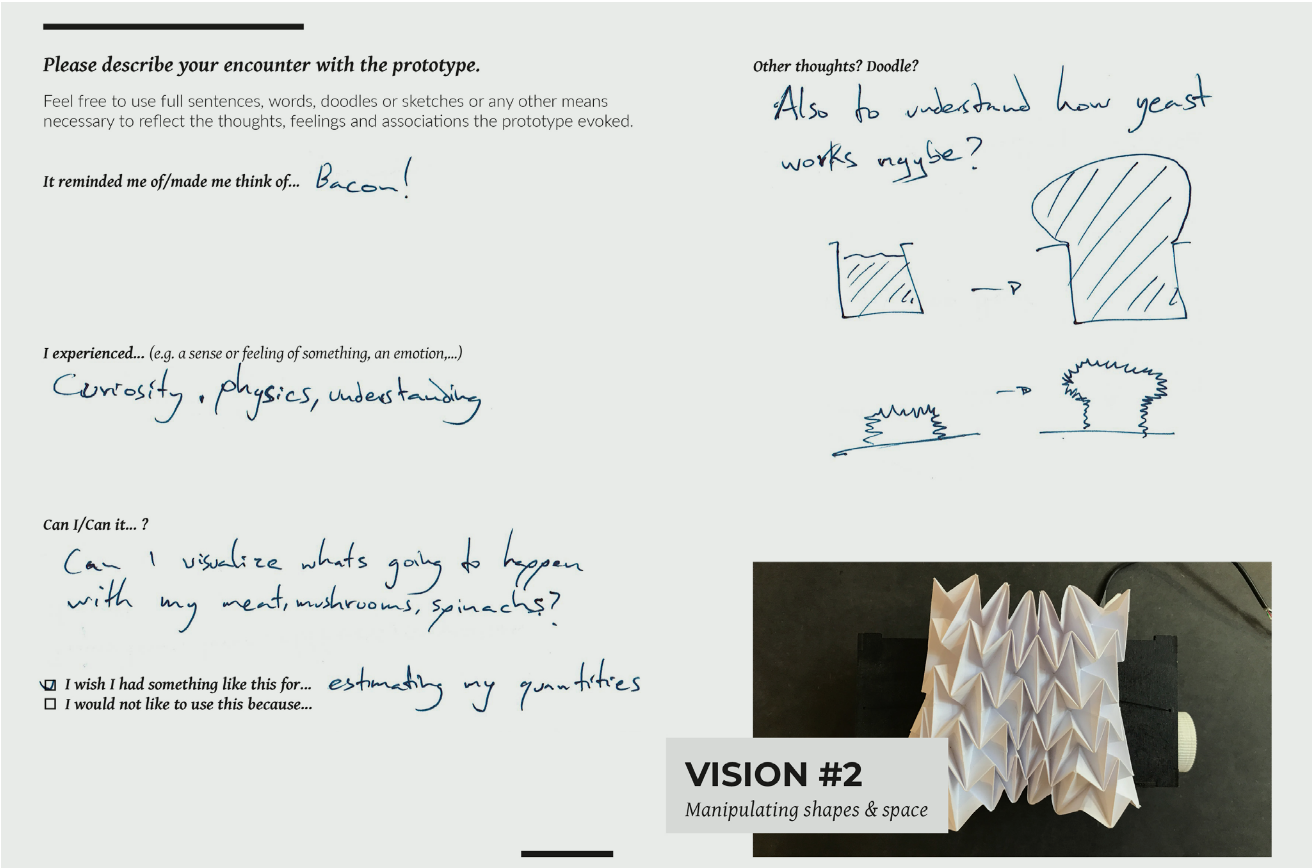


***Figure 52:** A selection of answers given to questions pertaining to each of the prototypes investigated, as part of the questionnaire administered after user testing sessions.*

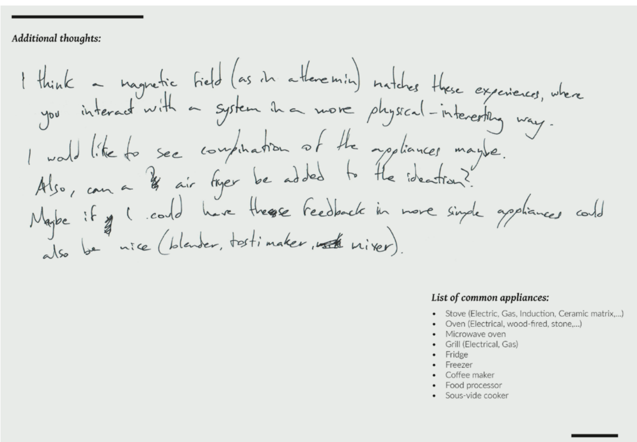
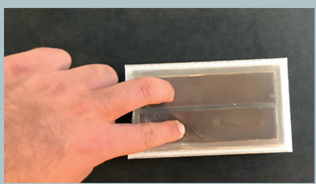


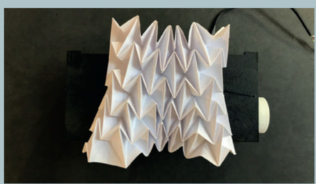
Figure 53: *The two final pages of the questionnaire, encouraging respondents to ideate further.*

The primary goal of the user tests was to validate the expressive qualities of the prototypes. This was a success and provided many additional insights. An arguably even more relevant outcome was the selection of new ideas the prototypes evoked in participants: Many new, relevant domains and potential applications therein were identified.

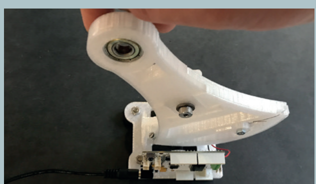
In order to gain a better understanding of this new knowledge, relevant responses to each prototype were selected and compared to the results of other validation activities. *Figure 54* provides a concise selection of the most relevant responses of the user test described here.



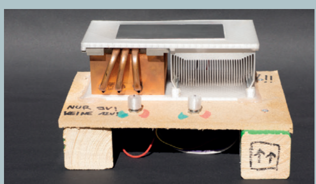
"Can I feel different consistencies in my food with it?"
"Can it show me how my food feels now and how it should feel?"
"I want to use this to feel how done my food is without opening the oven."



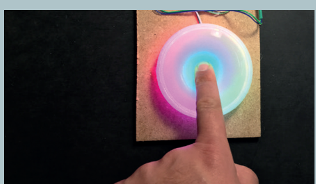
"I am controlling the density of something!"
"Can I use it to determine the strength of my coffee?"
"Can it tell me if things in my fridge are going bad?"



"It is amazing how you can actively experience evolving information with it!"
"Could I use this to feel the consistency of whatever is in my food processor?"
"It talked to my feeling instead of giving me a numerical value!"



"Can I use this to understand what is happening inside my food?"
"Can it also act like a dimmer switch?"
"Can it tell me if my ice cream/food is at the right temperature to eat?"



"I think this would allow me to better understand how to heat my oven."
"Can I shape/turn it?"
"Will it stay on & remember the exact point I pressed into it?"

Figure 54: *Relevant ideas and statements resulting from user interactions with different prototypes.*

MAPPING THE COOKING JOURNEY

With the evaluation of the prototypes well on its way, focus was placed on other important factors. So far, a theoretical understanding of the challenges arising in the kitchen space was used to start an ideation process and develop the first ideas and concepts. This yielded good results, but in order to apply these results to specific use-cases, individual challenges had to be better understood.

So far, sensory blind spots were identified as a major factor contributing to uncertainty and frustration in users. To better understand this process, more knowledge about the way senses are used throughout the cooking process was needed. This would not only help uncover the most crucial situations for providing assistance to users, but also show how sensory perception is used to for decision-making wherever it is available. In order to accomplish this, volunteers were asked to map out one of their cooking experiences. For that purpose they were provided a map guiding them through the process of documenting their experiences while cooking *(Figure 55)*.

This map was inspired by the “Experience Map”, a tool jointly developed by researchers at the Politecnico di Milano and TU Delft’s Rick Schifferstein. It is a tool supporting designers to formulate multisensory design visions. The process it describes consists of five levels. Starting from an abstract interaction vision, it guides designers through increasingly concrete steps that conclude with the identification of specific sensory properties a design needs to exhibit for it to create the desired experience (Camere, Schifferstein & Bordegoni, 2015).

This procedure described by the Experience Map is effective in supporting designers formulate coherent multisensory interaction visions. The aim of this exploration however was different: At its core was the assessment of existing multisensory interactions as well as the identification of their constituent sensory experiences. In order to achieve this, users had to be enabled to take conscience of different aspects of their perception as well as the way these aspects shaped their overall experience and decision-making.

The approach used in this case to provide guidance to the users was ultimately derived from two of the five levels that make up the Experience Map. Factors pertaining to different sensory modalities as well as to their expressiveness were mapped onto a timeline of the specific experience to be analyzed.

Participants were encouraged to work in groups, as documenting the experience as it occurred was crucial. Starting with the preparation of the process, leading through the cooking experience itself, up until the post-experience, participants were instructed to document their visual, olfactory, auditory, gustatory and haptic perception. Moments where sensory perception played an important role were to be documented alongside the activities or events causing them. Reflecting on the notes taken, participants were then asked to draw a graph representing the subjective importance of each sense throughout their experience *(Figure 56)*.

Eight participants agreed to mapping one of their cooking experiences. All participants were couples of young professionals between their late 20s and mid 30s. The resulting maps held a number of insights creating a more granular understanding of the multisensory journey involved in cooking: While the problematic nature of sensory blind spots was resoundingly confirmed, it became clear that their severity was strongly dependent on the circumstances of their occurrence. While ovens for example generally presented a larger obstacle for users than pans or pots, the behavior of the food itself also played a large role: While foods that develop little to no smells or do not show visual cues can make cooking harder even if direct access is possible (for example in the case of cooking with a pan), strong smells or signs of browning can facilitate decision-making even if a dish is hidden behind an oven door.

Appendix III contains the cooking journey maps generated.

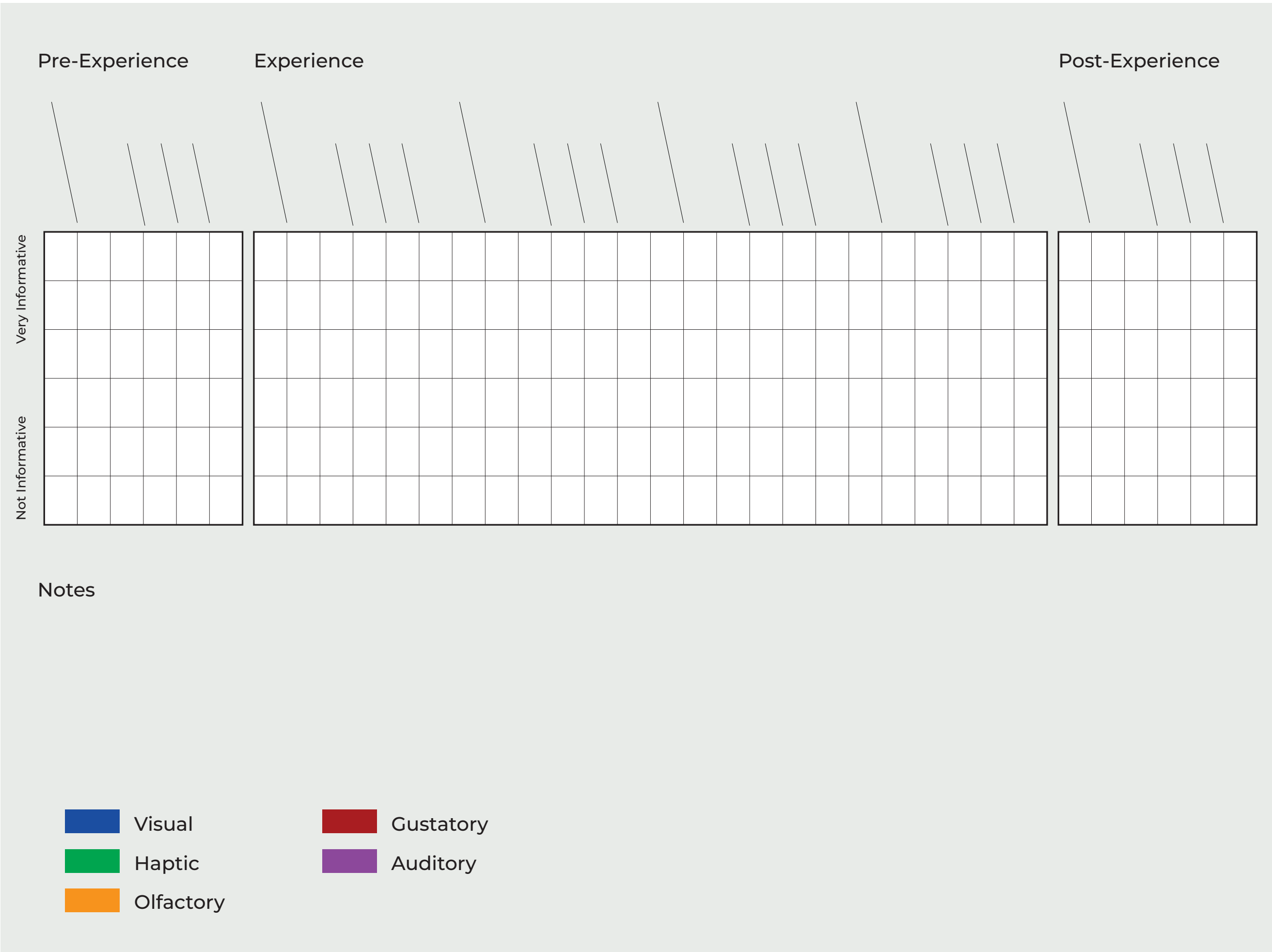


Figure 55: *The map template provided to participants to help guide them trough the process of mapping a cooking journey. The top section reflects the different events resulting in conscious sensory perception while the middle section serves to map out how informative a sensory modality is at a given time. The bottom section is for participants to provide more context, explaining their decisions and the experience.*

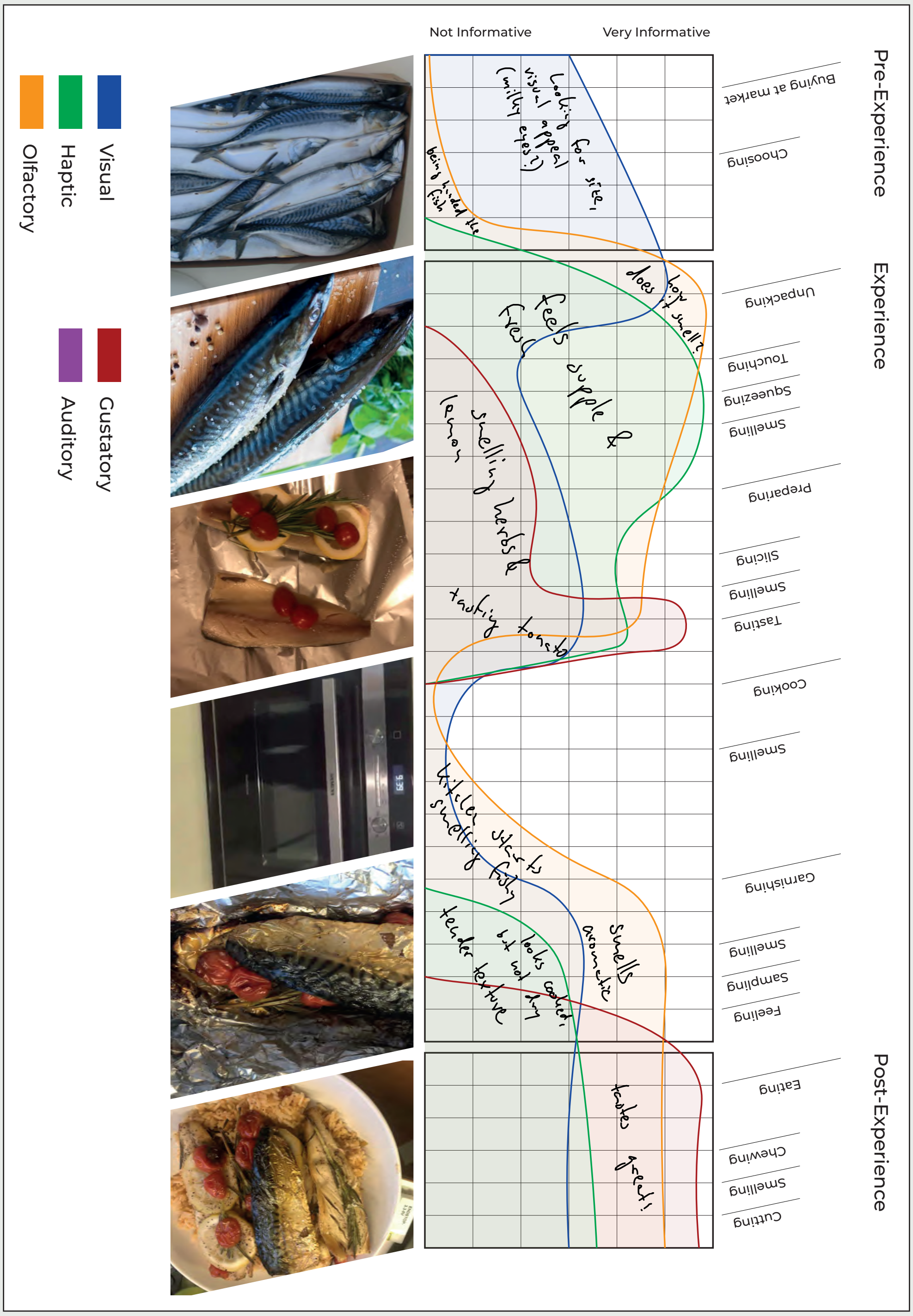


Figure 56: *One selected example of a cooking journey map. The example shown describes the preparation of baked mackerels. As the recipe involves many fresh, aromatic ingredients, sensory cues are readily available throughout most of the process. The notable exception in this example occurs while the dish is cooking in the oven.*

KITCHEN CONTEXT IMMERSION

The activities described on the previous pages provided important answers to a number of questions. They contributed to a better understanding of challenges faced by users in their kitchens, validated the assumptions that led to the design of many prototypes, and created insights into the affordances those prototypes created. Concretely, this means that both the broader context, as well as the prototypes, had been comprehensively been investigated.

This last set of validation activities described here served to complete the picture. Using a number of different methods, the prototypes were placed into various scenarios allowing participants to interact with them in an actual kitchen context. Two relevant questions remained largely unanswered by the activities previously described. The first question tried to answer how readily additional information provided via new modalities would be accepted and how helpful it would be. The second question related to the way users would respond to the different interface prototypes in an ongoing cooking scenario.

To answer the first question a volunteer was asked to cook a familiar dish. This allowed to later ascertain to what extent the additional information changed habitual behaviors. Heat radiation was chosen as the additional data to be provided to the volunteer. This was accomplished by installing an infrared thermal camera module above a stove and visually representing the data it collected on a screen *(Figure 57)*.

Figure 57: *The set-up for an augmented cooking session. A FLIR Lepton camera module was mounted above the stove and interfaced with a notebook, which provided a color-coded visualization of the heat data. This set-up was chosen as it visualizes data in a way that approximates the way the Visual-Haptic Display described on pages 50-52 would present visual data.*

The dish prepared during this cooking session was a relatively simple pasta dish, that involved frying and steaming fresh ingredients. A video recording was made of the session for later analysis. Throughout the session the cook can be seen observing the effect the heat has on the ingredients as they are gradually added to the dish *(Figure 58)*.

Based on the video recording as well as on an interview of the test participant, it became clear that, despite preparing a familiar dish, the additional information was readily accepted and organically integrated into the cooking process. The information helped determine the timing of adding ingredients and influenced factors such as the cooking duration and the chosen heat setting for a given step. It also enabled the cook to omit using a timer for certain steps of the process.

Figure 58: *A screen-shot taken from the recording of a cooking session augmented by the visualization of temperature data. The cook can be seen observing the effect of adding an ingredient.*

Answering the second question was somewhat more difficult, as functionally integrating the prototypes into a kitchen environment at this stage of the process would have presented significant effort not justifiable for this stage. For that reason, two user tests were performed that approximated a cooking experience involving the prototypes.

The first test was performed in the community kitchen of a student living facility. This created an opportunity to observe multiple people cooking over the course of an evening. During the cooking process, willing participants were then presented with one of the prototypes and asked how they would use it if they had to solely rely on it to perform the next step in their recipe *(Figure 59)*. Over the course of that evening, five people cooking two separate meals consented to participating in this test. All were students in their early 20s.

The strongest reactions were elicited by three of the five prototypes: Those were the Haptic Paddle (“It feels so natural! No ones and zeros, everything in between!”), the Temperature Display (“You suddenly feel a bit smarter!” / “You instantly know what’s going on!” / “You project how you feel onto what you do.”), as well as the Visual-Haptic Display (“A magical button that gives me multiple informations at once!”). A collection of the most relevant responses can be found in the aforementioned APPEDNIX XX alongside the results of prior user tests.

As a kitchen in a student living facility is hardly comparable to a Gaggenau luxury kitchen, a way to test the extent to which these insights may also be valid outside of a shared kitchen was needed. A projection mapping setup had already been constructed for use in the later conceptualization phase, so it was decided to use it in order to approximate an interactive Gaggenau kitchen *(Figure 60)*. This allowed for a quick and interchangeable way to render different Gaggenau appliances to scale. With the help of a volunteer that had worked with Gaggenau in the past and was therefore familiar with their product range as well as their customer's mindsets, the procedure of the user tests was repeated. This allowed to successfully establish that the testing circumstances were suitable to generate insights helpful for the formulation of concepts applicable to Gaggenau kitchen environments.

Figure 59: *Users can be seen interacting with prototypes during a cooking experience. Each prototype was applied to a different cooking process, allowing users to use them to explore different factors.*

Figure 60: *The projection-mapping setup used to approximate interactions of prototypes with different Gaggenau appliances. A modular wooden frame was used to hold up a tabletop, above which a mirror was suspended, That way, the distance of the projector could be adjusted to reproduce the appliances displayed at a 1:1 scale.*

CONCLUSION

Throughout all the validation activities described in this chapter, there was one recurring theme that stood out. In its most general form, the question that most test participants and users wanted answered through their interactions was “What is the consequence of my actions?”

This manifested itself differently in various situations. One good example was the test of haptic displays on an oven. Participant wanted to know if the display can inform not only about the current state of things, but also provide a point of comparison for what they should be looking for. In another case, a participant of the creative session pointed out that, while many ways to prepare an ingredient are technically correct, she would like to know what actions she had to take to achieve the one result she was looking for.

All these examples show the importance of providing reassurance. It is crucial to make information adequately tangible. This gives users the tools to seek reassurance by satisfying their curiosity.

Given the current trends of the digital age, an increasing amount of helpful data is becoming available to users. The activities described in this chapter reaffirmed the importance of finding adequate multimodal ways of embodying this data. The user tests showed that information can be made inherently valuable and intuitively understood if it is translated into an appropriate sensory vocabulary.

This vision for technology is not new: Prof. Hiroshi Ishii’s Tangible Media Group at MIT’s Media Lab formulated a vision for technology to become fully embedded in the physical world (Ishii, Lakatos, Bonanni & Labrune, 2012). This vision titled “Radical Atoms” describes a fully universal design material that is simultaneously physical, yet digitally programmable. On the way to this futuristic vision, Ishii describes Tangible User Interfaces (TUI’s) as an intermediate step. TUI’s are fully aware of the relationship between complex, digital information and the human intuition for the physical, which is why they perfectly describe the desired outcome of this project.

The activities described in this chapter largely validated both the problem definition as well as many of the technological visions explored. This understanding allowed for the adaptation and refinement of Tangible User Interface paradigms to fit the needs of this project. *Figure 61* provides a visually distilled version, serving as a guiding framework for the conceptualization activities described in the following chapter.

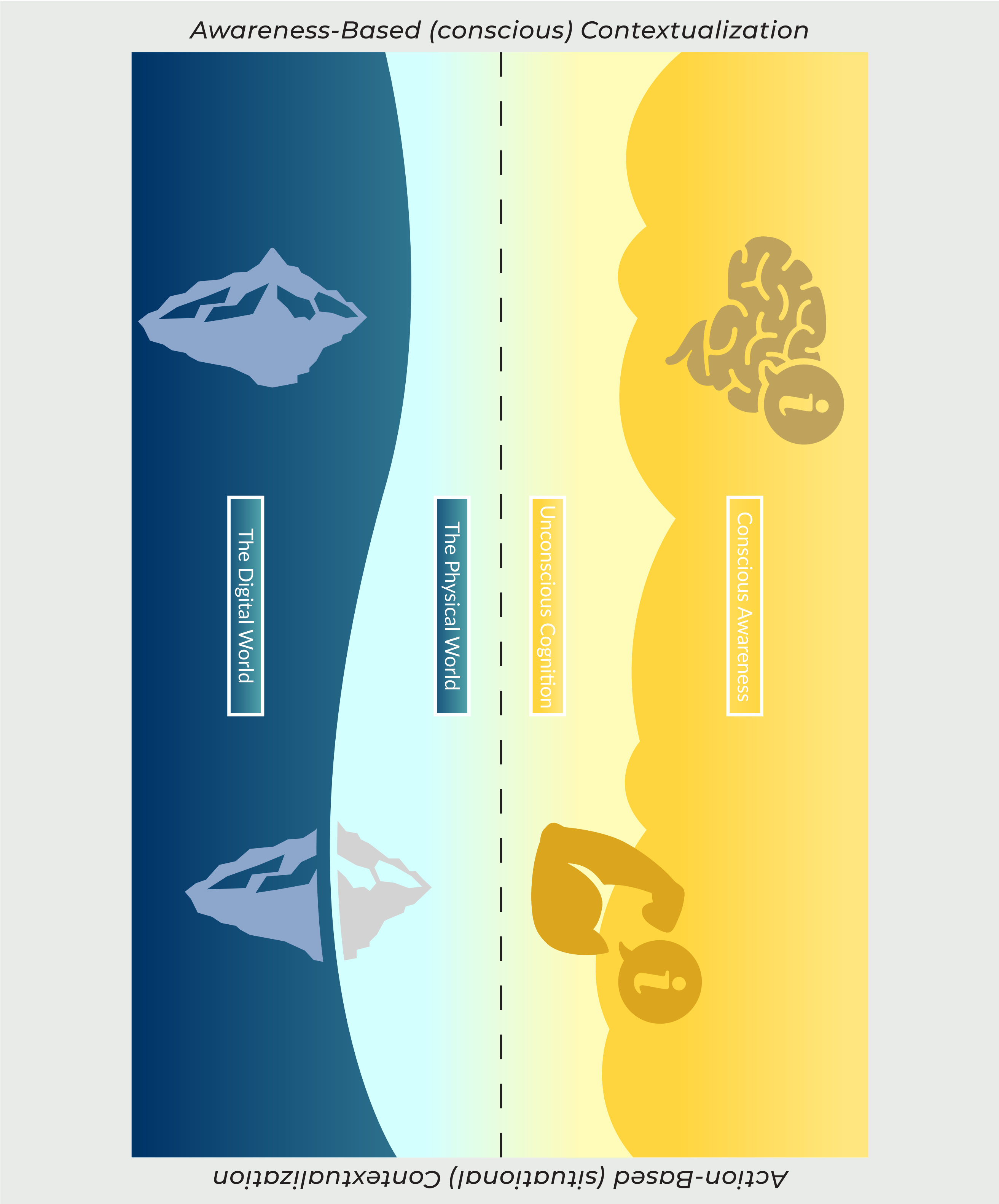

Awareness-Based (conscious) Contextualization
The Digital World
The Physical World
Unconscious Cognition
Conscious Awareness
Action-Based (situational) Contextualization

Figure 61: *Adaptation of the analogy used by the MIT Tangible Media Group to describe Tangible User Interfaces (TUI's). The awareness-based contextualization on the left side of the of the figure describes how universal digital interfaces work. An abstract piece of information can be digitally "seen", but only interacted with remotely. In this analogy this is visualized by fully submerging the information in the digital "ocean". This forces the observer to consciously deduce the properties of what he is observing, represented by the mirror-image of the digital world, in this case the realm of conscious awareness.*
The right side describes an action-based contextualization, as enabled by Tangible User Interfaces.
In appropriate situations, digital information can be externalized in the physical world. As beings fully embedded in the physical world, users can intuitively act and react to this information, requiring less conscious effort. As physical information is very specific, this only works in specialized environments, such as a kitchen space.

CONCEPTUALIZATION

IDEATING APPLICATIONS

Both the investigation of context and technology yielded a number of interesting and promising results. In order to reach the goal of making any such results tangible in a realistic scenario, a suitable concept had to be identified.

User testing reaffirmed many benefits of multimodality in addressing common usability issues in the kitchen. Participants furthermore identified several ways multimodal technologies could go beyond merely solving existing issues, but also enable them to be more involved with the cooking process. These tests were however conducted using prototypes of varying degrees of refinement; prototypes that were often intended as rough, proof-of-concept implementations of different multimodal technologies. This meant that less importance was attributed to technical constraints the kitchen environment would impose (space, safety, hygiene, reliability). It also did not leave much room to explore their capacity to be scaled and integrated into one another in order to enable more nuanced and rich applications.

Any concept developed in this chapter therefore should take the following aspects into account:

- **Which prototypes helped identify modalities that created the most value for users?**
- **Are there any synergies to be taken advantage of?**
- **What are good design opportunities in the kitchen environment as well as in Gaggenau's product line-up specifically?**
- **Can the concept be realized while respecting the technical constraints imposed by the kitchen environment?**

With this in mind, a number of concepts were developed. Some concepts placed a larger focus on showing the realistic potential for the most successful prototypes and interactions explored thus far to be applied in the kitchen. Other concepts arose from specific design opportunities identified in the kitchen space and re-envisioned Gaggenau's product line-up taking multimodal interaction concepts into account.

Ultimately, one concept was chosen and further elaborated, taking insights gained from the remaining concepts into account. *Figure 62* provides an index of the concept explorations described hereafter.

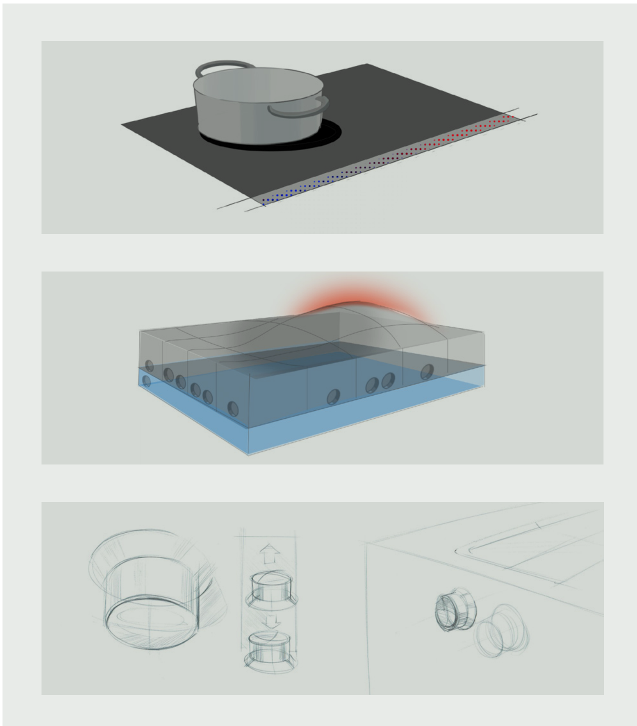


Figure 62: *The three explored concepts: The Embedded Temperature Display (p. 79), the Multimodal Display Matrix (p. 84), and the Multimodal Dial (p. 89).*

EMBEDDED TEMPERATURE DISPLAY

As the prototype which perhaps evoked the most obvious and intuitive responses during the initial explorations, the temperature display discussed in the second chapter's section on "Temperature" (pages 35-38) was a promising starting point for multiple concepts. While the prototype had worked well, its shape and overall construction were strongly limiting for many potential use-cases in the kitchen.

To make a viable proposal, the temperature display had to be embedded into existing kitchenware. This would allow for the externalization of processes unfolding in their interior, such as the permeation of heat through a volume, but especially the sharpness and intensity of temperature transitions.

The first possibility explored was directly informed by user feedback. An often recurring suggestion was for the thermal display to be incorporated into a knob or dial. This would enable users to directly sense and monitor the ramp up in heat inside their pan or appliance without the risk of burning themselves. But more importantly, it would help develop an awareness of the effect different heat intensities have on the outcome of a cooking process. Understanding the right circumstances for foods to properly brown is one example. Without needing a theoretical understanding of the Maillard reaction and its parameters, this chemical reaction that causes food browning could be experienced and manipulated. If combined with a "Visual-Haptic Display" (see pages 50-52) at the center of such a dial, this could also allow for a volumetric understanding of temperature distribution.

To get the required technology into that form factor, several considerations had to be made. Two possibilities to construct this dial were explored: In one case, a custom built, circular peltier element array would render the temperatures directly in the button. A cooling mechanism would then carry away any excess heat. In the second case, the temperatures to be displayed would be generated elsewhere, while heat pipes would transport them into the dial *(Figure 63).*

The first proposal would not be feasible using components available off-the-shelf, which is why it was quickly dismissed. The second proposal seemed feasible, but would likely require several iterations to realize. As this would have gone beyond the scope of this conceptualization stage, the approach was altered to take advantage of other, flat surfaces available in the kitchen space.

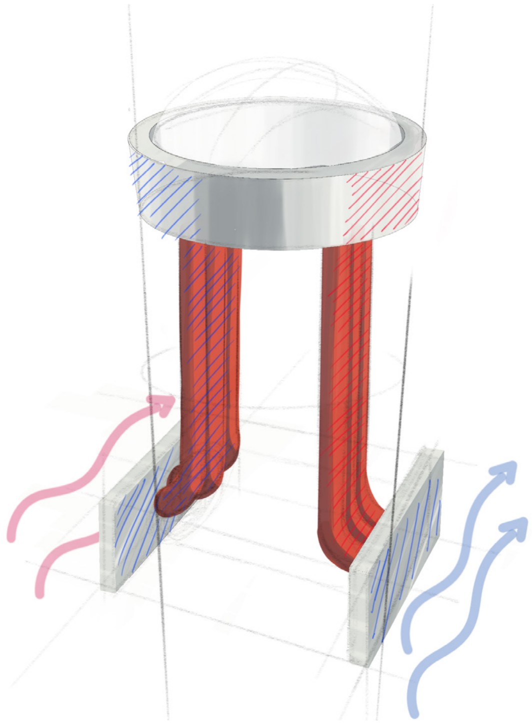


Figure 63: *Schematic sketch of a dial that incorporates a thermal display. The peltier elements under the base generate the temperatures, while heat pipes convey them to the interface's surface.*

The concept that was finally elaborated envisioned a thin, long metal surface that could be embedded within a metal handle of an oven or along a metal frame of a stovetop *(Figure 64)*. This would eliminate the necessity for engineering heat pipes alongside moving parts. With this, fewer challenges remained: For one, the interactive surface had to be made thinner, longer, and capable to show multiple temperature transitions to increase the fidelity of the display. Furthermore, the electronics and cooling had to be consolidated as much as possible, in order for them to be compact enough to be fitted into existing appliances.

Implementing this would require more components, more control signals to coordinate a larger number

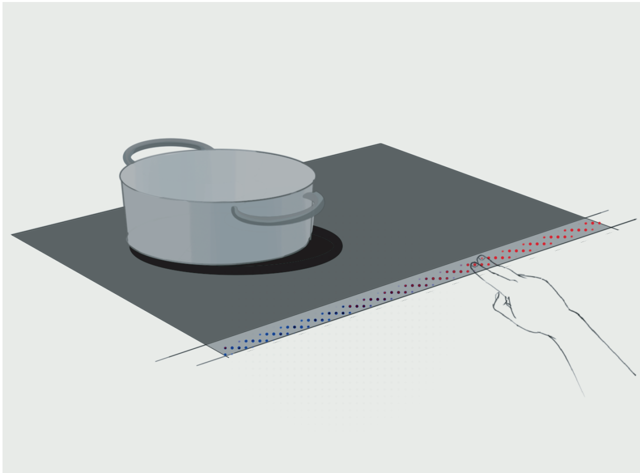


Figure 64: *Illustration of a kitchen scenario highlighting a proposal for integrating the thermal display technology into a cooking workflow.*

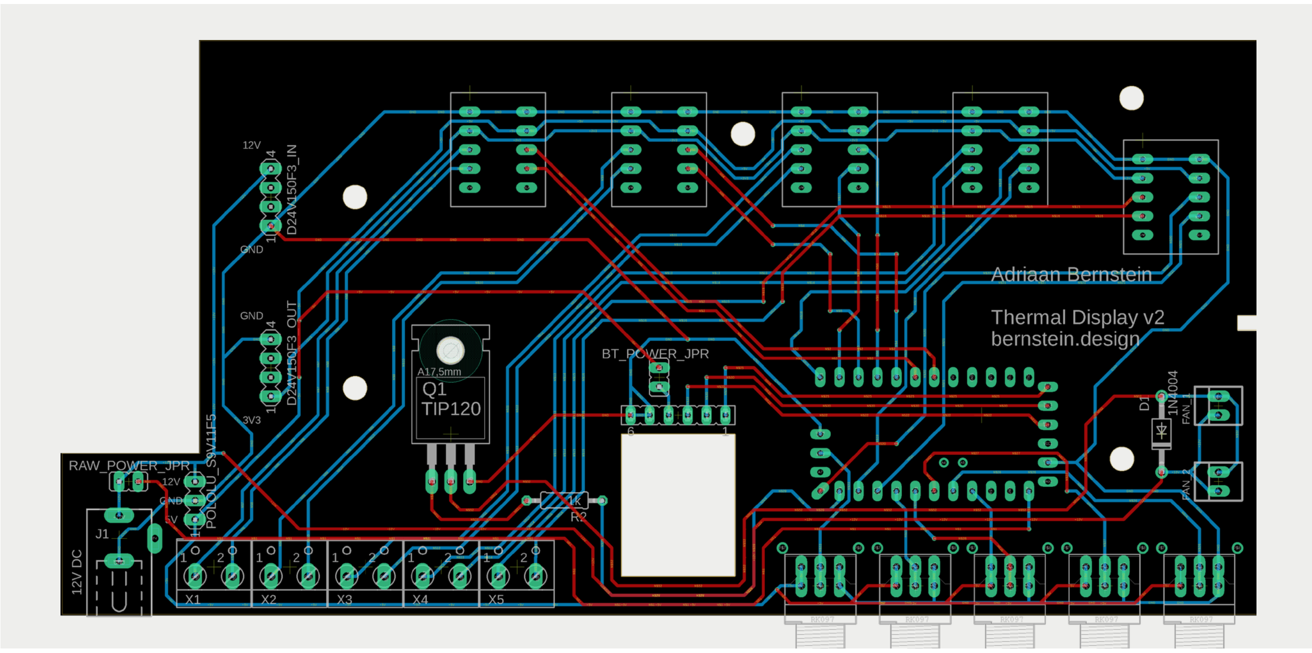


Figure 65: *The board layout of the custom PCB design. At the bottom right, up to five potentiometers can be mounted for temperature regulation purposes. The top of the board features pads to solder in five H-bridge drivers that control the individual peltier elements. The board also accommodates two power regulators, two software controllable fan connectors, a programmable microprocessor, and a control- and programming header accessible via USB or Bluetooth. The board schematics are located in Appendix IV.*

of peltier elements, as well as parts not commonly used by the electronics enthusiast community. To meet those demands, a fully integrated circuit board was designed using EAGLE, a software for the computer-aided design (CAD) of printed circuit boards (PCB's). This would allow for an efficient design and layout of the electronic components, that could easily be produced by any PCB manufacturing service *(Figure 65)*.

The rest of the assembly consisted of five miniature peltier elements (15 x 15 mm), an aluminum extrusion serving the dual purpose of a heat sink and cooling duct, two fans to circulate air, as well as 3D printed structural components *(Figure 66)*.

Figure 67 shows the full assembly, as well as a thermal analysis of the prototype.

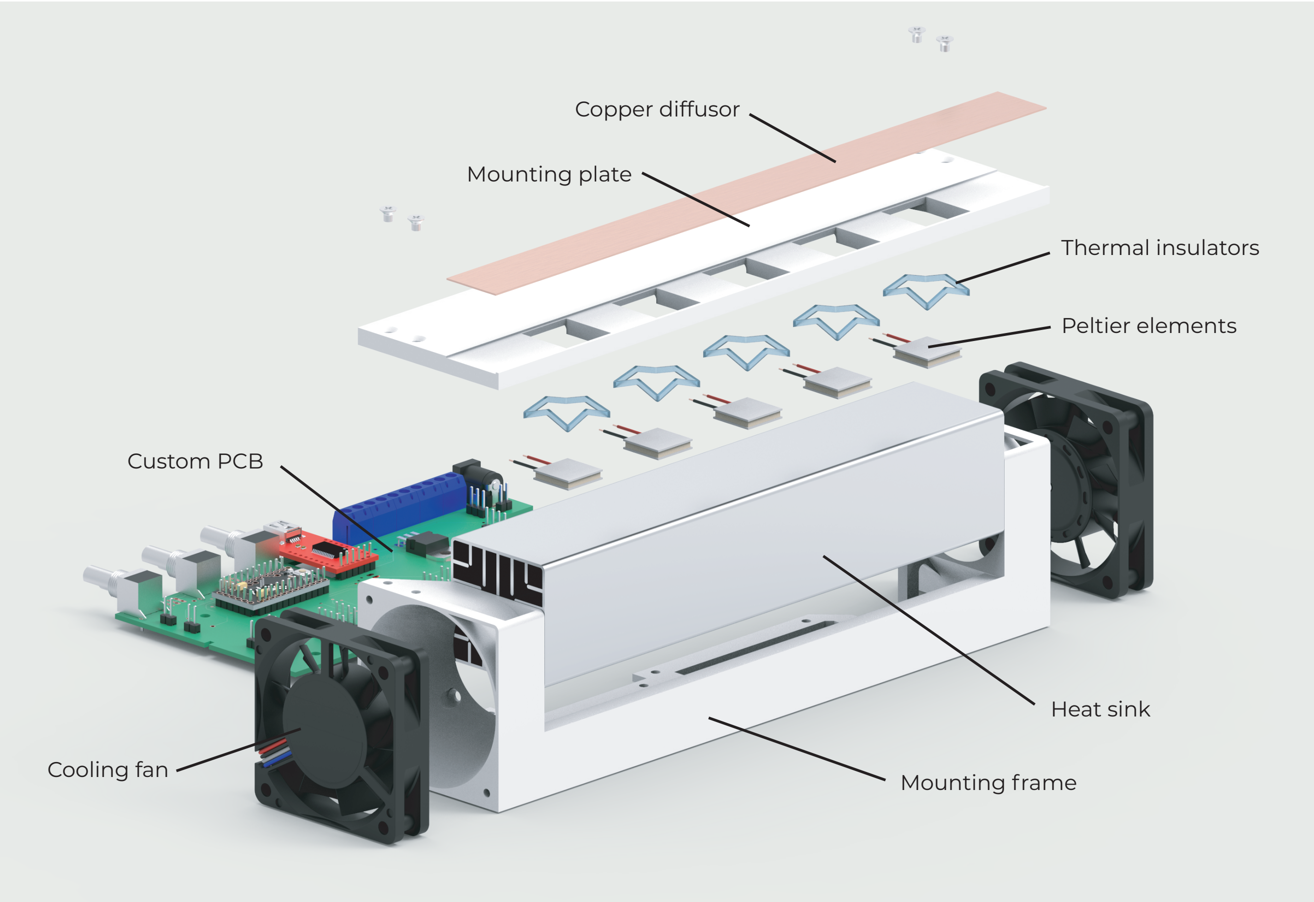


Figure 66: *Exploding view of the temperature display proof of concept. To ensure a good compromise between ease of construction and overall compactness, the prototype's size was dictated by the size of the cooling fans (60 x 60 mm). The PCB was mounted at the base of a mounting frame, a heat sink suspended above it. At the top, a mounting plate ensured the even spacing of the peltier elements. Thermal insulators prevent the plastic mounting plate from melting, a copper sheet serves as a diffuser.*

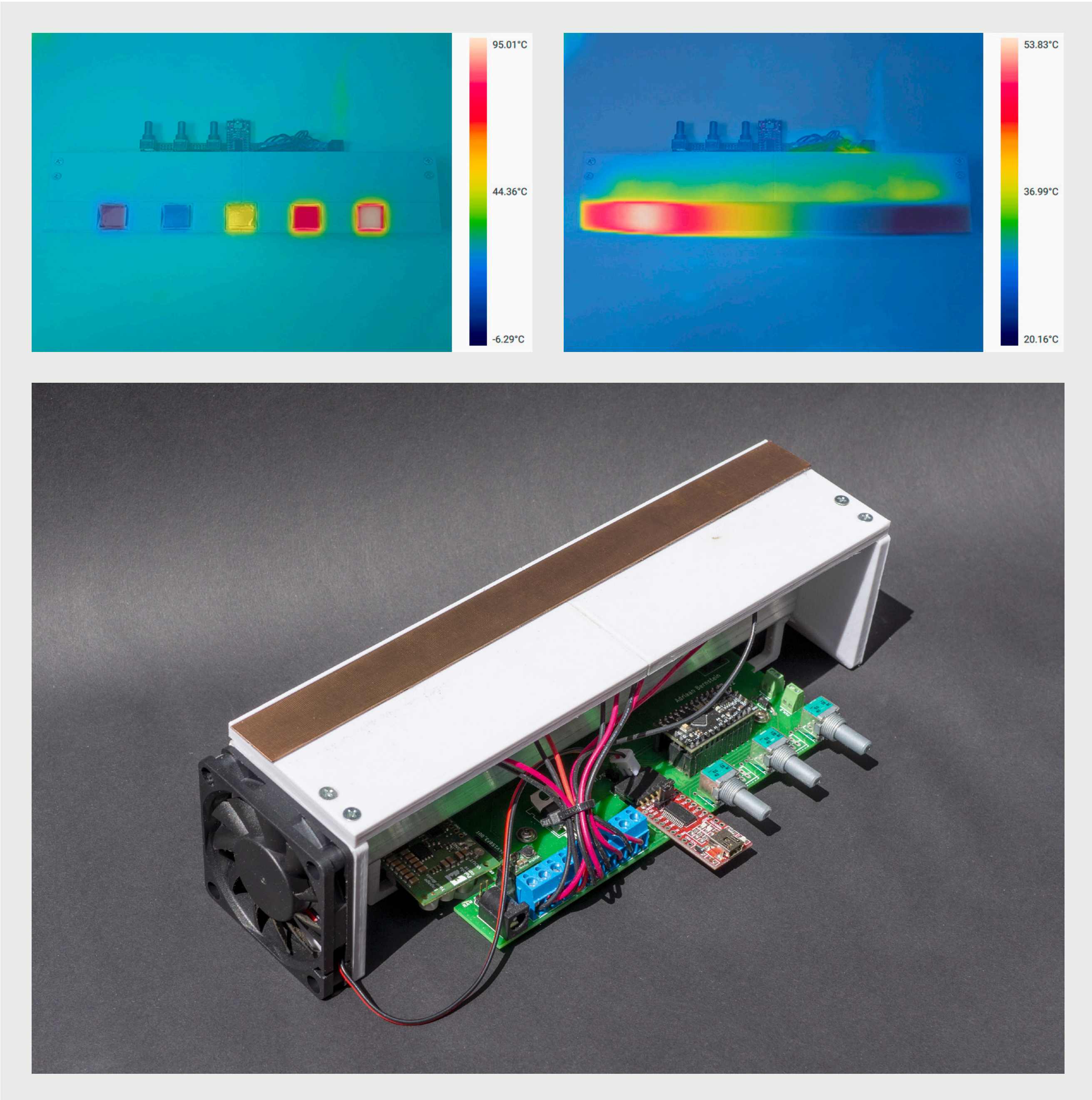


Figure 67: *Analysis of the full range of temperatures the prototype can theoretically produce (top left, -6 - 95°C), as well as a thermal image of a range potentially displays during normal use (20 - 54°C), using the copper diffuser (top right). The thermal imaging was done using a FLIR Lepton thermal camera. The fully assembled prototype is shown at the bottom. More thermal images can be found in Appendix V.*

The prototype ultimately proved that the technology was scalable and resilient enough to be applied in a kitchen context. While the prototype was a success from that perspective, it also showed that an integration with other modalities would be difficult to accomplish within the scope of this project.

Nevertheless, the range of information effectively communicated by the prototype was promising and may be justification enough to further explore its potential applications in the kitchen space. As, in its current form, it would be a unimodal interface, this concept was ultimately dismissed from the considerations for the final implementation. Its development still provided several ideas that would influence the concepts to come.

MULTIMODAL DISPLAY MATRIX

The concept outlined in this section was not directly informed by a specific technology previously explored. Instead, it was shaped by the feedback gained from all user sessions throughout this project. This allowed for more attention to be placed on the overarching ambitions of users, irrespective of any reflections limited by one distinct technology. By analyzing the design opportunities present in Gaggenau's product line-up, a technological approach could then be chosen to satisfy those requirements.

A strong desire for users to understand the significance of their actions and decisions was reaffirmed on multiple occasions throughout the project. This is a need that many of Gaggenau's existing designs already anticipate quite well. By designing in a deliberately physical way, Gaggenau's appliances uphold and cherish many of the established conventions for kitchen interfaces. Physical dials, mechanical switches, and classic material choices establish a clear correlation between appliance functions and the interface used to control them.

While this approach to interface design maintains the much-desired familiarity of analog, physical interfaces, it increasingly confronts Gaggenau with a dilemma. On the one hand, it, too, offers more and more appliances enabled by modern technology. On the other hand, such technologies often break with the static nature of how appliances used to work. This means that the physicality Gaggenau's interfaces relied on in the past is becoming a limiting factor. Instead of creating experiences highly tailored to their usage context, they inhibit the innovation of more flexible, digital functions.

Gaggenau's line-up of stovetops exemplifies this issue quite well. Most of their gas cooktops, electric grill surfaces, as well as some induction stoves can rely on correlations between heating surfaces and the physical dials that control them. However, the company also offers more modern, induction-based appliances that are taking advantage of the flexibility this technology brings with it. Appliances such as their full surface induction cooktops, for example, allow users to freely position and move multiple items of cookware on its surface *(Figure 68)*. Heat will then be applied only in the areas covered by cookware, while the settings freely move with their associated items of cookware. This creates a situation where both the number, as well as the location of control elements need to be as flexible as the appliance they control.

Like many other appliance manufacturers, and, in fact, many other industries that are undergoing a similar technological transformation, Gaggenau is meeting this demand for more flexibility by using

Figure 68: *Gaggenau's Vario 400 series full surface induction cooktop. Unlike traditional cooktops, it does not feature distinct heating zones but allows for the flexible usage of its entire surface instead.*

graphical user interfaces (GUI's) *(Figure 69)*. Borrowed from the world of computing, a very conceptual and versatile domain, these interfaces bring a high level of flexibility and adaptability with them. By sacrificing its physicality, the interface's flexibility comes at the cost of its unique, inherent relation to its context of use (for more context, see pages 8 - 9 as well as pages 73 - 75). While well-designed use-cues are sometimes able to mitigate this loss, it presents a threat to the ability of users to understand the significance of their actions.

As pointed out earlier, this is an ability users value greatly. Situations in which the company and its users are faced with this dilemma, therefore, present clear design opportunities for the implementation of multimodal interfaces. Interfaces that go beyond graphical elements alone may be able to benefit not only from the flexibility of digital interfaces but may also be able to provide the reassurance physical interfaces offer.

It is this understanding that informed the idea to explore the possibility of combining a graphical display with haptic elements.

Using the "Haptic-Visual Display" (pages 50 - 52) as a starting point, particle jamming was revisited as an option to construct such a multimodal display *(Figure 70)*. It already featured the ability to incorporate visual elements into interactions, on top of being able to render various haptic experiences.

For the purposes of this concept, however, both, the display's visual range, as well as its haptic capabilities, had to be expanded. Projection mapping was successfully tested as a means of showing detailed graphical elements, such as text and symbols. The glass substrate used to construct the display created a scattering effect, yet retained sufficient clarity for a prototype at this stage *(Figure 71)*. The expansion of the haptic range presented a more significant technical challenge.

Figure 69: *The interface of a full surface cooktop. The flexible nature of the appliance makes controlling it with fixed, analog dials impractical.*

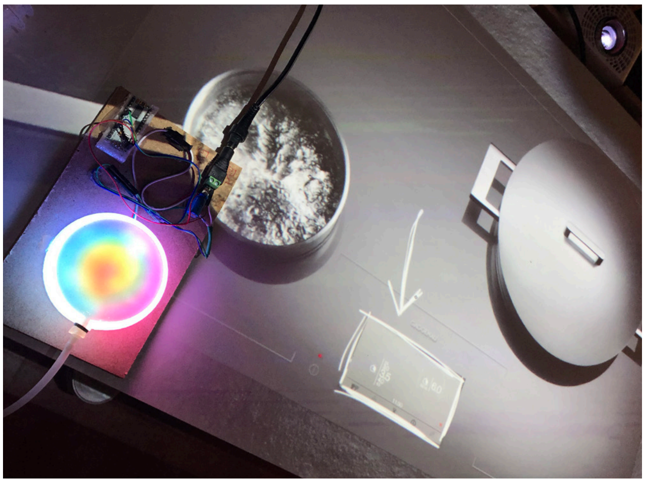


Figure 70: *Exploring the Visual-Haptic Display as a potential means to integrate the flexibility of digital, graphical interface elements with the reassurance provided by physical interfaces.*

Previous prototypes, such as the “Haptic Display” (pages 47 - 49) already attempted to create tactile gradients and texture transitions. Their resolution would, however, not suffice to enable the interface to create tangible shapes and objects.

Inspired by the original design of the Haptic Jamming Array *(Figure 16, page 27)* developed at Stanford University (Stanley, Gwilliam, Okamura, 2013), a simplified version of the assembly described in that paper was attempted. This simplification had to meet a number of criteria: First and foremost, the assembly had to be fully translucent, as to allow for the continued use of an LED Backlight. That meant that materials had to be altered. Furthermore, the depth, as well as the part count of the device, needed to be reduced. While this would limit the accuracy of tactile experiences, the added visual modalities justify this trade-off (more on visual modalities and the distinction between focal and ambient vision on page 51).

In order to conform with the shape of the induction cooktop at the heart of this concept, the prototype was based on a rectangular layout. In keeping close to the aspect ratio of the appliance’s original display, widely available LED matrices were used to prototype different sizes (Figure 72). The individual LED matrices were wired up in parallel to a dithering-enabled, USB controlled driver board. To test its brightness, resolution, and power requirements, the resulting LED matrix was then programmed to interface with a FLIR Lepton thermal camera as an exemplary data source (Figure 73).

Finally, the haptic component of the display was envisioned as a fully pneumatic version of Stanford’s Haptic Jamming Array. By doing away with any mechanical parts, such as pistons, pulleys, etc., a shallow assembly using only transparent or translucent materials was envisioned. The assembly would consist of two

Figure 71: *Concentric rings projected onto the Visual-Haptic Display. Light scattering created a halo effect, yet enough clarity was maintained to distinguish smaller details.*

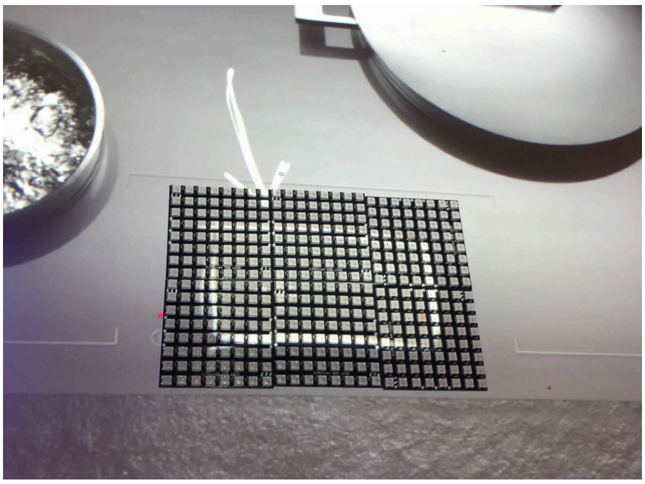


Figure 72: *Individual 8x8 LED matrices arranged into one larger 24x16 LED matrix. The dimensions of the resulting panel are 216 x 144 mm.*

parts: A 4x5 grid of individually jammable, glass-substrate-filled rectangular cells would create the upper part. The lower part, a large, continuous chamber with rigid outer walls, would create an air-tight seal with the underside of the 4x5 grid. The entire assembly would then be mounted atop the LED backlight matrix *(Figure 74)*. Twentyone valves would allow the device to be operated by the vacuum pump platform developed earlier in the project *(Figure 41, page 49)*: Twenty of the valves connected to one vacuum pump would allow for the selection of any number of compartments to be jammed or unjammed. The last valve would assist another vacuum pump to selectively apply a vacuum or positive pressure to the bottom compartment. This would cause the deformation of currently unjammed cells. Subsequently jamming the deformed cells would then enable the rendering of additional shapes in other locations of the display, resulting in a three-dimensional landscape of concave and convex shapes *(Figure 75)*.

While this platform appeared to be a reasonable approach to blending physicality with the flexibility provided by digital displays, it started to become clear that the scope of this concept was not defined clearly enough. The original intent was the reduction of complexity and confusion, yet throughout the development of this prototype, it became increasingly clear that it attempted to solve too many problems at the same time. With many of the technical challenges out of the way, the process of shaping interactions for such a relatively complex interface uncovered several risks. If used carelessly, its many capabilities could end up being distracting. This would merely replace a familiar kind of complexity with a new kind of complexity.

While other scenarios for its implementation also were explored *(Figure 76)*, the decision to take the learnings gained and apply them towards a narrower, more clearly defined use-case was ultimately reached.

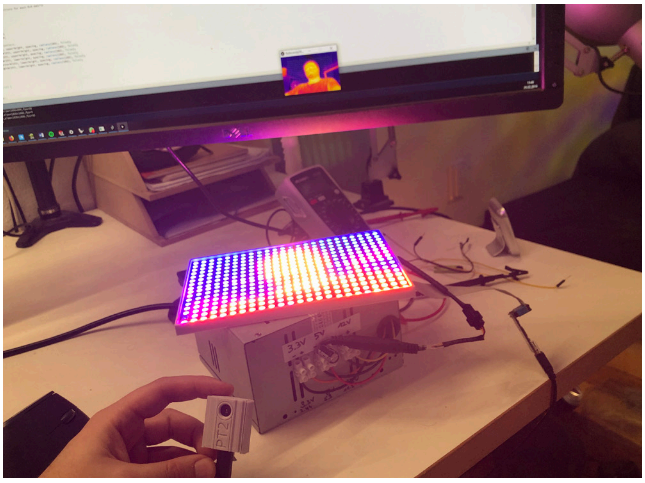


Figure 73: *Live video feed of a FLIR Lepton thermal camera displayed on a 24x16 LED matrix.*

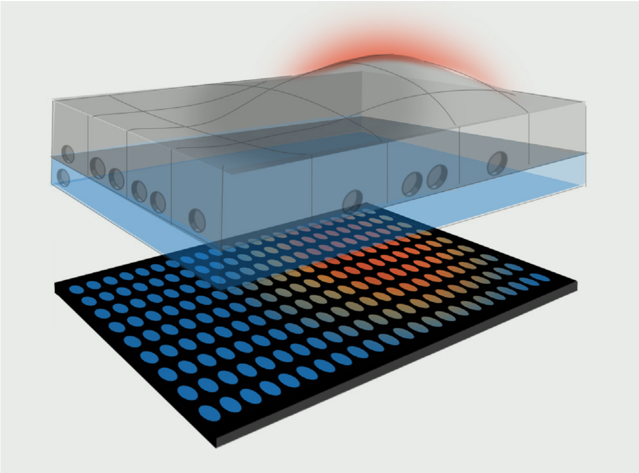


Figure 74: *Illustration of the envisioned assembly and function of the multimodal display matrix. The 20 individually jammable haptic jamming cells are shown in gray, the rigid, lower chamber in blue.*

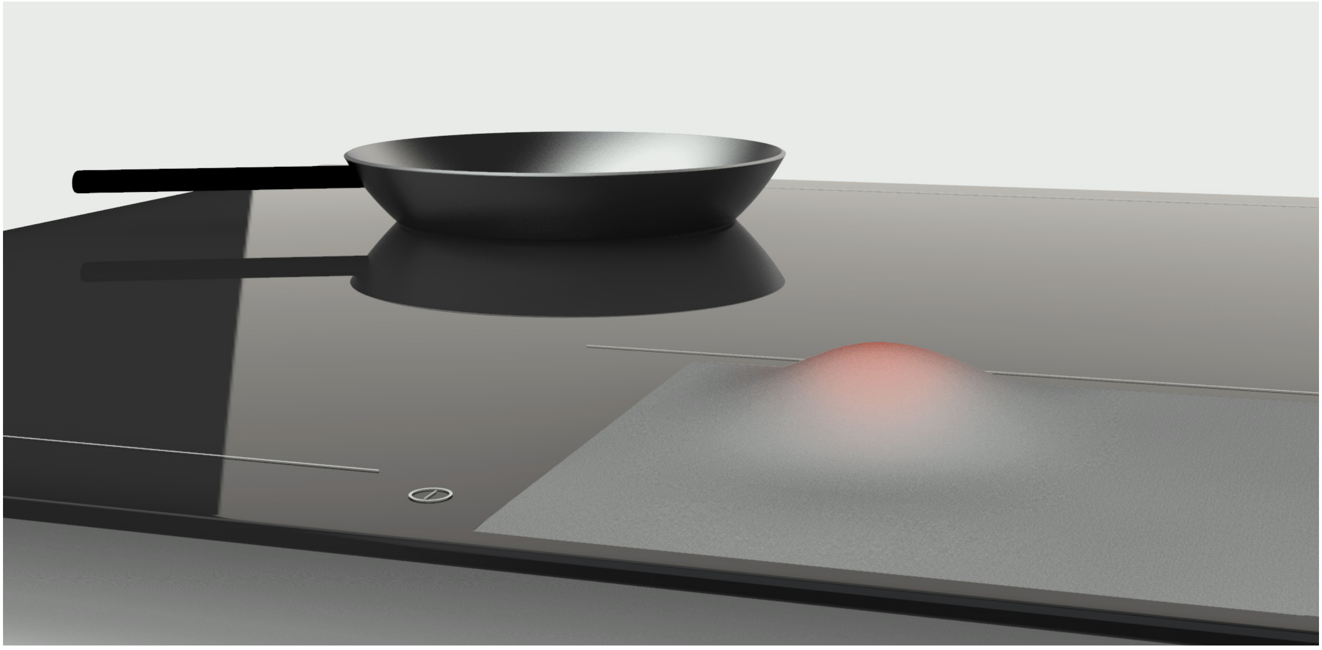


***Figure 75:** The vision behind the Multimodal Display Matrix. The appliance's display would not only be able to display conventional, graphical user interface elements, but also allow for the creation of physical characteristics correlating with the appliance's use. These could include factors such as the location and size of cookware, as well as representations of heat and volume.*

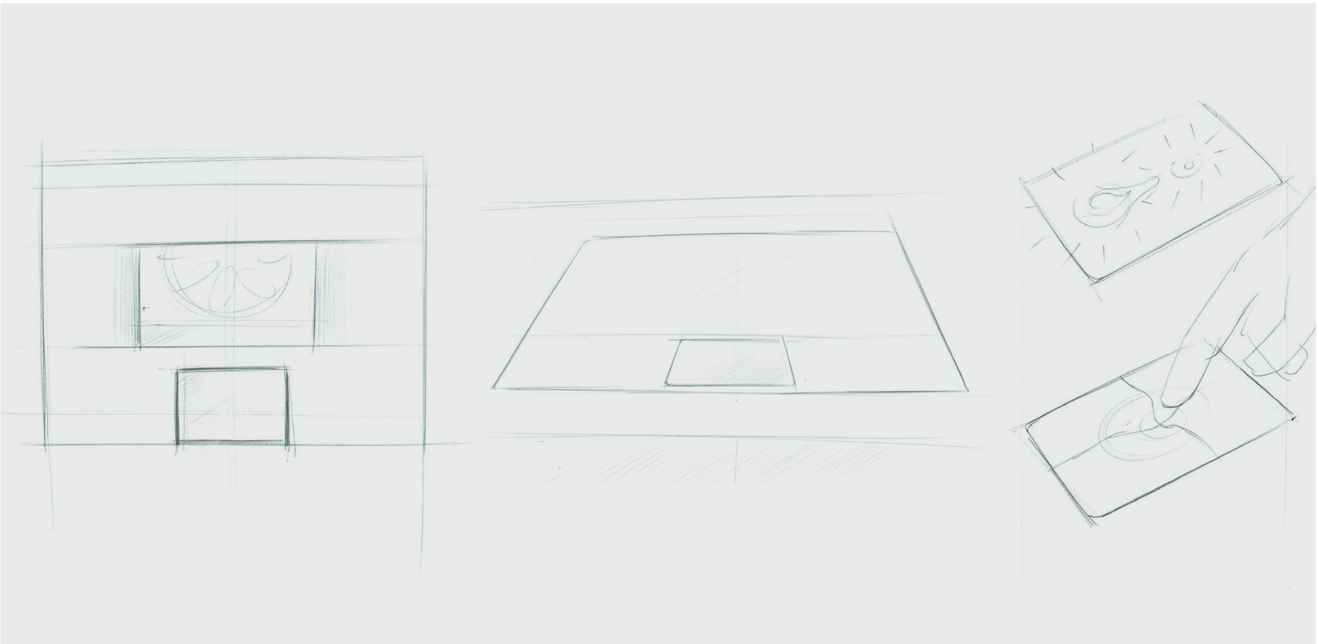


***Figure 76:** Sketches envisioning the Multimodal Display Matrix in different contexts: Applied to an oven, it may be able to represent the temperature distribution throughout the oven cavity, or even allow for direct interactions with the temperature settings. In the case of the full surface induction cooktop, communicating position and size of cookware, as well as the temperature of its content, may be more relevant.*

MULTIMODAL DIAL

The Multimodal Dial concept emerged from a clearly defined objective that resulted from the work done on the previous two concepts. In some ways, this concept may be seen as scaling back on some of the ambitions put forward by the two prior concepts. It would, however, be more correct to see it as their logical conclusion.

This objective can be summarized as follows: Firstly, the purpose of any design in the context of this thesis must be the simplification of complex information. The goal is to leverage appropriate multimodal analogies to accessibly and engagingly represent information. Secondly, this newly actionable knowledge should not get in the way of existing affordances (see page 62 for more on affordances). This means that working conventions should not be replaced or watered down. The proposed design should enable users to find just the right amount of information; information users are actively seeking out. Information going beyond that should be unobtrusive, allowing users to discover and seek it out in their own time.

This creates a much more clearly defined design space. Prior concepts sought to counter complexity introduced by new technologies wherever it occurred. While multimodality may be the right tool to do so, creating a wholly new and meaningful interface analogy goes beyond the possibilities of this thesis project. Instead, this concept focuses on the instances where older conventions can be expanded instead of being replaced. Multimodality becomes the tool to leverage established analogies; expanding them in order to meet the needs of newer technologies.

It is for that reason that the dial was revisited as the central element for this concept. Ever since the introduction of electric and gas appliances, dials have been an integral part of many kitchens. Their simple shape and function help users understand the relation of cause and effect in their actions. This can happen through directly observing correlations between the dial position and the size of a flame, or through visual changes over time on a mechanical kitchen timer. These kinds of direct associations are what this concept aspires to create.

Both examples rely on two distinct modalities the dial already offers (see *Figure 9,* page 23 for common sensory modalities). The temperature setting relies on the dial's position, ergo the perception of its orientation in space. The kitchen timer relies on the perception of changes in appearance and shape over time.

An essential step towards a multimodal dial is, therefore, the sensible embodiment of new modalities in the design. The direct incorporation of temperature, as explored by a prior concept, already had to be dismissed due to the project's scope. The idea at the core of the "Multimodal Display Matrix," however, combines successful aspects of prior prototypes with the added dimension of shape.

By drawing inspiration from the shape as well as the single jamming cell of the "Haptic-Visual Display," a centerpiece for the Multimodal Dial was envisioned. The two-layer construction of the "Multimodal Display Matrix" was also reprised. This allowed for the inclusion of deformation in the device's repertoire, in addition to renditions of depth, stiffness, and color. At the same time, technically cumbersome aspects of the "Multimodal Display Matrix" were dropped; neither the ability to display graphical elements nor the ability to cause deformations in multiple locations was needed.

With the concept clearly defined on a theoretical level *(Figure 77)*, specific use-cases were explored.

Initially, cooktops were part of this ideation process *(Figure 78)*. While design opportunities for cooktops exist, many of them do not stem from specific usability challenges. Instead, their main focus lies on increasing convenience and comfort. While this is a noble pursuit, the intent of this thesis was to propose solutions to close "sensory gaps" (see chapter "Introduction," pages 8 - 11). For that reason, the focus was shifted towards the oven *(Figure 79)*.

Going into this topic, the oven and the sensory blind spots it causes was used to exemplify the need for interface innovation. In that sense, proposing this concept as a solution for the oven closes the loop. More importantly, the proposed Multimodal Dial fits many requirements identified by users, as described in the chapter "Validation" (pages 55 - 75). It is for this reason that this concept was chosen to be fully embodied and implemented.

Embodiment choices, technical construction, as well as the full scope of the prototype's capabilities are described in the following chapter.

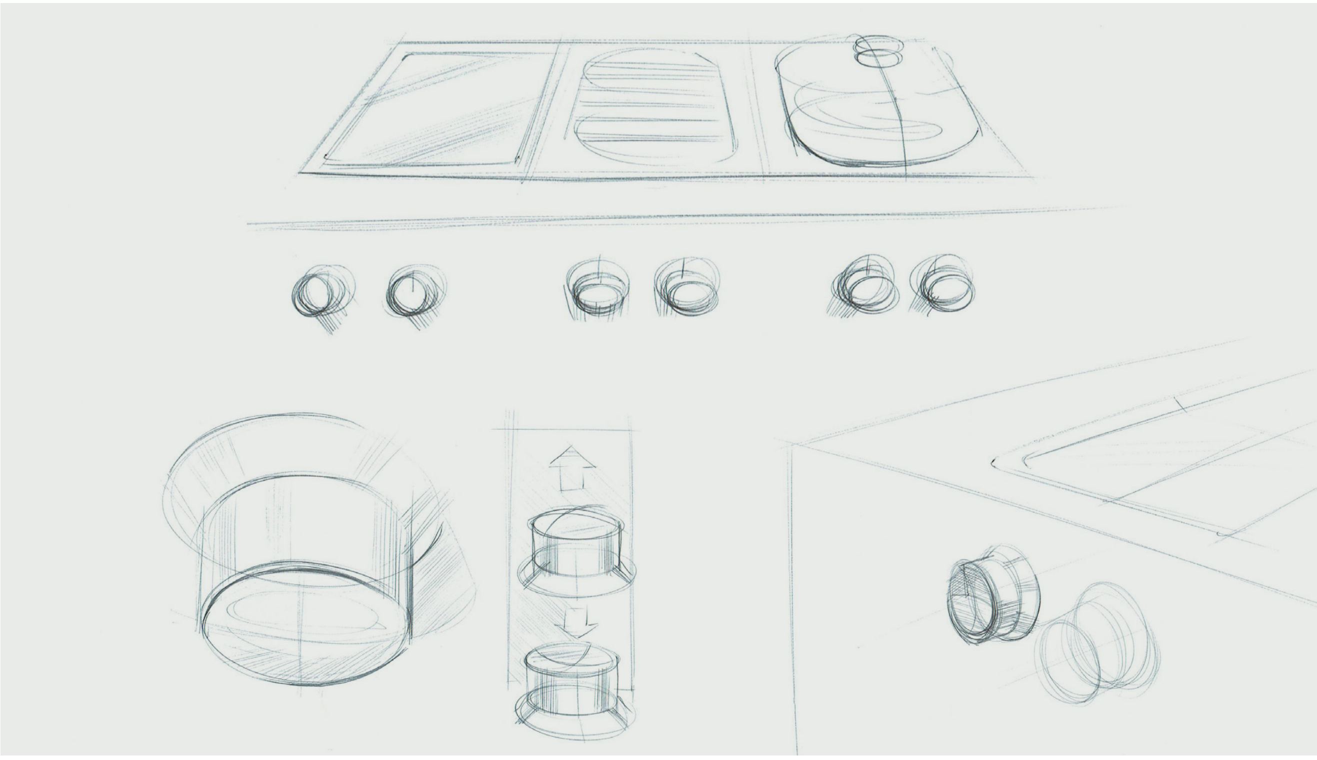


Figure 77: *Sketch envisioning different use-cases for the Multimodal Dial. Similar in appearance to conventional, analog dials, the Multimodal Dial features a centerpiece capable of spatial deformation, stiffness representations, as well as renderings of depth and color.*

Figure 78: *A Multimodal Dial on a Gaggenau cooktop.*

Figure 79: *Two Multimodal Dials on the iconic Gaggenau EB 333 oven. This first rendering served as a basis to start formulating vision for the integration, appearance, and function of the Multimodal Dial as part of an oven interface. The resulting process is described in the following chapter "Implementation".*

IMPLEMENTATION

BUILDING THE DEMONSTRATOR

With the conclusion of the conceptualization phase, the embodiment of the “Multimodal Dial” had to be tackled. As stated in the section “Approach” of the introduction (page 14), embodying the final concept would serve two primary purposes: Firstly, a working demonstrator would help communicate the project’s ambitions. It would enable interested audiences to experience the interface’s vision in a tangible, interactive way. Secondly, it would result in something testable. With a demonstrator, the success and relevance of the assertions made in this theses can be evaluated.

This chapter discusses the necessary steps, considerations, decisions, as well as the construction process of the demonstrator. As the concept vision consists of a physical, a digital, and an interactive aspect, the following pages will discuss each one of them in turn.

Figure 80: *Gaggenau’s iconic EB 333 oven. Its unique role in the company’s product offering made it an interesting platform during the ideation process.*

Figure 81: *Display unit on a range of Gaggenau appliances. This feature is shared by a number of the company’s appliances, including coffee machines, microwaves and steam ovens.*

EMBODIMENT

As previously discussed, the Multimodal Dial was to be realized as part of an oven's interface. Gaggenau's oven line-up includes a wide variety of appliances. It, therefore, had to be determined which oven would best be suited for the Multimodal Dial to show its capabilities.

The EB-333 *(Figure 80)*, Gaggenau's most iconic product, seemed like an obvious first choice. While it played a role during the evolution of the concept, a different appliance was ultimately chosen, as the EB-333 aesthetically sets itself apart from Gaggenau's remaining oven offerings. Instead, the focus was shifted towards the Gaggenau 200 and 400 series ovens. This line-up of ovens includes a variety of conventional ovens, as well as steam ovens and microwave ovens. Along with several other Gaggenau appliances, such as coffee machines, these appliances share a common feature: Their display unit *(Figure 81)*. Incorporating the Multimodal Dial in a redesigned display unit would have a clear advantage: It would make it easier to envision the role a Multimodal Dial might have for other appliances in the future. For a case study such as this, this was seen as a favorable factor.

This meant that first and foremost, the demonstrator would take the shape of a display unit redesign for Gaggenau's oven line-up. To get a better understanding of the dimensions, a mock-up was built using a 3D print of Gaggenau's current display unit and a foam-core oven front. With the help of 3D CAD (computer-aided design) software,

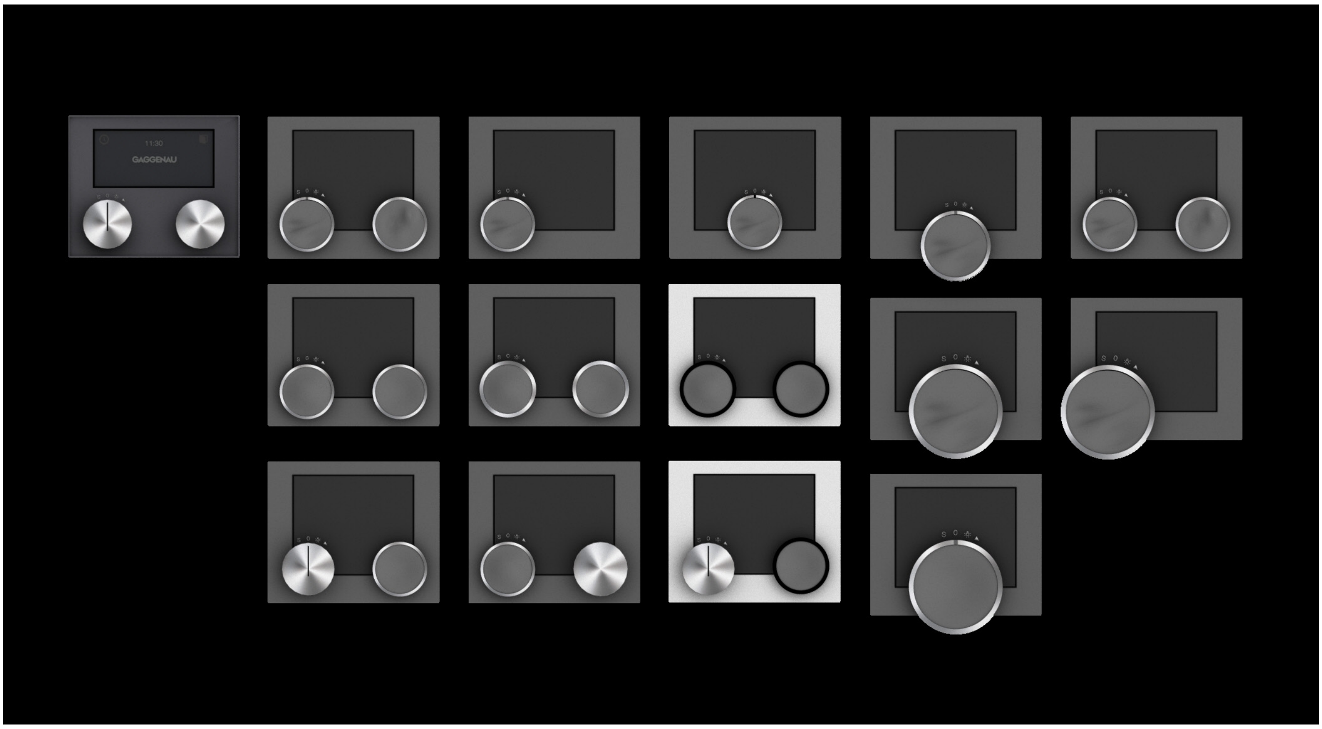


Figure 82: *First iterations of a redesigned display unit stayed close to Gaggenau's original design. Changes include a new screen size, as well as several integration approaches for the Multimodal Dial.*

first design directions were explored. These explorations tried to retain as many aspects of the original display unit as possible. The idea was not to draw too much attention to the redesigned unit itself, but rather allow the focus to be on the Multimodal Dial. One notable change was examined nevertheless: A larger display that would make better use of the available space and allow the dials to overlap the screen. That way, graphical elements could be used as part of the cross-modal experience, as suggested in the section on the "Multimodal Display Matrix" in the previous chapter (pages 84 - 88). It would also allow for seamless visual use-cues across both the Multimodal Dial and the display, merging both into a single interface.

These first iterations *(Figure 82)* also explored the possibility of reducing the number of dials from two on the original unit to one in the redesign. Before doing so, however, a better understanding of Gaggenau's existing interaction philosophy was needed. To that end, a rough flow diagram *(Appendix VI)* was created using manuals from the company's website as well as a prototype display unit kindly provided by Gaggenau. As can be seen in *Figure 83*, Gaggenau's current interfaces rely on three sources of input. Two input sources are the existing dials, the last one being touch-enabled areas on the screen. Using the flow diagram, the relevance of each element was ascertained: The left dial turns the oven on and serves as the selector for the cooking mode. The temperature, timer, as well as secondary functions, are set using the right dial. The touch zones are used for navigation and to control individual functions.

As the left dial mainly serves as a power switch and only plays a role in the interaction intermittently, it appeared sensible to only include a single dial in the redesign. This would also avoid either having to divide the interaction across two Multimodal Dials or creating confusion by installing two different types of dials.

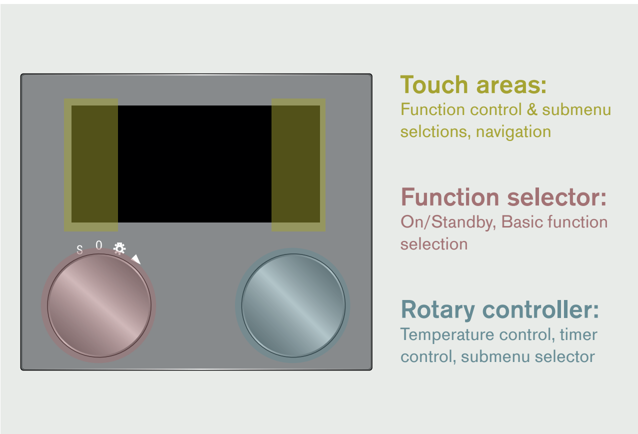


Figure 83: *The interaction concept of Gaggenau's current display unit. It encompasses three touch-points, each one with a distinct role.*

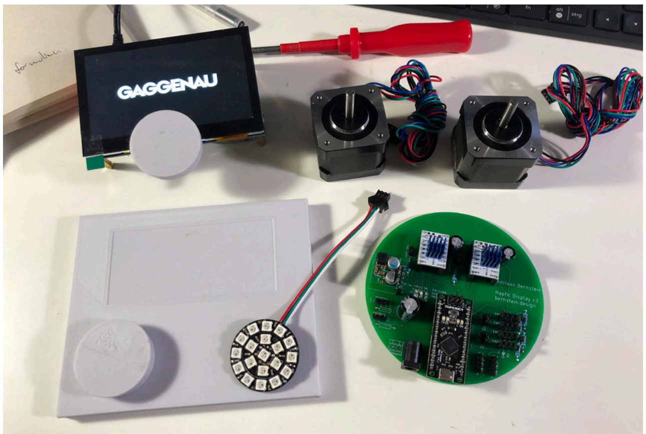


Figure 84: *A partial assembly of an early display unit design. Aside from the working, programmable screen, components needed for its further assembly are shown.*

With the single dial approach chosen, a first, rudimentary assembly was built *(Figure 84)* and subsequently assessed with the company. This assessment led to a move away from the minimal intervention approach and towards a more radical redesign.

Making the display unit more contemporary in appearance required a larger display area. By taking advantage of modern OLED technology, a new design vision was formulated. OLED displays have the advantage of being able to control the brightness of each pixel individually. This means that, unlike other display technologies, this technology can brightly display an element in one location, while the rest of the display can remain dark. Furthermore, OLED panels can be built in a wide variety of shapes. These benefits enable the design vision ultimately proposed: An elongated display unit with a single Multimodal Dial at the center of a display covering the entire front of the unit *(Figure 85)*. The OLED display panel would create the appearance a seamless, black glass front with the ability to blend static, unchanging interface elements with dynamic ones.

The illustration in *Figure 85* was created to showcase a broader vision for the Multimodal Dial's application. To build a working demonstrator, significant deviations from the proposed design had to be made in order to accommodate limitations imposed by available components. In keeping close to the envisioned design, different component arrangements were explored.

Figure 85: *The embodiment vision for a display unit designed around the Multimodal Dial. This illustration was created to suggest a direction for the technology's future exploration, irrespective of the limitations of this thesis.*

Figure 86: *An overview of various shape explorations leading to the final redesign of the display unit. The overview shows a selection of 3D printed mock-ups. These explorations focused on the spatial distribution of components, as well different levels of visual and physical distinctions between them.*

Sketches and mock-ups were used to investigate a number of shapes for the display unit body *(Figure 86)*. To maintain the central position of the display, various ways of integrating the dial were explored. Some constructions attempted to place the dial in a recessed base, making the dial appear flush with the screen. Other attempts had the dial overlapping the display. Both were attempts at maintaining the close integration of display and Multimodal Dial, as suggested earlier in the chapter.

Finally, the decision was made to turn the display by 90° and to mount the Multimodal Dial underneath it. The anticipated size of the dial itself led to this decision: Testing various diameters *(Figure 87)* indicated that a diameter between 50 and 60 mm was identified by most to be the most comfortable to use. This would cause right-handed users to cover up a large part of the display during use if the dial was mounted on the left-hand side, and vice-versa. Additionally, this design would not break with the symmetry of existing display units and would greatly simplify the mechanical assembly, as described in the following section.

Figure 87: *Samples of diameters for the body of the multimodal dial. After testing simple cylinders with diameters between 40 and 70 mm, a narrower scope was selected. This narrowed scope was tested using simple, 3D printed dials incorporated into different display unit mock-ups, as shown in Figure 86.*

TECHNOLOGY

With most technological challenges already resolved during the development of earlier prototypes, two significant challenges remained.

The base assembly of the Multimodal Dial, as previously described, revolves around an air pressure controlled silicone actuator. To avoid twisting the hydraulic tubing connected to the actuator when turning the dial, a mechanical system had to be devised around the silicone actuator. The assembly's purpose was to allow for the outer shell of the actuator to be twisted, while the inner construction remained still.

Inspired by the inner workings of a ball bearing, several mechanical assemblies were prototyped and tested *(Figure 88)*. The final assembly consisted of three parts: The dial's outer shell, which featured a groove at its base large enough to accommodate 3.25 mm bearing balls. Additionally, a base and a retainer plate were developed to sit at the center of the dial. The base would allow for the dial to be mounted to the display unit later on, while the retainer plate was intended to enable the mounting of the LED matrix and the particle jamming cell. The edge profiles of both, the dial's base, as well as the retainer plate, would complete the groove on the dial's shell once assembled. This would create a channel for the bearing balls to run in, facilitating a smoothly twisting outer dial shell, with a stationary base.

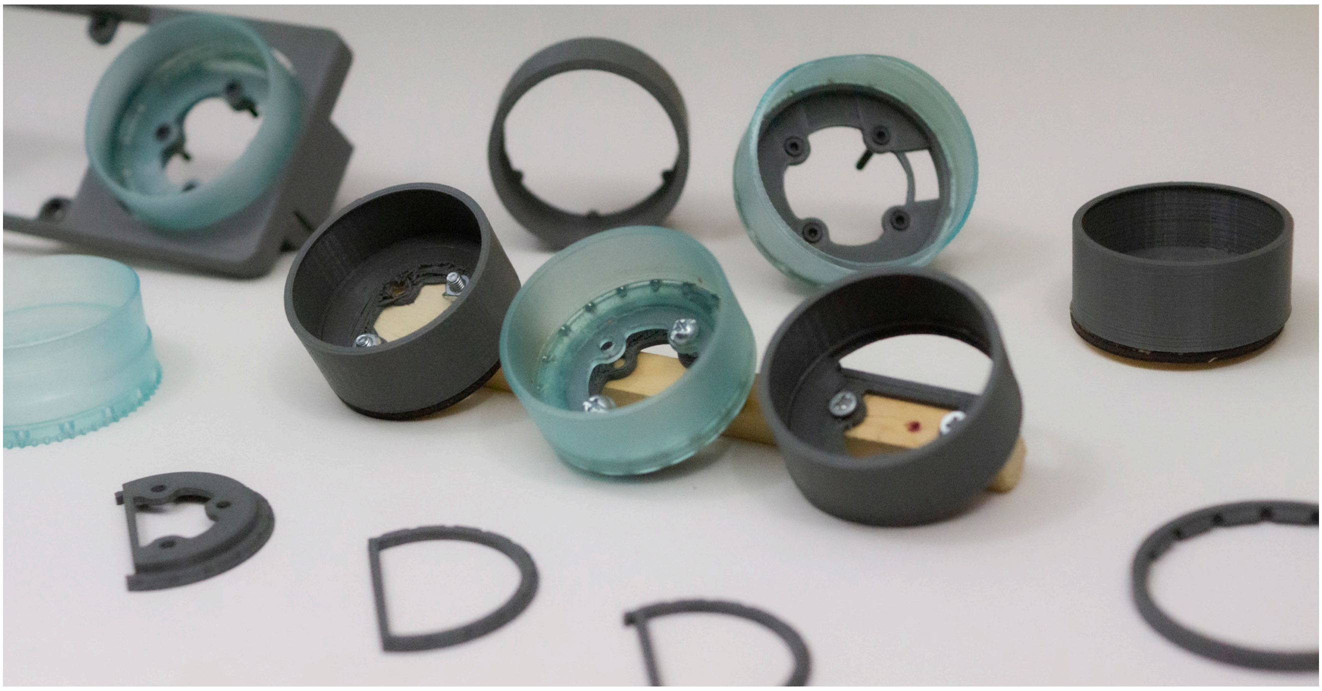


Figure 88: *Iterations of the ball bearing mechanism allowing the shell of the dial to spin freely. Various assemblies were tested, including some using partial bases to allow for the dial to be mounted overlapping a display. The assembly seen in the middle was finally chosen. It allowed for smooth and noiseless rotation by keeping the bearing balls at a fixed distance from one another.*

The second critical challenge to resolve had to do with the particle jamming actuator itself. Unlike the actuator elaborated previously (see “Haptic-Visual Display”), this new actuator should also include the ability to create deformations actively. For this purpose, the two-layer construction described by the “Multimodal Display Matrix” was adapted. This meant that a rigid, translucent material had to create a single, air-tight assembly with the silicone particle jamming cell. As silicone is very chemically inert, there are not many options to create a chemical bond using glue. While silicone glues are available, their reliability varies and strongly depends on the silicone itself, as well as the material it is to be attached to. For this reason, the decision was made to create a mechanical bond.

After multiple prototypes and tests *(Figure 89)*, an assembly was achieved that succeeded at creating an air-tight, two-chamber design. To make this possible, the manufacturing process had to be split into three steps.

In a first step, SLA (Stereolithography) technology was used to 3D print a solid, translucent shell. This technology uses UV curable resins to create parts, making it possible to fuse separate parts at a later point. That way, the shell, and its base could be combined into a single part after casting silicone into it. Furthermore, SLA allows for the print of intricate details. This ability was used to create small, three-dimensional features, such as ridges and channels, on the inner wall of the shell. These

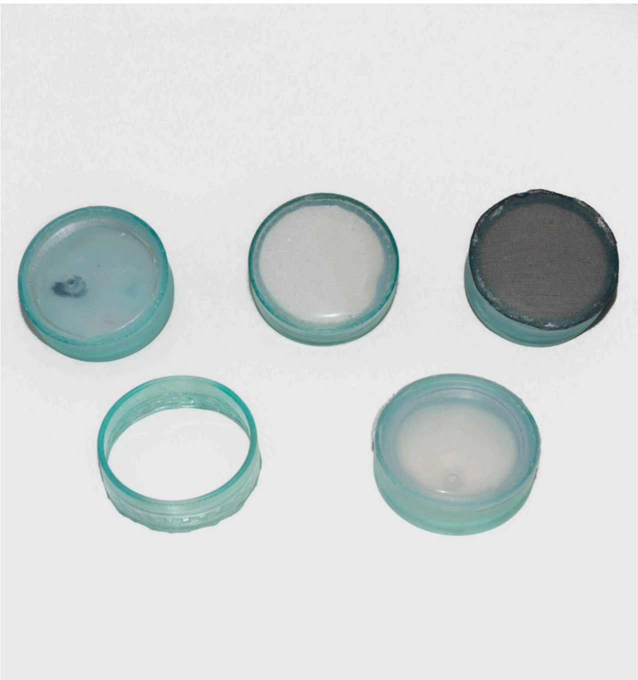


Figure 89: *Different versions of the particle jamming actuator at the center of the Multimodal Dial. Several iterations were required to achieve a reliable air-tight seal.*

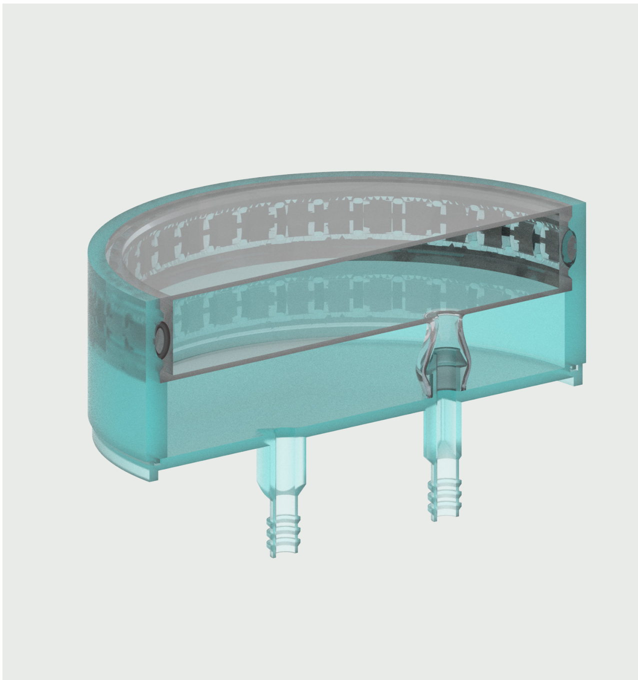


Figure 90: *Section view of the actuator. The upper silicone cell is used for particle jamming; the rigid lower compartment causes deformations depending on the pressure being applied.*

features would be engulfed by silicone, creating a mechanical bond. After casting the silicone in a second step, the shell's base was connected to the newly created silicone compartment. In a third step, the shell and its base were fused into a single part, creating an air-tight, solid compartment below the silicone chamber. Finally, the actuator was flipped upside-down, to cast the top layer of silicone, before completing the assembly by filling the jamming cell with a substrate consisting of small glass beads (see page 50). *Figure 90* provides a cross-sectional view of the Multimodal Dial's central actuator.

With the resolution of these last challenges, all parts had to be integrated to form the final assembly. To run the actual interface, a Raspberry Pi Single Board Computer (SBC) running the Linux operating system was attached to the back of the OLED display. Using a fully-featured operating system on the prototype allowed for the easy integration of further components via USB. Furthermore, the interface could be programmed using wide-spread web technologies, such as JavaScript, HTML, and CSS.

To coordinate the capabilities of the Multimodal Dial itself, an Arduino-compatible SBC was developed (shown in *Figure 84*). As was the case for the electronics for the "Embedded Temperature Display" (page 80), a fully-integrated circuit board was created using the EAGLE software. *Figure 91* shows the resulting board lay-out, while the full schematics can be found in *Appendix VII*. This PCB would interface with all necessary sensors and actuators on the one hand, and communicate with the interface running on the Raspberry Pi via USB.

With the help of a Force-Sensing Resistor (FSR) and a rotary encoder, the Multimodal Dial was enabled to sense the force applied to it, as well as track the dial's rotation. With the FSR mounted directly below the dial, the pressure reading could be used to determine the depth of the user's finger in the actuator. That way, color and stiffness responses could be controlled accordingly, representing information deeper within a three-dimensional volume a user would be interacting with. The rotary encoder engaged with the Multimodal Dial via a gear attached to its shaft. An encoder that locks twelve times per revolution was chosen. Thanks to the 12:60 gear ratio, a full revolution of the dial would be equivalent to 60 steps. This meant that one revolution of the dial could be associated with a full hour on a timer, or 5°C temperature increases per step, covering Gaggenau's entire 0-300°C temperature range in a single revolution.

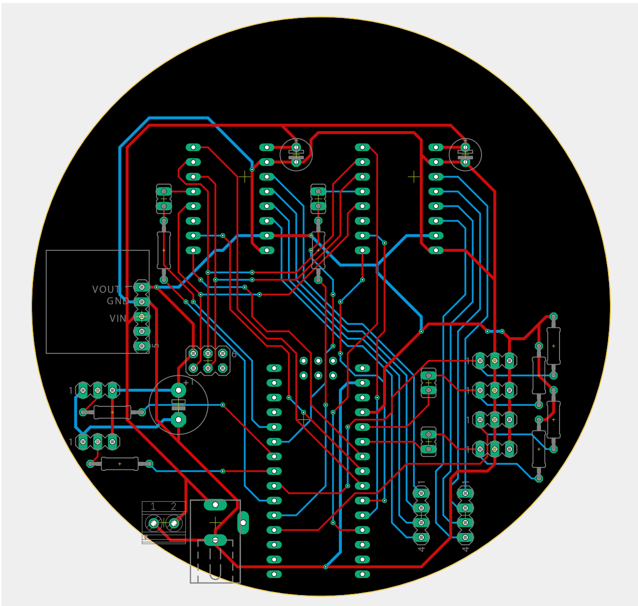


Figure 91: *PCB layout for the Multimodal Dial's control electronics. This board controls all necessary actuators and sensors and interfaces with a Raspberry Pi running the interface via USB.*

To integrate the assembly as much as possible, everything was consolidated into two units. The display unit *(Figure 92)* would consist of the prototype the user would interact with: The Multimodal Dial, the screen, but also the Raspberry Pi controlling the interface. A second unit, to be placed out of the user's sight, would consolidate all the electronics necessary to control the sensors, LED lights, as well as the motors of the hydraulic pumps *(Figure 93)*. This electronics box would also double as the mechanical frame for an improved syringe pump. Compared to the one previously used in this project (*Figure 41*, page 49), the new pump was more compact, stronger, and silent. By eliminating noise during the interaction, potential distractions that may falsify the experience could be avoided.

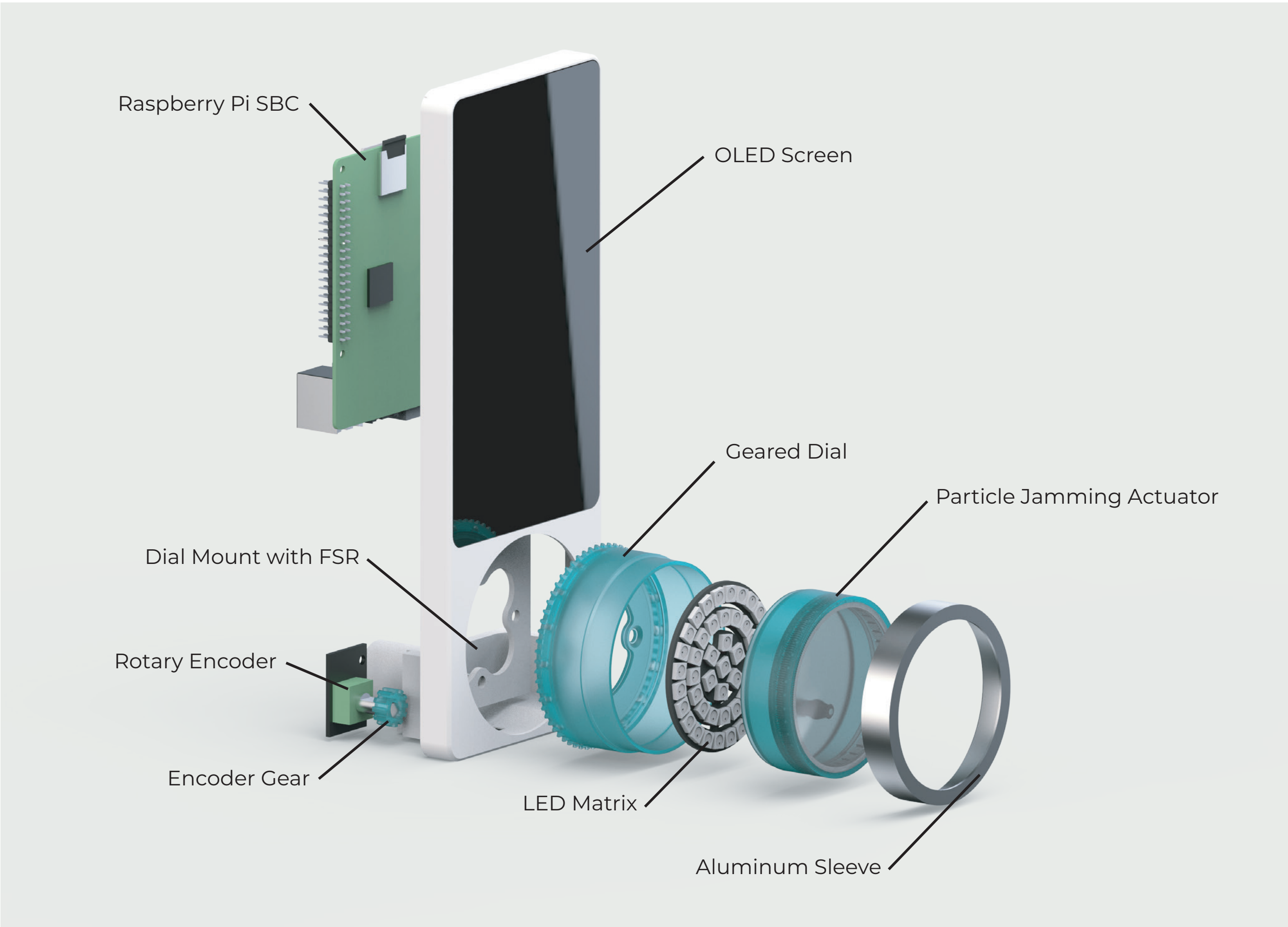


Figure 92: *Exploding view of the display unit and Multimodal Dial. The OLED screen is embedded in the unit's frame; a Raspberry Pi SBC mounted to its back. A force-sensing resistor is embedded in the dial's mounting plate. When mounted, the geared dial engages with the gear on the rotary encoder's shaft. That way, rotation, as well as pressure applied to the actuator, can be measured.*

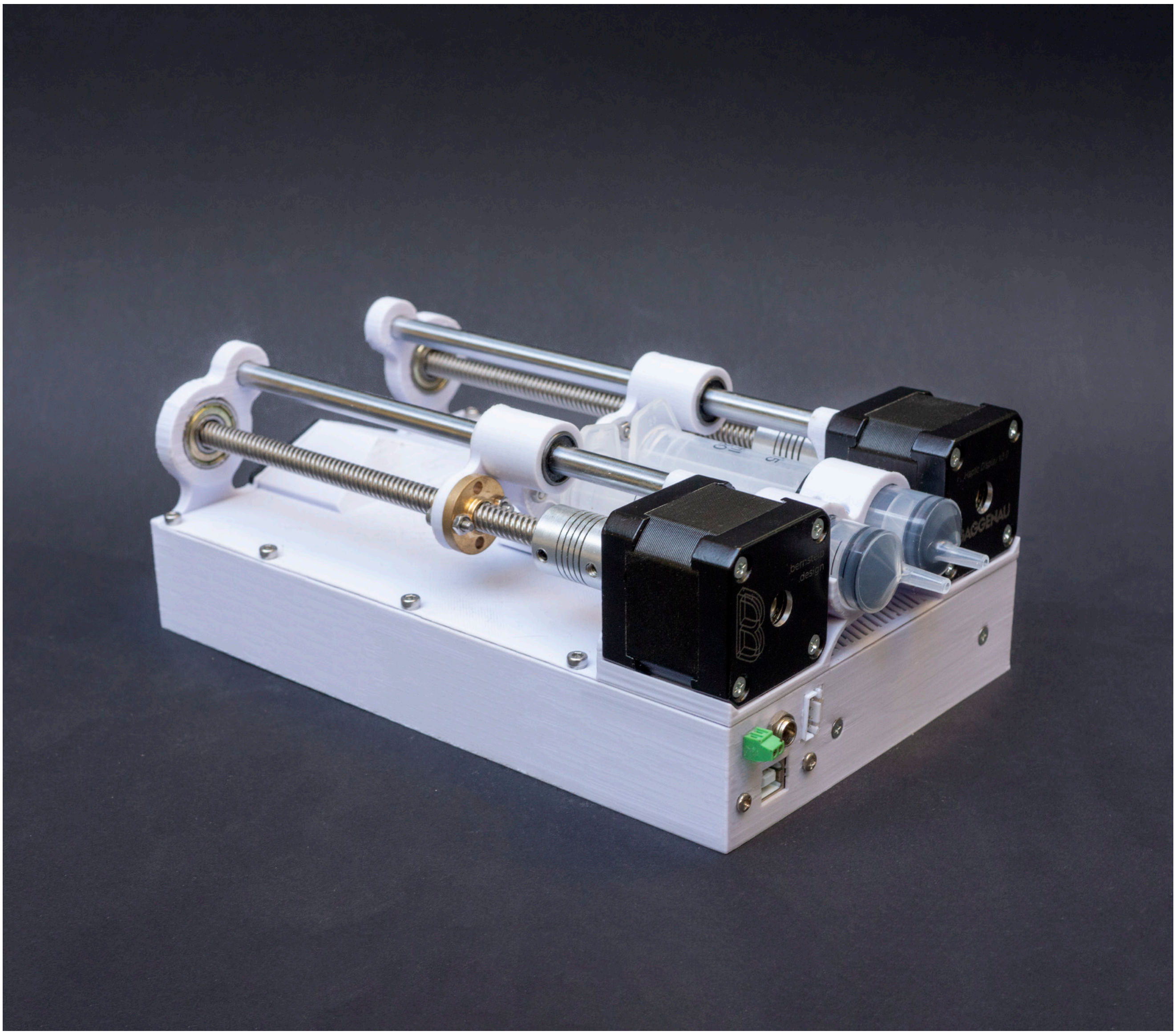


Figure 93: *Syringe pump and electronics box assembly. Aside from the two syringe pumps actuating both chambers of the Multimodal Dial, the assembly also features a power- and data connector for the display unit, as well as a connector for a pressure release valve. A USB serial connection is used to exchange data with the interface.*

INTERFACE

With the embodiment, as well as the mechanical and technological assembly completed, a simple interface providing some context for the Multimodal Dial had to be developed.

With the help of the flow diagram found in *Appendix VI*, a selection of core features was made. These features would be adapted to the new interface, integrating the Multimodal Dial into the overall interaction. The chosen features included essential tasks, such as choosing a heating program, regulating the temperature, as well as basic timing functions *(Figure 94)*.

A list of recommendations for the interface to adhere to was compiled to ensure the experience stayed as close as possible to the stated project goal. Most recommendations were intended to keep the interface simple and to define the role of the Multimodal Dial clearly:

- **Use visual elements statically, allowing users to form habits**
- **Associate dynamically evolving information with the Multimodal Dial**
- **Avoid navigation elements and menu structures as much as possible**
- **Take advantage of the OLED screen to create seemingly physical function keys in dedicated places**
- **Create a clear, consistent distinction between screen-only interactions and multimodal interactions**
- **Relate all relevant information back to the same touch-point**
- **Try to stay close to Gaggenau's existing visual language**

Based on these recommendations, several quick iterations of the visual interface were created *(Appendix VIII)*. Using the Adobe XD software, these iterations were translated into partially functional click-dummies *(Figure 95)* and tested with available volunteers. As the interfaces were designed to incorporate the Multimodal Dial, some of the use-cues were missing from these click prototypes and could not be tested. Despite this, these tests allowed to make informed choices on necessary improvements and alterations.

The interface ultimately incorporated into the demonstrator had several improvements compared to prior designs. It achieved the most apparent distinctions between different use-cases, tying them together into coherent, understandable functional units. Additionally, it relied on a comparatively low number of interface elements and avoided navigation elements most effectively.

The distinction between screen-only interactions and multimodal interactions was created via the use of color. Simple, unchanging tasks made use of a color scheme closely related to the existing Gaggenau oven interfaces. Examples of such tasks include turning the oven on or off, selecting function modes, or turning the light on or off.
In these cases, the interface relies on close-to-monochrome colors: Black for the background, white for text and symbols, as well as various shades of gray for subdued text or symbolic elements and buttons. In rare cases, subtle accent colors further emphasize essential elements.

This quasi-monochrome color scheme changes as soon as multimodality comes into play: To associate the dial as an input source to an interaction, it takes on a color associated with a functional domain: Red for temperature settings,

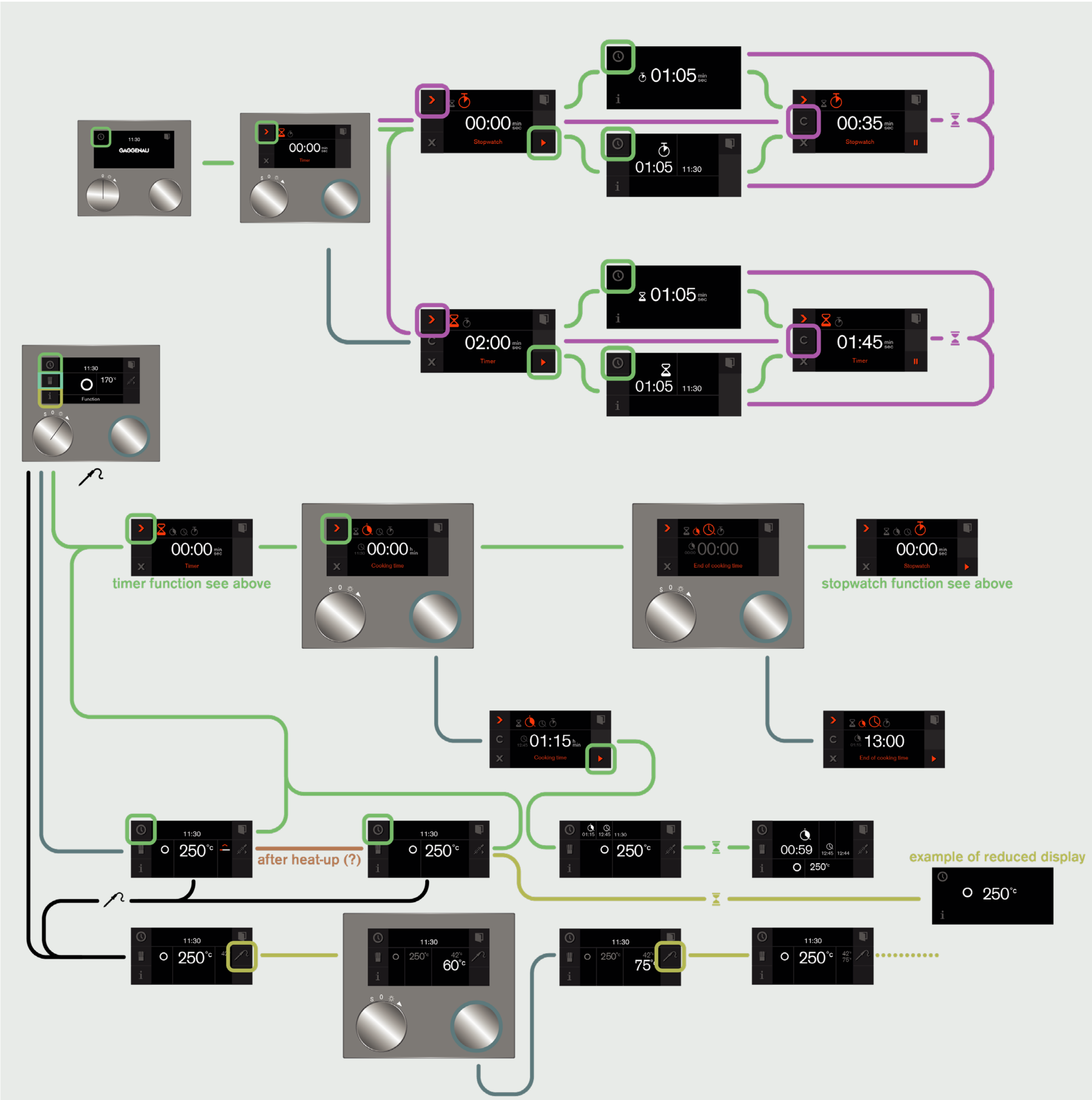


Figure 94: *An overview of basic and advanced timing functions as well as heating functions. This diagram shown here is an excerpt from the full flow diagram created to gain an overview of Gaggenau's current usage philosophy. The full diagram can be found in Appendix VI.*

blue for time settings. At the same time, a radial scale appears concentrically to the dial *(Figure 96)*. Elements of the scale reflect the function color, to further associate the scale to the dial. The position of the scale corresponds to the motion of the dial, making both elements appear as a single part.

The particle jamming actuator is used to convey more complex information, such as texture, stiffness, and temperature distribution throughout the food. This information is increasingly becoming available to users, as technologies like multi-point temperature probes, humidity- and weight sensors, as well as molecular sensors, are increasingly used in the industry. Instead of cluttering the graphical interface, the multimodal dial can directly and tangibly externalize this information. That way, these technological advances are used to illuminate sensory blind-spots, using the user's sensory expertise. To create an initial touch-point for these types of interactions, the dial can respond to the user's presence. Depending on the state of the oven's content, the dial can expand towards the user's extended hand or collapse away from it. Pressing a finger or the hand into the actuator triggers other kinds of responses: The texture, elasticity, and stiffness of food in the oven are represented by different actuation patterns of the

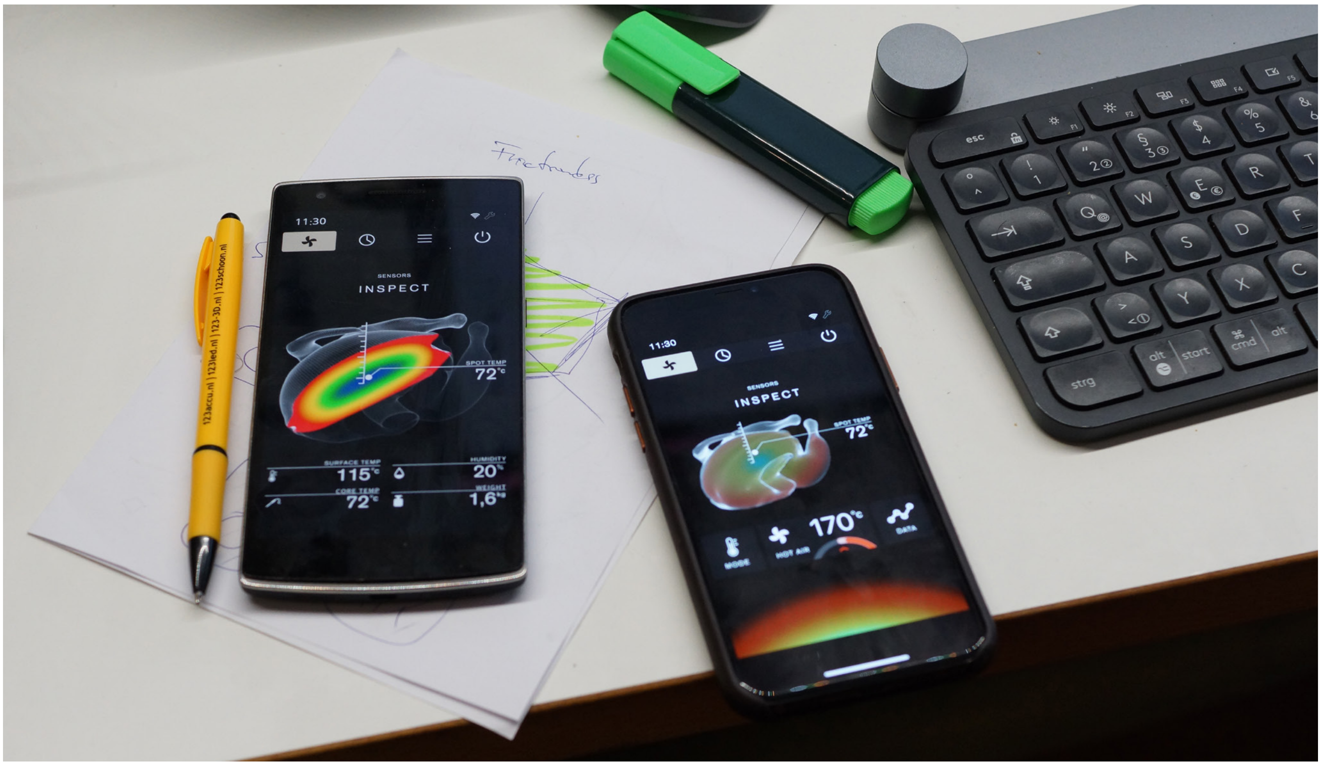


Figure 95: *Two versions of a click-dummy of the demonstrator interface running on phones. The phones were used to evaluate the interface to scale, as well as assess its aesthetic qualities and its performance.*

particle jamming cell. This can create sensations of breaking through the crust of baked goods, or of probing the doneness of meat at its core. Simultaneously, colors in the actuator are used to create an association between the depth the user is probing, and the temperature conditions there *(Figure 97)*.

Figure 96: *Illustrations of the demonstrator's interface showing temperature and time setting. A radial scale appears concentrically to the dial whenever the dial can be used to alter settings. The accent colors are meant to provide guidance and context to the user.*

Most of the functions described in this chapter have been functionally integrated into the demonstrator. To enable all functions, the further integration of a proximity sensor would have been required. As the lack of this sensor only affects a low number of described features, the sensor was omitted in the demonstrator. In those cases, workarounds were used to test the described behavior.

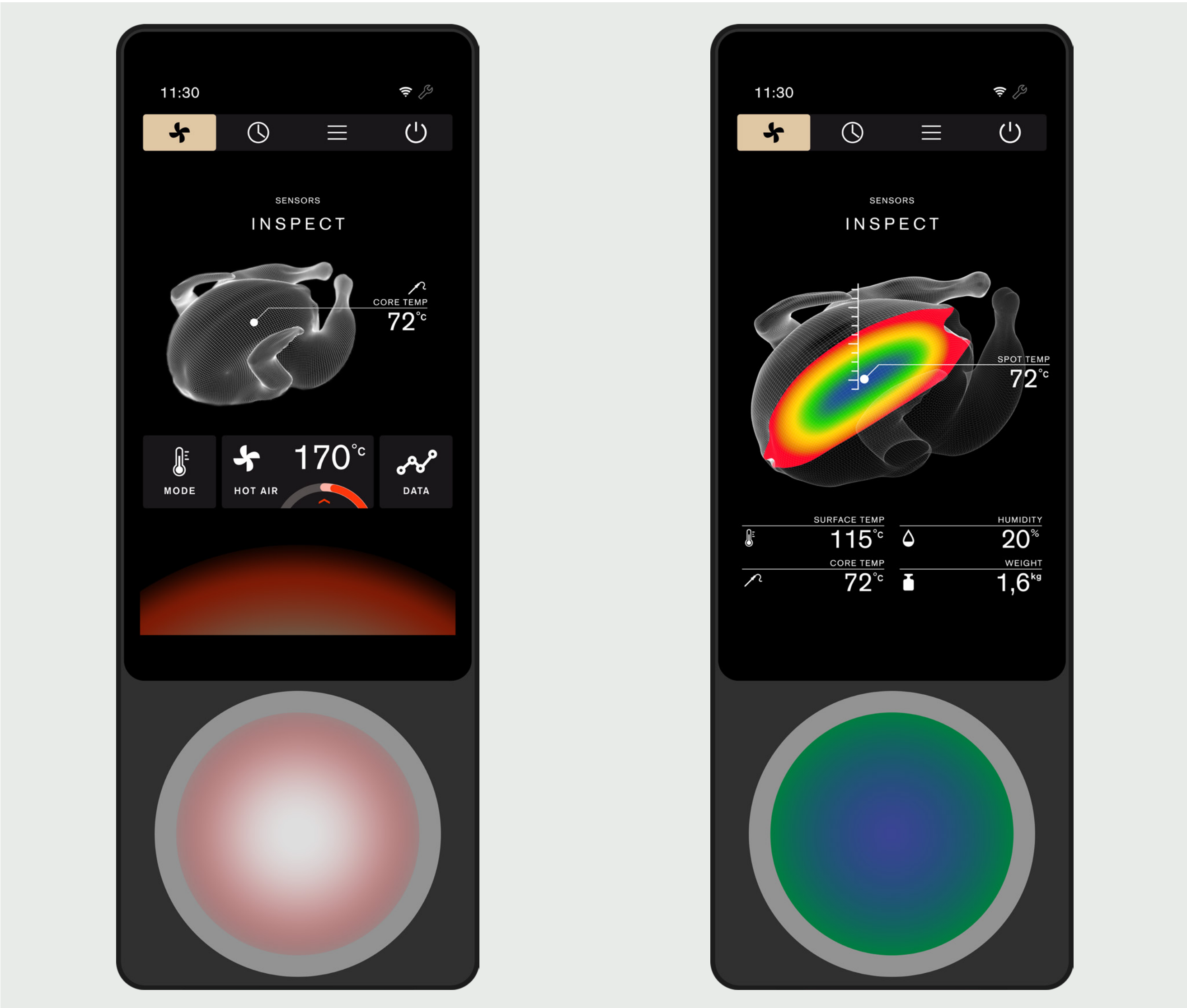


Figure 97: *Illustrations of the demonstrator during the exploration of temperature and doneness. The dial's appearance and behavior subtly indicate that additional data is available to the user. If the user chooses to interact with the haptic interface, information on the screen is correlated to the dial's color and shape. This helps the user contextualize the sensations the dial is producing.*

EVALUATION

ASSESSING THE OUTCOME

The purpose of this project was to make a case for multimodality in interactions with technology. New modalities were to provide novel opportunities to create strong analogies to provide context and reassurance to users. This thesis was primarily intended as a hands-on exploration of possibilities, culminating in an application example. For that reason, the primary focus was the development of a vision showing the potential of multimodality, not its stringent evaluation. With the completion of the demonstrator, it nevertheless becomes relevant to gain an understanding of its performance. Does it benefit from the purported benefits of multimodality? Does it fulfill the goals set at the beginning of this project, most notably to create experiences analogous to physical interactions wherever these are not currently available?

To get a sense for the interaction created by the proposed design, a simple user test was set up. Individuals with no prior knowledge of the project, as well as of a more affluent, luxury-aware background were chosen as participants. This would allow the user test to produce results that would better reflect the experience for Gaggenau's clientele.

***Figure 98:** The Multimodal Dial demonstrator mounted to an oven mock-up.*

Four participants in their late 20s and mid-30s were willing to participate. Both were couples of young professionals. The test itself was conducted using a mock-up constructed from translucent acrylic sheets closely emulating the appearance of a Gaggenau oven. A display was mounted behind the acrylic front, to allow for the simulation of different oven usage scenarios. The mock-up allowed for the integration of the Multimodal Dial demonstrator *(Figure 98)*. As going through an actual cooking process would take several hours, a scenario was developed in advance. This scenario would confront participants with a decision. To make an informed choice, participants would have to be able to navigate the provided interface successfully. Interactions resulting from the test were documented for later evaluation. To conclude the analysis, the participants were asked to recall their experiences and were given a choice to answer a questionnaire *(Figure 99)*.

Due to the low number of participants, any results have to be considered with caution. Nevertheless, the results were encouraging. The feed-forward worked throughout the interaction, triggering users to explore existing touch-points. Aside from some ambiguity around different color-mappings, users were able to navigate most situations they encountered. Participants later also reported that in some cases, associations were not immediately clear. Despite not initially knowing what to expect, they felt the interface provided "a more natural and engaging way of interacting with a machine" and "triggered their curiosity." They furthermore reported that "it might take a while to fully make use of the interface's potential," but appeared to enjoy the experience of exploring it: The participants appreciated the "aesthetics and sensual feedback" the interface provided, as well as its "organic characteristics." Perhaps, the most crucial response was the mention of the interface's capacity to create "organic characteristics" associated with "archaic elements" of cooking, a quality that was missed "in conventional kitchen appliances." The complete answers to the administered questionnaire can be found in *Appendix IX*.

With the conclusion of this user test, it may be interesting to note that issues uncovered during earlier activities did no longer negatively impact the user experiences. Many of these issues were due to the aesthetic qualities of previous prototypes. Notable examples include a fixation on the surface quality of silicone, as well as the appearance of individual technology components. While new surface textures and finishes for silicone components were prototyped and provided to test participants *(Figure 100)*, the unaltered surface finish was perceived to be the most pleasing. This is likely due to the clarity of product- and interaction vision in this final demonstrator. Its appearance and functionality are sufficiently far developed not to create unnecessary distractions.

Overall, the prototype itself, as well as first experiences made with its use, produced encouraging results. Users were able to navigate a challenging scenario and found the experience to be pleasant and appealing to their sense of curiosity. It is for future explorations and research to determine the next steps, as well as where to take the process started by this project next.

Imagine you and your partner are baking a bread.
Your partner left you in charge of taking the bread out once it's ready.

You know the oven is set to 170°C and the bread has been in the oven about 30 minutes ago.

You come into the kitchen, you see the oven and its interface. What are your first thoughts?

Did the interface steer you towards the right touch point (the dial)?

Was the meaning of the interface clear to you? Describe your experiences.

What benefits or drawbacks do you see compared to conventional interfaces?

How satisfied were you with the experience of discovering the meaning of the interface?

Would you want to use it in your own kitchen?

Any further ideas or suggestions?

Figure 99: *The scenario presented to participants, as well as the questions featured in the questionnaire.*

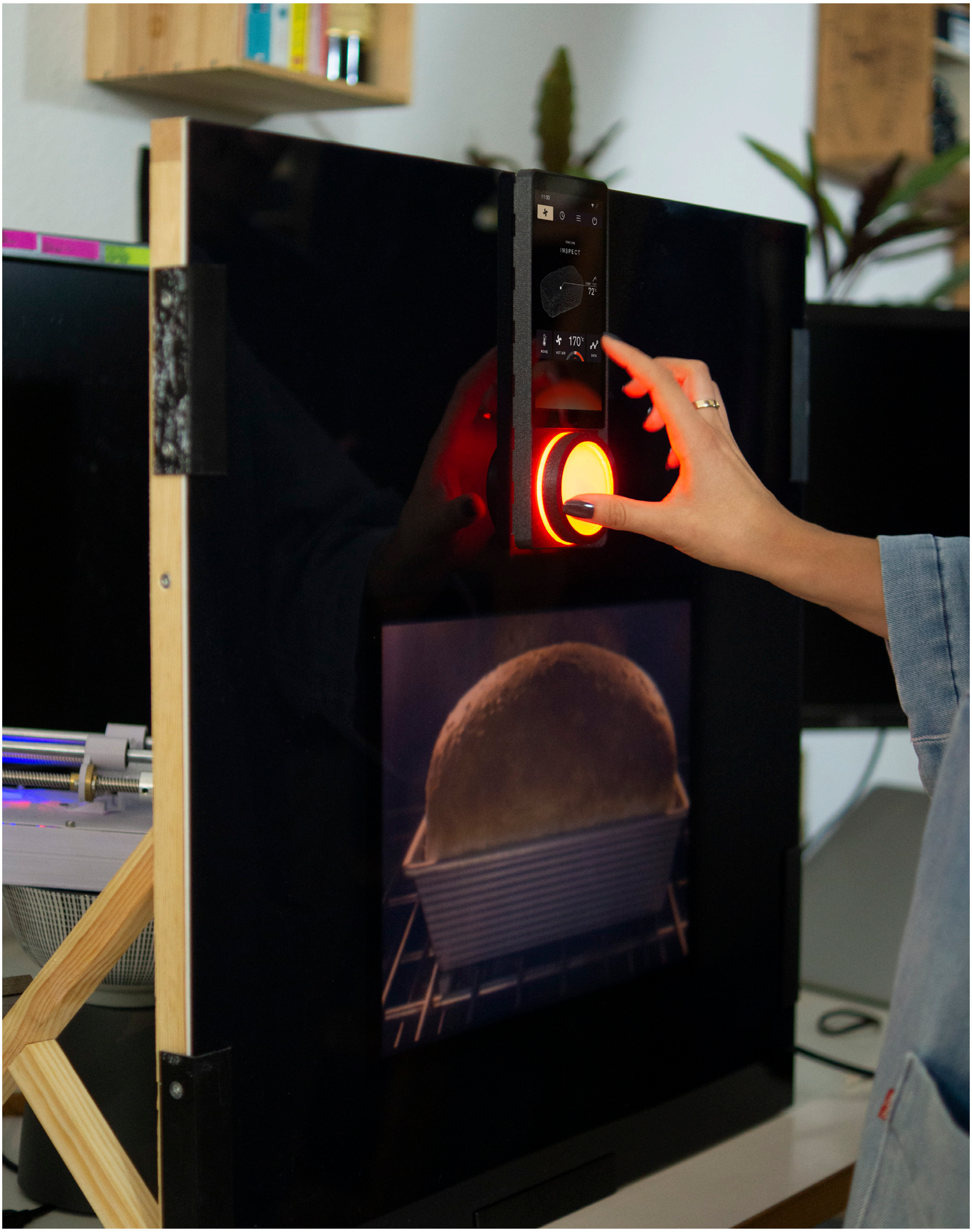

INSPECT
170°

Figure 100: *The working demonstrator mounted to an oven mock-up during a user test. The mock-up consists of two acrylic sheets mounted to a weighed wooden frame. A screen embedded in the lower sheet of acrylic is used to simulate different situations within a presented scenario.*

RECOMMENDATIONS

Due to the project's framing as a case study, its broader potential has yet to be explored. This is true both concerning its application in the kitchen, as well as for its use in other fields.

For Gaggenau, it may be interesting also to investigate more advanced functions. Some of them might not fit the goal of this graduation, which is the strengthening of archaic, physical qualities. Outside this immediate objective, however, many more exciting use-cases can be explored. An example of this would be the use of the Multimodal Dial as part of an interactive learning system. Instead of theory-heavy texts on a screen, it would make food knowledge tangible. Users may enjoy learning about the meaning of various food properties, such as texture or stiffness, by touching the dial to experience them.

Other possible explorations revolve around the placement of the Multimodal Dial. Instead of being fixed to a display unit, it might be possible to take the dial off the oven. This would allow users to take it with them to probe their food from their desk or the living room. The technology required to enable this is currently under development. Solenoid pumps that are compact and silent already exist. It is conceivable to fit them into the body of the dial, along with a battery. While the volume of air they move per second does not yet allow for fast transitions in the actuator, solenoid pump technology is continually improving.

Aside from the Multimodal Dial, many earlier prototypes created promising interactions. It may be worth further exploring their potential as well. This holds true especially for the temperature interface, but also for interactions enabled by the haptic paddle. Ideas explored earlier in this thesis deserve additional attention. These include temperature renderings as a means of further immersion in the cooking process. Also of interest are elements that are able to move in space, offer varying levels of resistance, or alter their size. These may be useful for creating potent analogies for a wide range of situations, including light switches, food sensors, or home automation. Many more potent analogies remain to be uncovered.

Notwithstanding these recommendations, a more stringent and systematic evaluation of the results presented by this thesis is needed. Learning how usage and acceptance evolve over time is are questions that urgently need to be asked. Additionally, a more extensive study is required to observe subjects representative of Gaggenau's clientele in a fully-featured kitchen context.

CONCLUSIONS

This project set out to find an answer to one overarching question: How can people be enabled to benefit from technological advances without needing to compromise on simplicity or autonomy? This question was approached by trying to resolve this dilemma for innovations in the kitchen sector. Moments of frustrations were identified that were caused by the role technology played within the context. The assertion was made that technology often gets in the way of sensory impressions and human intuition. The proposed solution, therefore, tried to apply multimodal interface design to these situations. By doing so, these sensory gaps were to be closed to provide reassurance to users.

These goals, albeit ambitious for a master's graduation, were widely met. The range of investigative activities answered most of the relevant questions sufficiently. The Multimodal Dial was successful in using new modalities to engage users in novel ways, creating analogies for challenging domains of information. This was accomplished by building an interface capable of externalizing processes that were taking place out of the reach of the individual controlling it. The interface enabled users to interact with food in the oven much in the same way they would have done if they held the food in their hand. Not only did this prove to be a satisfying experience, but it was also perceived as being natural and enjoyable.

To phrase this in the terms used during the introduction to the project: The interfaces succeeded in bridging sensory gaps and strengthening user engagement. It was shown that technology can also be used to help enhance an interface's inherent intuitiveness, instead of cluttering it. The reactions and responses of users involved in the process confirmed that multimodality has the potential to play an essential role in the future of technology and the way it is made accessible.

This thesis took early steps in the right direction. Overwhelmingly positive responses to the project were shared by most people coming into contact with it, either as participants or otherwise. This included the company partner accompanying the project, but also researchers whose work played a role in developing the technology needed for the demonstrator. Hopefully, these results will inspire continued interest in multimodality as a powerful tool to create user engagement. As a study that sits between disciplines (interaction- and industrial design, electrical- and mechanical engineering, as well as humanities), it was hopefully able to provide new perspectives. During a time where the interest in physicality seems to be resurfacing in research and industry, this thesis can hopefully contribute.

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Accessed 09.09.2019
- Induction stove interface: *https://www.gaggenau.com/*

Figure 80 (Page 94)
Accessed 30.05.2019
- EB 333 oven: *https://www.gaggenau.com/press/*

Figure 81 (Page 94)
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- Gaggenau products: *https://www.gaggenau.com/*