

Designed for Delight

EXPLORING SURPRISING
APPLICATIONS OF
3D PRINTING IN
LIGHTING DESIGN



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Te Wahanga Waihanga-Hoahoa

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Sebastien Voerman
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ABSTRACT

How can the unique qualities that 3D printing offers generate surprise through visual-tactile incongruities in lighting design?

Designs that surprise us challenge our expectations and impact the experience and perception of our surroundings. Surprise is a useful tool for designers and can elevate a product from mundane to memorable; drawing attention and inviting engagement. Existing strategies have explored surprise in product design through the exploration of sensory incongruities, most notably visual-tactile incongruities (Ludden, 2008; Ludden, Schifferstein, & Hekkert, 2008). 3D printing is an evolving technology that has capabilities traditional manufacturing is unable to achieve, including: building internal and complex structures, building with multiple materials simultaneously, and creating material gradients. Lighting design has been explored with 3D printing, attaining previously unachievable patterns, moving structures and light permeation control. Lighting design has also investigated surprise and sensory incongruities. However, research has not yet been done to investigate how visually-tactually incongruous 3D printing can offer new strategies for eliciting surprise in lighting design.

This research addresses this identified gap by assessing the applicability of Ludden's (2008) strategies to 3D printing. This was done through the design of a series of experimental objects and lights that sought to surprise through the use of visual-tactile incongruities. Developing and testing these experiments aided the development of new approaches to designing that addressed the unique opportunities of 3D printing. The potential of the proposed approaches are expressed through the final designs of the interactive lamps; objects designed to inspire delight and enjoyment through their unique interactions and surprising qualities.

PREFACE

“We forget just how painfully dim the world was before electricity. A candle, a good candle, provides barely a hundredth of the illumination of a single 100 watt light bulb.”

~ **Bill Bryson**

I often find myself sitting, staring, and marvelling at electric light. There’s a reason I decided to devote a year of my life to exploring it.

Light represents *possibility*.

The possibility to explore new ideas late into the night. The opportunity to create neon-clad buildings that stretch into the inky blackness of the night sky. The ability to understand the fabric of the reality we happen to inhabit.

Light gives *hope*.

The comfort of a warm, well-lit home. The bright lights over the work bench of an artist. The beam of photons you use to talk to your far-off, but always dear friend.

Light brings *joy*.

The glimmer in the eye of a child on the biggest ferris wheel they’ve ever seen. The shine of a thousand cellphones at a famous concert. The flash of a hundred bulbs at the red carpet.

Light *is* our world.

DEDICATION

I dedicate this thesis to my family.

Mum and Dad, I could not have done this without your help and support.
Thank you for always being there when I needed you, and for eternally
supporting my hare-brained endeavours.

Anneke, for making me laugh and boosting my spirits, all the spontaneous
coffee dates, as well as being the best sister anyone could ask for.

Oma and Opa, for the frequent heart-felt calls and check-ups, as well as
reminding me that family is never too far away.

Grandma, for the encouragement and all the baking that reminded me of
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salt.

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INTRODUCTION

Surprise represents a useful and powerful tool for product designers looking to inject more dynamism and intrigue into people's relationships with their objects. It has the potential to draw people in; inviting touch and encouraging interaction. One technique for exploring surprise in the design of objects is by manipulating the user's visual perception of the tactile experience they expect to have. This is known as a visual-tactile incongruity (referred to as a VTI in this thesis). The use of this was identified by Ludden (2008) as a common technique for eliciting surprise (p. 24) in product design. A collection of strategies were developed that addressed the various ways in which VTIs had been employed. These strategies stemmed from the analysis of a collection of products, most of which employed traditional manufacturing techniques. Multi-material 3D printing; a new, advanced additive manufacturing technology, offers capabilities and qualities that existing manufacturing is unable to achieve. This thesis explores how the unique qualities that 3D printing offers can generate surprise through the exploration of Ludden's (2008) strategies, seeking to ascertain whether there is the potential for developing new specific approaches.

Fox-Derwin (2011) identified that surprise generated through a VTI in existing products is often marred by a lack of longevity, a property that she called a "one-liner" (p.2), also referred to as a "one-time experience" (Desmet, 2004; Ludden, 2008). Since surprise can be perceived as value-adding, this loss of surprise could be translated to a loss of perceived value in the product. Fox-Derwin (2011) suggests using the layering of surprise into the interaction as a way of extending the experience and encouraging a rich reflection and relationship with the object. This thesis explores the potential by layering surprise into the interactive elements of lighting design, seeking to extend and expand the way that tactile interactions can activate light. Lighting design acts as a focal point, offering direction and a specific outcome for both the interaction and the surprise: Light. This directed focus and expectation of illumination offers an expansive field of design opportunities to experiment with the potential of VTIs and surprise.

Incorporated into interactions, surprise can be a catalyst for reflection and a way of enhancing the relationship between the person and their object. VTIs offer a means of eliciting surprise through the manipulation of the visual perception of an object. Multi-material 3D printing offers opportunities that other manufacturing technologies cannot. This thesis systematically evaluates how the unique qualities that 3D printing offers can generate surprise through VTIs in lighting design.

Thesis Overview

How can the unique qualities that 3D printing offers generate surprise through visual-tactile incongruities in lighting design?

This section gives a brief overview for structure of the thesis.

Chapter 1 (*Background: Literature & Design Review*) analyses and explores three distinct areas: Surprise, 3D printing, and Lighting Design. Each of these areas was identified as a key area of interest, and was critical to comprehending the direction of the research question. This chapter also highlights existing designs and particular literature that pushed the envelope and expanded knowledge.

Chapter 2 (*Methodology*) discusses the relationship between Research through Design and other appropriate research methods. It details and expands the fundamental research aims and objectives as well as highlighting the criteria used for assessing the design work.

Chapter 3 (*Design Phase 1*) is the first of two main sections of design work in the thesis and develops the first aim of the research, systematically exploring surprise and 3D printing. This phase develops an understanding of how the

qualities of 3D printing could explore the strategies for eliciting surprise in product design developed by Ludden (2008). This was derived from two collections of prototypes that each experimented with different 3D printing technologies. The chapter culminates in a reflection over the user testing, which sought to gather the thoughts and opinions of 10 participants on the second collection of prototypes. This included qualitative measuring of the presence of surprise through VTIs. The data gathered, coupled with what was learned from the development of the final collection, was used to develop design approaches for the next phase.

Chapter 4 (*Design Phase 2*) is the second of the design-based phases, developing the second aim of the research. The identified approaches and design elements from the most successful prototypes in Design Phase 1 were used as starting points for the new process. This phase brought lighting into the equation and detailed the development of 4 individual lights that each focused on one of the approaches identified at the end of Design Phase 1. The emphasis in the lights was the development of surprising interactions that specifically showcased 3D printing capabilities. Once the lights were finalised, they were tested with 10 participants and conclusions were drawn from the subsequent analysis of the data and responses.

Chapter 5 (*Discussion*) provides a critical reflection, analysing the final outputs of the design phases as well as assessing identified strengths and weaknesses of the entire research process. This section also looks at potential directions for investigation outside the scope of this thesis. It also discusses the potential of 3D printing as a tool for designers looking to surprise in lighting design and beyond.

Chapter 6 (*Conclusion*) closes off the thesis; finishing with the final thoughts on the outcomes of the research as a whole.

1

BACKGROUND RESEARCH

THEME A: SURPRISE

Emotions & Pleasure

You can see a vase on the table. It looks like crystal glass. You have seen vases like this one before. You know that they are heavy, have sharp edges and the glass feels cold. Your grandmother had one of these, and she never let you touch it. As you reach out for it, you think about how it might look stuffed to the brim with wildflowers, reminding yourself of past summers down at the farm.

After our first glance over an object, we build an idea of what that object is, what it does, what it will feel like, and how it might make us feel. This is an example of Appraisal Theory (Demir, Desmet, & Hekkert, 2009, pp. 41-51; Lazarus, 2006, pp. 86-93; Smith & Lazarus, 2001, pp. 94-114), which Demir et al. (2009) described as “an automatic assessment of the effect of a product on one’s well-being” (p. 41). If this appraisal elicited a positive assessment, then this was likely to lead to a positive emotional or affective response, which can encourage the person to interact more closely with the object. This appeared to imply a emotion-driven call to action and seemed an overly simplistic view of emotional responses. Everyday experiences tell us that behaviour is not singularly controlled by our emotions, but is also dependant on our past experiences, as proposed in a counter to Appraisal Theory. Baumeister, Vohs, DeWall, & Zhang (2007) suggest that behaviour is instead indirectly influenced by the retrospective appraisal of actions, developing a feedback system. This encourages consideration and learning in order to develop superior behaviour patterns, leading to the attainment of desired emotional states (p. 167). This appears more in line with our everyday experiences, as we happily listen to music, watch films, and read books without the emotional weight of those charged experiences driving us to complete specific actions.

The search for pleasure is an ancient one, arguably as old as the species. (Jordan, 2000, p. 11). While the sources of these pleasures have shifted over the course of human history, surprise has remained a potent tool for

unexpectedly eliciting pleasure. A core framework that defined different sources of desired pleasures, originally posited by Tiger (1992) in The Pursuit of Pleasure, described the different pleasures as “physiological, psychological, sociological, and ideological” (pp. 63-65). This framework of pleasures was furthered and applied to products by Jordan (2000) and found to involve “bodily sensations, achievements of the self, social interaction, and intellectual stimulation” (pp. 11-18). These aspects appear essential in the development of sentiments towards objects. The distinction of the different emotional theories and resultant pleasures highlights the complexity of the person-product relationship. This complexity has expanded further with the emerging prominence of digital interactions and multi-functionality. These developments add completely new facets of interaction to a variety of systems and products. We still seek unique sensations, memorable achievements, fun interactions and mental stimulation; all of which surprise can be a useful tool for unexpectedly eliciting.

Surprise & Effect

As you reach out to touch the vase, it feels unexpectedly warm, soft and pliant in your hand. You pick it up, realising that it is actually made of a rubber that distorts in your grasp. The edges that looked hard are more akin to soft contours that warp under your touch.

Surprise is a powerful tool for designers, and when used carefully has the ability to “elevate a product beyond the banal” (Urquiola & Hudson, 2007, p.136) and separate it from its competitors. Designs that generate surprise can add value, indicate what ought to be done, persuade potential buyers, challenge perceptions and command attention (Fox-Derwin, 2011, p. 2; Green & Jordan, 2002; Grimaldi, 2006; Hekkert, 2006; Ludden et al., 2008; Rodríguez Ramírez, 2012, p. 263). Semantically, surprise is defined in two ways; either

as an “an unexpected event, piece of information, gift, or party”, or as “the feeling caused by something that is unexpected or unusual” (Merriam-Webster, 2016). This thesis concerns the latter definition, where surprise is an emotional response that can be instigated by the disconfirmation of expectation.

The key problem that surprise often runs into is that it can be a short-lived or one-time-only emotion (Desmet, 2003, p. 11; Fox-Derwin, 2011, p. vi; Ludden, 2008, pp. 18-20), as it is heavily tied to novelty (Desmet, 2003, p. 11, Rodríguez Ramírez, 2011, pp. 8-11). An aspect of novelty most will be familiar with is its decay. That new product you bought last week may no longer excite you in quite the same way it used to. This decay of novelty can result in two distinct outcomes. The first: A progressively negative outcome if the surprise were the sole defining feature of the design, leading to disinterest, disappointment or irritation. The second outcome could lead to a reflective, growing relationship with the object, extending the positive emotional experience. Fox-Derwin (2011) explored the latter by facilitating a multi-layered surprise experience. This alteration is one way surprise can be extended positively.

Another way the experience of surprise could be extended is by ensuring the product is surprising every time it is encountered. Physical products are limited in their ability to adapt and change in a unique way for every single encounter. Digital software can have this adaptability; such as a new background for your computer every day, but there has to be a tradeoff between how much should be altered for surprise to be elicited and how much must stay the same for the sake of usability. Surprise must therefore be used with caution, as employing surprise unnecessarily or where it is not needed can “lead to disappointment, and users may even feel misled or fooled” (Ludden et al., 2008, p. 37). If a product is designed to surprise, it can alter the normal appraisal path a product would elicit. This channels peoples’ attention through alternate avenues and deceives viewers into thinking things are different to how they really are. This can build false expectations and emotional appraisals, which is where surprise becomes unexpectedly contentious. Rodríguez Ramírez (2011) mentions that

when it comes to pleasure, there are authors who believe surprise has “no pleasure value at all” (p. 8) and that it can equally create a negative emotional response. Green and Jordan (2002) posit that to produce pleasurable products is to find the optimal arousal level, which can be achieved through controlling the nature of surprise, complexity and novelty (p. 78). Norman (1990) suggests that users project their own desires and dreams onto the products they think about buying (pp. 86-95), so understanding and controlling the way elements of the design will be interpreted is a key factor in mitigating disappointment and negative surprise. It appears to be imperative that the designer makes the surprise meaningful and worthwhile to the functionality of the object.

Surprise, like other emotions, has a propensity to be context-dependent. In relation to the person-product relationship, in order to fully understand and appreciate the emotional response a user might have, “one must understand the users’ concerns given the context in which the product is or will be used” (Desmet, 2003, p. 6). One contextualisation of surprise is to situate it amongst familiarity. Hekkert, Snelders and van Wieringen identified that people prefer products with an optimal combination of typicality and novelty (as cited in Ludden et al., 2008, p. 31), which ties into Raymond Loewy’s (1951) principle of MAYA, or “Most Advanced, Yet Acceptable” (pp. 277-286). This reuse of the familiar is seen today in successful consumer products; as showcased by the consistency of forms, structures and interactions employed by Apple (2016) in the design of their iPhone series of products. In this context, familiarity offers a ‘touchstone’ quality that the user uses to ground their appraisal. With regards to surprise, it appears the importance of familiarity is to ensure a comprehensible, positive context for the user to experience something new and unexpected in. A familiar, positive context for surprise could lead to a more pleasant experience.

Visual-Tactile Incongruities

Looking down at the vase in your hands, you realise it is not at all what you expected when you first saw it. A smile cracks across your face and your eyes go wide. Maybe that is why your grandmother never let you touch it.

Ludden (2008) explored the use of surprise in product design and identified that a substantial number of designs that employed surprise were based on a sensory incongruity; the instance where different sensory appraisals provide conflicting information. Ludden (2008) showed that sensory incongruities could be achieved between almost any series of senses (pp. 15-16). Schifferstein (2006) highlights that “The sense of touch is judged to be second in importance for evaluating products, after vision” (p. 59), and Ludden (2008) adds that given our propensity for visual perception of space and evaluation at a distance, “forms of sensory incongruity that start with a visual impression seem to be the most relevant for product design” (p. 17). Ludden’s (2008) research investigated three different sensory incongruities with the starting point of a visual appraisal. She identified the potential of “Visual–Olfactory, Visual–Auditory and Visual–Tactile incongruities” (p. 16). The most common incongruity identified was the visual-tactile incongruity; where a user would make an incorrect visual appraisal about the tactile qualities of an object. The reason why the VTI is the most prominent incongruity is because tactile qualities are visible, and the visual appraisal is often directly relatable to a tactile confirmation. This stands in opposition to smell and sound, where we can only infer the connection between what an object looks like and what it sounds like (Auditory) or smells like (Olfactory).

Ludden (2008) split the ways VTIs were used to generate surprise in product design into two categories: Visible and Hidden Novelty. Visible Novelty (VN) is where the user can identify the unfamiliarity of the product. This is distinguished from Hidden Novelty (HN), where the user believes that the product is familiar (p. 30). The surprise generated by a VN product appears to usually be elicited



by qualities emerging from the user’s state of uncertainty. An example of this kind of product would be the Konko lamp (figure 1.1) by Evenhuis & Gabriel. “The curved shape and fine texture make it look like cloth or paper, but it feels inflexible, rougher and heavier” (Ludden, 2008, p. 43).

For a HN product the surprise emerges out of the user having a definite expectation that results in being incorrect. A product that explores this kind of strategy is Flexlamp (figure 1.2) by Hecht. This lamp “looks like it is made out of matt glass...but is actually made out of flexible polyurethane rubber” (Ludden, 2008, p. 29).

Figure 1.1 - Konko (Evenhuis & Gabriel, 2008)



Ludden (2008) identified six strategies for eliciting surprise in the design of a product: “new material with unknown characteristics; new material that looks like familiar material; new appearance for known product or material; combination with transparent material; hidden material characteristics; and visual illusion (p. 31). These six strategies all sit within the aforementioned categories of Hidden and Visible Novelty. This thesis explores the applicability of these six strategies to new manufacturing processes. One of the main limitations of current literature on VTIs and surprise is that it has not yet addressed the potential opportunities of new digital manufacturing techniques, particularly 3D printing.

Figure 1.2 - Flexlamp (Hecht, 2003)

THEME B: 3D PRINTING

Technologies & Capabilities

3D printing (also known as Additive Manufacturing and often grouped under Rapid Prototyping) has been heralded as a manufacturing wunderkind, achieving feats out of the reach of most other manufacturing techniques (Lipson & Kurman, 2013). 3D printing separates itself from other manufacturing technologies by being an additive process; as it uses only the material needed for the final object in the building process (Chua & Leong, 2015). This differs from other subtractive technologies, where the process of building an object is severely linked to “cutting, molding, or other manipulation of raw materials” (Michalski & Ross, 2014, p. 2213). 3D printing encapsulates a variety of distinct technologies that encompass a massive catalogue of machines capable of building objects in a myriad of materials. Commercially available 3D printing technologies print materials such as: plastic, metal, chocolate, wax, ceramics, and glass, among many others. The layer-by-layer construction process that most 3D printers use gives them a distinct advantage over traditional manufacturing processes (such as milling, turning, routing, molding or casting), because of the complexity possible through this additive approach. This complexity includes the ability to print all-in-one moving parts, advanced 3D textures, multiple materials simultaneously and complex internal geometries (Chua & Leong, 2015). 3D printing technologies (Adapted from descriptions (Robb & Kim, 2014, p. 19; Prince, 2014, pp. 41-42)) include:

- » *Fused Deposition Modelling (FDM)*
 - FDM is one of the least expensive and most widely available technologies to consumers, hence a lot of desktop 3D printers utilise this technology. FDM relies on building models using support material made from the same material as the model itself, which can be problematic for post-processing and building moving parts as one.
 - Materials typically used: Acrylonitrile Butadiene Styrene (ABS) or Polylactic Acid (PLA)

-
- » *Polyjet Photopolymerization* (Will be referred to as PPP in this thesis)
 - PPP uses a liquid polymer or resin that is cured by Ultraviolet (UV) light. It is substantially more expensive than FDM. The process is mechanically similar to inkjet printing. When the objects are printed, a gummy-like support material is used to fill in the gaps and encase the object. PPP supports extensive high resolution multi-material printing; for example, being able to print in rubber and a hard resin simultaneously.
 - Materials typically used: UV-sensitive resins and rubber.
 - » *Selective Laser Sintering (SLS)*
 - SLS builds objects from a vat of powder, focussing a LASER beam onto the powder in order to melt it together, layer by layer. The powder that is not melted together provides support for the model while it is being built, and can then be reused for later printing jobs. SLS can be quick, light and strong, depending on the material used.
 - Materials typically used: Nylon, various metals, glass, ceramics or powdered polystyrene.
 - » *Stereolithography (SLA)*
 - SLA is the original 3D printing technique, relying on a beam of light to cure incremental layers of resin while the object sits in a vat of resin. As the layers are built, the object is lowered into the resin (or raised from it), allowing the following layers to be built on top. This technology can achieve high resolution results, as well as the machine being smaller possible to fit into desktop-sized printers.
 - Materials typically used: Light-sensitive resin.
 - » *Laminated Object Manufacturing (LOM)*
 - LOM is a unique technology, as outside of the support material produced by other technologies, it is the only printing technology that actively produces waste. By layering and gluing thin sheets of a

-
- material, it builds up an object layer by layer, cutting away the waste that is not needed.
 - Materials typically used: Paper, metal foil or plastic film.
 - » *Syringe Extrusion*
 - Syringe Extrusion is used to print any material that can be extruded using a syringe and plunger. This is the technology used for materials that have a paste-like texture.
 - Materials typically used: Silicone, chocolate, cheese, dough, clay or concrete.

3D printing at present has limitations that have prevented its adoption as a dominant manufacturing technique. The cost-per-object is high if compared to the individual cost of an item from a full injection mold production run. Robb & Kim (2014) explain that systems such as desktop ABS or SLA machines and other “lower-end printers have a long way to go in terms of accuracy and product integrity” (p. 23). Higher end machines such as the SLS machines operated by Shapeways (2016) can achieve levels of resolution and surface finish that are able to rival those of traditionally manufactured products, yet these machines are too large and expensive for consumers. PPP 3D printing offers users a toolset even more extensive with the addition of multi-material printing (Chua & Leong, 2015, p. 52) and the capability to simulate a large number of distinct material properties. However, like the SLS machines these printers are too large costly for consumers. That said, the ability to blend materials with distinct properties and create hybrid materials with selective qualities makes it an ideal candidate for exploring the potential of visual-tactile incongruities.



Polyjet Photopolymerisation (PPP)

Designing for multi-material PPP involves knowledge of the materials at your disposal, as well as an understanding of how different volumes of distinct materials will interact. For example, multi-material PPP could produce a hairbrush (figure 1.3) that uses a material with a tiny bit of give for the body, a hard material for where the bristles meet the body, and then a soft material for the bristles. This hairbrush was produced in a single continuous print.

Figure 1.3 - 3D Printed Hairbrush (3D Hubs, 2016)

PPP 3D printing capabilities include the ability to (Adapted from Chua & Leong, 2015, pp. 48 - 58):

- » *Build internal structures or mechanisms.*
 - This capability allows for the building of objects that have moving parts, hollow components, or complicated internal strengthening all in just one printing job.
- » *Build simultaneously with different materials, showcasing distinct properties.*
 - This allows printers to blend materials with soft or hard properties in ways that could only be done with separate parts in traditional manufacturing techniques.
- » *Create gradients between hardness & softness and transparent & opaque within one built object.*
 - This allows the blending of distinct materials to create complex material properties that can shift over the course of an object, allowing for potentially new and intricate material variances. This can include hard-soft, clear-opaque, black-white, among others.
- » *Create complex structures and textures with ease.*
 - Advanced texture and forms are no harder for a PPP printer to create than a simple box. Texture and complexity can be effortlessly incorporated and can be simply adapted between produced objects.

These capabilities, especially the ability to blend and make gradients with materials sets PPP apart from the other mentioned 3D printing technologies and gives it the most potential to investigate VTIs.

THEME C: LIGHTING

Lighting Design, 3D Printing, & VTIs

Light is a key contributor to our ability to catalogue and observe our world. Depending on the qualities of the light and how it shines on an object, certain elements can be obscured while others are revealed. Light has been a ubiquitous muse for designers of all ages and experience levels. The famous notion that every designer will attempt to design a chair, I would argue, holds true for lights as well. Fortunately for the design world, the imaginations of the designers appear to be limitless with the perpetual emergence of new designs and ideas. Some designers have developed interesting light designs that explore the special manufacturing capabilities that 3D printing technologies possess. However, few have capitalised on the unique capabilities that PPP offers.

Lighting design is undergoing a paradigm shift away from the incandescent bulb. The replacing technologies afford a myriad of opportunities due to their low energy consumption, high levels of efficiency (often resulting in energy consumption reductions of over 80%), and small form factor. While all of these aspects seem immediately positive, Traldi (2011) writes that one aspect that appears to be hard to replicate with new technologies is the light quality that incandescent bulbs afford (p. 3). Light-Emitting Diodes (LEDs) and Compact Fluorescents (CFLs) boast impressive lifespans and focussed directionality of light, but at present seem unable to emulate the warm, fire-like, sunset-like glow of a traditional Edison bulb. Traldi (2011) notes a way that designers have sought to adapt to the less pleasing glow of the new light sources has been to revive a more significant use of natural, warmer materials. This shift underpins the ecological mindset that accompanies the shift to more efficient lighting (p. 5). Some materials that had been excluded from certain roles are finally getting their time in the sun, with materials such as paper, wood, card, and fabrics suddenly usable in close proximity to the light source without fear of fire hazards. These new possibilities for materials have been met with more compact and dense lighting constructions, as well as more experimental



approaches to material combinations. This experimental approach has also included the incorporation of 3D printing.

One avenue of lighting that designers have explored using 3D printing is for the generation of new patterns and forms that are too difficult or even impossible for traditional manufacturing techniques to achieve. Alex Buckman's (2016) Colony Series (figure 1.4) showcase a beautiful exploration of pattern and form that highlights the potential for 3D printing. This design sought to minimise the weight while maximising the visual impact. Nylon SLS printing lends itself nicely to creating ethereal, delicate forms. David Graas' (2012) Huddle (figure 1.5) explores the poetic visual of multiple architectural forms 'huddling' together. This design employed 3D printing because it is impossible

Figure 1.4 - Colony Series (Buckman, 2016)



to manufacture any other way. The illumination from within showcases the material qualities nicely as well.

Unlike using 3D printing for complex patterns; which is a reasonably common application for the technology in this field, using 3D printing for its ability to generate moving parts is technically much more challenging. Using 3D printing to facilitate kinetic lighting structures is still relatively untouched, with few successful and beautiful designs on the market. One notable product is Patrick Jouin's (2011) Bloom lamp (figure 1.6), which exhibits organic forms, creating a light that expands outwards when interacted with. This light demonstrates the capabilities of SLS printing to produce moving structures, as well as the design itself being exceedingly elegant. Lighting designers are keenly exploring the

Figure 1.5 - Huddle (Graas, 2012)



potential of new technologies at present, with explorations into 3D knitting, 3D printing, and other freeform manufacturing techniques as well.

Explorations into surprise are more extensive in lighting design, and include some fascinating examples. Christo Logan's design series two.parts (figure 1.7) explores surprise through 3D printed ceramics. By developing a form that can hide LED lighting amongst the shade itself, the light appears to have a 'missing bulb' and appears to be illuminated by nothing. This encourages exploration into the deceptively simple structure. Grimaldi (2008) explored the potential of surprise in The On-Edge Lamp (figure 1.8), where she sought to create unique experiences and challenge perception. The light creates suspense and worry; as it only turns on when the lamp is near the edge of the table. If it falls, the light is not damaged since it is made of a soft, rubbery material; rather than the brittle

Figure 1.6 - Bloom (Jouin, 2016)



ceramics it appears to be made from. This exploration of a VTI begins to toy with emotions beyond just surprise. Konko by Willeke Evenhuis & Alex Gabriel (figure 1.1) and Flexlamp by Sam Hecht (figure 1.2) also explore the potential of surprise through eliciting VTIs. These different lamps showcase examples of Ludden's strategies, but neither of them employs the surprise for a useful or functional interaction. This limits their potential for surprise to a "one-liner", where the surprise highlights the end of the experience, as opposed to "starting a reflection process where the surprise might be extended" (Fox-Derwin, 2011, p. 2).

There is an opportunity to explore how VTIs and surprise might be brought into interactive- or control-based elements of lighting design. No lighting designers have yet systematically explored the properties of 3D printing for eliciting VTIs.

Figure 1.7 - two.parts/atom & two.parts/heatsink (Logan, 2016)



Control & Tactile Interaction

In lighting design, most familiar systems generally utilise one of two types of controls, on/off switches and dials (generally used for dimming light). These are the main components that people interact with through their sense of touch and offer an opportunity for eliciting VTIs. By offering a different tactile sensation to the one visually apparent, this can layer the surprise directly into the interaction. By building the surprise into the light, as well as the interaction, this can further layer the surprising experience. "As a result, the beneficial aspects of eliciting surprise through interactions with products will have the potential to be prolonged" (Fox-Derwin, 2011, p. 3).

Figure 1.8 - The On-Edge Lamp (Grimaldi, 2008, p. 171)



Sonneveld & Schifferstein (2008) highlight that touch is the only two-way sense; seeing does not imply being seen, hearing does not imply being heard, yet touching implies being simultaneously touched (p. 41). Touch is responsible for a lot of our emotional investigation and investment, as well as our bodily awareness (Sachs, 1988, p. 28; Scott, 2001, p. 149). There is a clear opportunity to extend interactions with electronic systems, especially since the outputs of these systems are becoming ever more complex. There are a variety of sensors that can interpret tactile interactions for controlling lights, including flex sensors, capacitive touch sensors, potentiometers, pressure sensors, knock sensors, among many others. These sensors can each facilitate different aspects of tactile interaction. The design of the interaction should revolve around the outcome and the desired usability of the object; as well as making the interaction pleasurable.

Figure 1.9 - Fonckel One (Ross & Wensveen, 2010)

Pleasurable tactile interaction with products have been connected with usability (Donn, Dugar, & Osterhaus, 2011; Jordan, 2002; Ross & Wensveen, 2010). Ross and Wensveen (2010) looked into interactive product behaviour, suggesting that the interactions with a product are of significant importance and should underpin the entire process of designing the product. "Once we start designing the aesthetics of interactive behavior, a social and ethical dimension is introduced as well" (p. 3). Sonneveld and Schifferstein (2008) suggest touch enjoys a certain reciprocity, whereas sight is often a one-way interaction (p. 41). Touch allows us to make sense of the world around us, so when an object's tactile interactions fail to make sense, usability is lacking (Sonneveld & Schifferstein, 2008; Donn, Dugar, & Osterhaus, 2011). This importance of the interaction being both pleasurable and usable is a key tenet for design. If the interaction falls short on either pleasure or usability, it could become mundane or frustrating, respectively.

The design of pleasurable interactions needs to take into consideration both person-product relations and the activity involved (Popovic, 2002). The actions involved in tactile interactions with products vary from object to object, but the nature of the actions need to reflect the actual activities themselves in order to make sense. In order to achieve this, the designer needs to have a deep understanding of what the user is looking for and what actions the user is likely to experiment with. Ross (2010) understood this exceedingly well when developing his Fonckel One lamp (figure 1.9), which responds to tactile interactions that we are familiar with through our smartphones. Ross (2008) also explored the potential for products to tempt interaction. He argued that "people can be attracted to act, even irresistibly so, by the expectation of beauty in interaction" (p. 40). This thesis explores the potential for evocative, beautiful, and surprising tactile interactions.

2

METHODOLOGY

SITUATING THE RESEARCH

How can the unique qualities that 3D printing offers generate surprise through visual-tactile incongruities in lighting design?

This thesis aims to address the prior explored areas of surprise elicited through VTIs, Polyjet Photopolymerisation (PPP) 3D printing, and lighting design. The literature on surprise highlighted its value as a powerful emotive force, the importance of carefully and considerately employing surprise, as well as its potential to be elicited through sensory incongruities. Literature on 3D printing brought to light the importance of considering the unique manufacturing possibilities of 3D printing, as well as the possibilities of eliciting surprise through PPP's ability to blend soft and hard materials. The literature and existing designs in lighting design highlighted the relevance of beauty as an invitation for interaction, as well as the importance of pertinent and comprehensible tactile interactions. Surprise was identified as a key element in setting apart designs from competing products, as well as being a useful aspect to integrate into the interaction for extending the person-product relationship.

AIMS & OBJECTIVES

This thesis explored a design-driven research process. While Milton & Rogers (2013) suggest that three different forms of design-based-research exist; Research about Design, Research as Design, and Research through Design, this thesis focuses solely on the final approach. The Research through Design (Burdick, 2003, p. 82; Martin & Hanington, 2012, p. 146) approach acknowledges design as a legitimate research process, and explores the potential of a designer's array of tools in the context of research. Godin & Zahedi (2014) elucidate that Research Through Design takes advantage of the skills gained through design practice to provide a better understanding of complex and future-oriented issues in the design field (p. 1).

Following are the aims and corresponding objectives for this research. They have been expanded with all the methods used to respond to them.

Aims	Objectives
First Aim / Background + Design Phase 1: To explore the potential for 3D printing to elicit surprise through visual-tactile incongruities.	Identify and intersect theoretical approaches to 3D printing and surprise.
	Develop experimental prototypes that investigate the relevance of 3D printing to identified strategies for surprise.
	Test and identify which experiments' 3D printed qualities have most potential to elicit surprise.

Figure 2.1 - The first aim, with the objectives it aims to achieve. Included are the methods used to respond to the aim, as well as criteria for the Research through Design approach.

Methods	Criteria
<p>Literature & Precedent Review (Cresswell, 2013, pp. 27-47, Martin & Hanington, 2012, p. 112)</p> <p>Exploring previous literature on relevant areas was a key component of this thesis. It is an essential tool for gaining in-depth understanding of the areas involved as well as for discovering research opportunities in the state of the art.</p>	Designs should aim to elicit surprise through the expression of one of Ludden's (2008) VTI strategies.
<p>Morphological Analysis (Zwicky, 1967)</p> <p>This method was used as an idea generation tool, enabling the rapid exploration of intersecting fields. This allowed for a clear, systematic approach to designing within the context of the existing strategies for surprise.</p>	Designs should highlight one or both of the potential VTI angles possible with PPP:
<p>Research Through Design (Burdick, 2003, p. 82; Martin & Hanington, 2012, p. 146)</p> <p>This approach utilised sketching, iterative ideation and prototyping, as well as: Computer Aided Design (CAD) modelling, parametric design systems and 3D printing. This formed the body of the design phase, moving from technique to technique to develop the final physical outputs.</p>	Visually referencing softness but making the prototype tactually hard, or vice versa.
<p>Evaluative Research / User Testing (Kittur, Chi, & Suh, 2008, pp. 453-456)</p> <p>An adapted version of evaluative user testing was conducted to test the prototypes, facilitating the collection of qualitative and self-reported information. The testing incorporated Interviews (Kuniavsky, 2003; Martin & Hanington, 2012, p. 140), Questionnaires (Robson & McCartan, 2016) and the Geneva Wheel of Emotions (Scherer, 2005, pp. 720-725) (Will be referred to in this thesis as the GWoE) for participants to self-report on their emotional responses to the physical prototypes. The GWoE was modified to include surprise (negative and positive).</p>	Visually referencing texture but making the prototype tactually smooth, or vice versa.
<p>Data Analysis (Mogey, 1999)</p> <p>The collected responses were aggregated and combined, for the purpose of providing a simpler overview and allowing insight to be gleaned, as well as to facilitate easy visual representation.</p>	Designs should explore the range of qualities and capabilities possible with PPP.
	Designs should explore a visually consistent look between each other.

Aims	Objectives
Second Aim / Design Phase 2: To design, build and test interactive lighting that aims to elicit surprise through the use of VTIs and 3D printing.	Further explore identified approaches to investigate eliciting surprise through 3D printing in lighting design.
	Test the designs' abilities to generate surprise with participants and analyse responses.

Figure 2.2 - The second aim, with the objectives it aims to achieve. Included are the methods used to respond to the aim, as well as criteria for the Research through Design approach.

Methods	Criteria
Concept Mapping (Ausubel, 1963; Martin & Hanington, 2012, p. 38) This method was used to develop a broader understanding over a complicated design space, as well as develop relationships between disconnected concepts.	Designs should each explore one of the approaches developed in response to the exploration of Ludden's (2008) strategies in Phase 1.
Morphological Analysis (Zwicky, 1967) Again, this was used as an idea generation tool to explore various ways of incorporating tactile interactivity into 3D printing.	
Research Through Design (Burdick, 2003, p. 82; Martin & Hanington, 2012, p. 146) This was used as the core approach for the second half of the thesis, and involved sketching, iterative ideation and prototyping, as well as more specialised tools such as: Computer Aided Design (CAD) modelling, parametric design systems and 3D printing.	Designs should explore the range of qualities and capabilities of PPP.
	Designs should employ evocative interactions and activation controls.
Evaluative Research / User Testing (Kittur, Chi, & Suh, 2008, pp. 453-456) An adapted version of the previous evaluative user testing was conducted to test the lights, facilitating the collection of qualitative and self-reported information. The testing incorporated Interviews (Kuniavsky, 2003; Martin & Hanington, 2012, p. 140), Questionnaires (Robson & McCartan, 2016) and the Geneva Wheel of Emotions (Scherer, 2005, pp. 720-725) (Will be referred to in this thesis as the GWoE) for participants to self-report on their emotional responses to the physical prototypes. The GWoE was modified to include surprise (unpleasant and pleasant).	Designs should be visually coherent between each other.
Data Analysis (Mogey, 1999) The adapted versions of the questionnaires included some new data points and responses to track.	

3

DESIGN PHASE 1

INTRODUCTION & QUESTION

The literature on surprise highlighted its value as a powerful emotive force, the importance of carefully and considerately employing surprise, and its potential to be elicited through sensory incongruities. Literature on 3D printing brought to light the importance of considering its unique manufacturing possibilities, as well as the possibilities of eliciting surprise through PPP’s ability to blend soft and hard materials. PPP offers a myriad of opportunities that designers must gain an appreciation and solid understanding of if they wish to apply them effectively. This holds especially true if the designer wants to elicit surprise through a VTI.

This chapter focuses on a sub-question derived from the main research question discussed in the methodology. This chapter also focuses on responding to the first aim of the research, which sought to systematically explore the how 3D printing could be applied to Ludden’s (2008) strategies. The question this design phase responds to is:

How can 3D Printing generate visual-tactile incongruities through the exploration of given strategies?

The structure of this chapter is akin to a miniature thesis, with its own methods, results and discussion. The removal of light from the question at this point was to encourage a specific focus on just the materiality, form and texture of the 3D printing, in order to look at how it could be used to generate VTIs. Light is revisited again at the end of this chapter, in combination with the final outputs of this design phase. The knowledge from this phase informed the starting point of the next phase.

METHODS & CRITERIA

This design phase responds to the first research aim of: ‘*explore the potential for 3D printing to elicit surprise through visual-tactile incongruities*’. The second and third objectives of this aim are expanded below with the relevant methods and criteria for fulfilling this aim. The first objective was explored through the background research.

Objective 2: Develop experimental prototypes that investigate the relevance of 3D printing to identified strategies for surprise.

1. *Morphological Analysis* (Zwicky, 1967)
This method was used as a systematic idea generation tool to enable rapid exploration of intersecting fields.
2. *Research Through Design* (Burdick, 2003, p. 82; Martin & Hanington, 2012, p. 146)
This approach incorporated sketching, iterative ideation and prototyping, as well as CAD modelling, parametric design systems and 3D printing. This design phase also employed the following criteria identified in the methodology:
 - a. *Designs should aim to elicit surprise through the expression of one of Ludden’s (2008) VTI strategies.*
 - b. *Designs should highlight one or both of the potential VTI angles possible with PPP:*
 - i. *Visually referencing softness but making the prototype tactually hard, or vice versa.*
 - ii. *Visually referencing texture but making the prototype tactually smooth, or vice versa.*
 - c. *Designs should explore the range of qualities and capabilities possible with PPP.*
 - d. *Designs should explore a visually consistent look between each other.*

OPERATING CONSTRAINTS

Objective 3: Test and identify which experiments’ 3D printed qualities have the most potential to elicit surprise.

- 3. *Evaluative Research / User Testing* (Kittur, Chi, & Suh, 2008, pp. 453-456)
An adapted version of evaluative user testing was conducted to test the prototypes, facilitating the collection of qualitative and self-reported information. The testing incorporated *Interviews* (Kuniavsky, 2003; Martin & Hanington, 2012, p. 140), *Questionnaires* (Robson & McCartan, 2016) and the *Geneva Wheel of Emotions* (Scherer, 2005, pp. 720-725) (Will be referred to in this thesis as the GWoE) as well as modified Likert Scales (Matell & Jacoby, 1971) for participants to self-report on their emotions and material perceptions with respect to the physical prototypes. The GWoE was modified to include surprise (negative and positive).
- 4. *Data Analysis* (Mogey, 1999)
The collected responses were aggregated (Calculating the mean, primarily) and combined, for the purpose of providing a simpler overview and allowing insight to be gleaned, as well as to facilitate easy visual representation.

The capabilities that can be achieved with the PPP are mentioned in the background section of the thesis. These identified qualities of 3D printing were deconstructed slightly in the upcoming sequence in order to take a closer look at the specifically achievable qualities with the PPP. The mentioned quality ‘create gradients in material within one built object’ was broken into two different qualities; ‘create gradients in material from hard to soft’ and ‘create gradients in material from almost clear to almost opaque’. The materials that have been selected that also enable this level of control are:

VeroWhite - A slightly off-white, hard resin that is mostly opaque. It allows the transmission of some light in a way akin to a slightly translucent acrylic or very dense candlewax.

TangoPlus - A clear, soft rubber that is flexible and reasonably durable. It has a slightly yellowish hue and after printing is almost transparent.

The Objet Connex 350, the machine that this research employed, is capable of blending these materials at various ratios, creating combined materials that have qualities of both materials to varying degrees. The materials are not listed as pure ratios, instead based off the Shore A values of the outputted hybrid material. Shore hardness is a durometer scale that measures hardness in rubbers or polymers (Stratasys, 2016). The Objet Connex 350 is able to produce 6 different Shore hardnesses between VeroWhite and TangoPlus, meaning that the total material range for PPP printing available is 8 different materials. The full list of materials available (in order from the highest Shore hardness to the lowest) is:

- » *VeroWhite* - White, opaque, & hard.
- » *DM 9795 Shore 95* - White, opaque, hard with little flexibility.
- » *DM 9785 Shore 85* - Off-white, opaque-translucent, medium-hard with some flexibility.
- » *DM 9770 Shore 70* - Off-white, translucent, medium with reasonable flexibility.

-
- » *DM 9760 Shore 60* - Off-white, translucent, medium-soft with reasonable flexibility.
 - » *DM 9750 Shore 50* - Cloudy yellowish-clear, translucent, soft with substantial flexibility.
 - » *DM 9740 Shore 40* - Almost yellowish-clear, translucent, very soft with flexibility.
 - » *TangoPlus* - Yellowish-Clear, transparent, extremely soft with flexibility and stretch.

DESIGN PROCESS

The design process for this phase explored sketching, CAD modelling, rendering, and 3D printing. These processes enabled rapid ideation, which allowed the testing of a multitude of different ideas before moving into dedicated manufacturing techniques.

Development: Collection One

This phase began with Collection One, an initial and broad exploration of the ability of ABS 3D printing to generate VTIs. ABS has, without significant post-printing processing, a very consistent look, which made it challenging to achieve a VTI by only using ABS. Collection One looked at the potential for the form of an object to create a VTI. These experiments explored digital simulations of materials as well as designing objects that attempted to recreate real objects and materials. Experiments were also carried out to look at the way that ABS prints could be designed to flex and give, extending the material possibilities through the process.

While assessing Collection One, one recurring issue with the various explorations was that the models were too disjointed and would have benefitted from having constraints placed on them. Imposing constraints on the design process is; in my opinion, critical to ensuring a focussed direction and considered outcome.



Figure 3.1 - Collection One, all made using ABS FDM printing, showcasing various possibilities for exploring VTIs.

Morphological Analysis & Idea Generation

After the potential of ABS was explored through a variety of printed prototypes, Zwicky's (1967) Morphological Analysis was used for a systematic analysis of how Ludden's strategies, both Visible Novelty (VN) and Hidden Novelty (HN), could be applied to multi-material 3D printing qualities, in order to come up with new opportunities for eliciting surprise through VTIs. The resultant avenues were explored through sketching and prototyping.

One realisation while completing the Morphological Analysis was that strategies in the HN category seemed to allow for more specific investigation of the distinct properties 3D printing afforded. The HN strategies also encouraged exploring the potential of 3D printing to emulate recognisable, familiar forms. In order to more explicitly explore this potential of HN, I decided to develop 5 prototypes for each of the HN categories, and two for each of the VN categories.

As the key exploration angle on this was the use of PPP printing, the employment of the VTI would be reliant on the qualities achievable with that technique. Resultantly, all of the concepts explored the employment of two sets of opposing visible material qualities. The first set of qualities was 'softness to hardness', while the second looked at 'texture to smoothness'. These formed the basis for the ideation of the VTIs for each of the prototypes. Some of the concepts seemed feasible without multi-material printing, so these were designed for FDM printing instead, as it was readily available and easy to do.

Approaches To Surprise 3D Printing Qualities	VN: Combination with Transparent Materials	VN: New Appearance for Known Product or Material	VN: Hidden Material Characteristics	
	Build internal cavities that are visible from the outside.	Enhance the structure of an understood form with internal complexity.	Hide material variance inside another object.	
	Build simultaneously with different materials showcasing distinct properties.	Create objects that sit inside layers of other materials.	Create layered forms that have the characteristics of different materials.	Hide certain materials and the qualities that they have.
	Create gradients in material from hard to soft.	Create objects that allow users to “feel” untouchable objects.	Create a material that visually looks hard but feels soft.	Hide soft sections of material beneath harder areas.
	Create gradients in material from almost clear to almost opaque.	Create objects that have depth that appears deeper or shallower.	Create visual qualities that do not reflect the true nature of the material.	Hide objects in plain sight.
	Create complex structures and textures with ease.	Use texture to show form more intensely.	Emulate textural feel of original product closely.	Create texture that hides true function.

VN: New Material with Unknown Characteristics	HN: Hidden Material Characteristics	HN: New Material that looks like Familiar Material	HN: Visual Illusion
Alter the perceived structure of an object with unknown materials.	Hide moving parts and structural elements.	Make a material have similar optical qualities to a real object.	Use internal structures to distort perception.
Apply materials to objects in new ways.	Hide functionality and potential qualities in the variances between materials.	Create visual effects with material variation that simulate other materials.	Create forms that are only visible from certain angles.
Combine hard and soft sections in new ways.	Intertwine soft and hard sections in innovative ways.	Create a material that looks hard but feels soft.	Deceive the viewer into misinterpreting the structure.
Embed unique visual qualities where they might not be immediately apparent.	Hide light- transmitting components under the skin of an object.	Deceive viewer into misinterpreting a material.	Create unique illusions and control light permeance precisely.
Create deceptive texture that can enhance experience.	Use texture to throw off visual perception.	Emulate real texture in order to create recognition.	Create texture to distort perception of object.

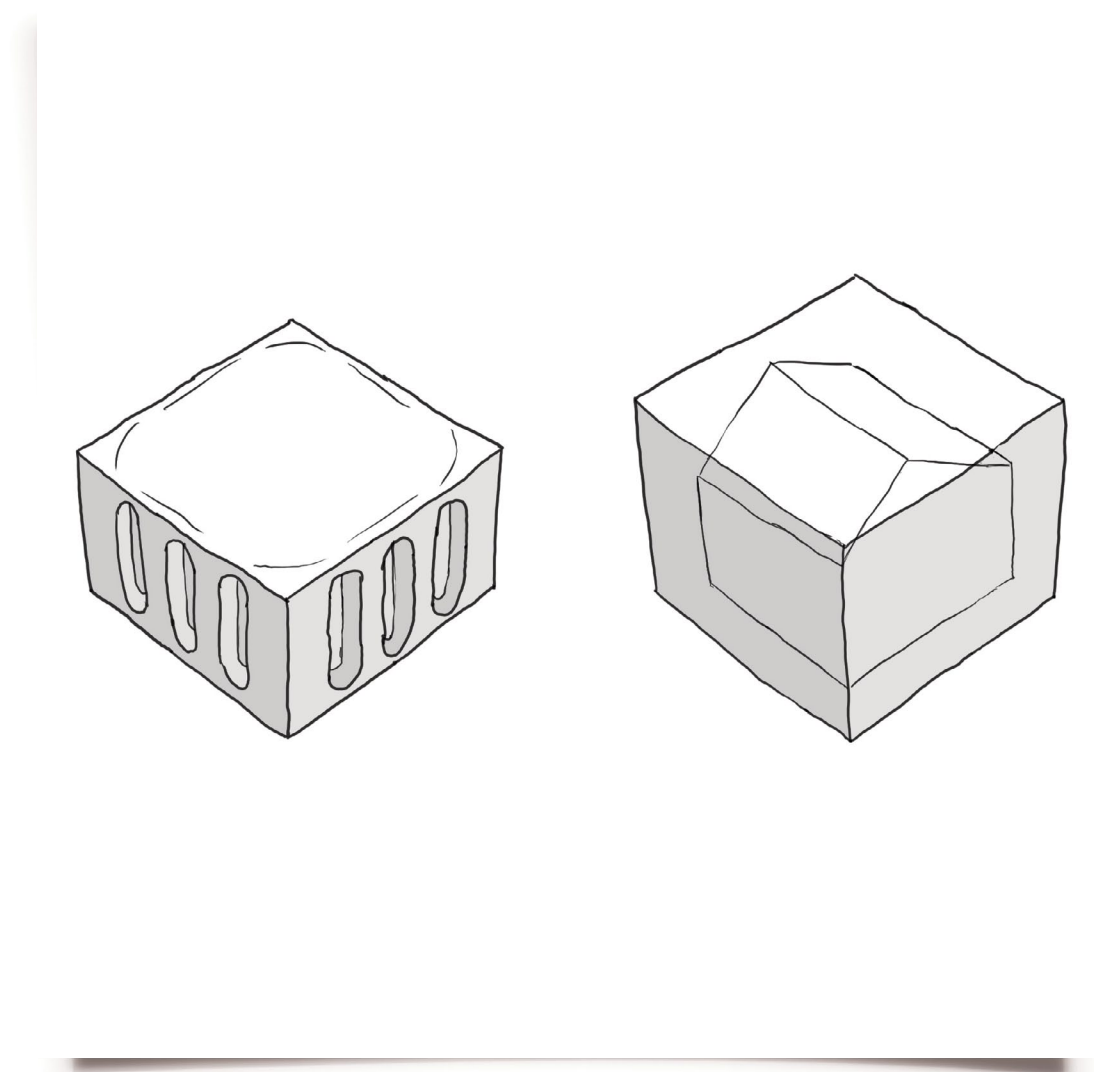
Figure 3.2 - Morphological Analysis intersecting Ludden’s strategies with the potential qualities of 3D printing.

In order to maintain a visual consistency and enable comparison between the individual prototypes for Collection 2, constraints were put in place. These constraints included:

- » Limiting the manufacture of the prototypes to only the two chosen 3D printing technologies (FDM & PPP).
- » Limiting the manufacture of the prototypes with PPP to only use VeroWhite, TangoPlus and their available blends.
- » Limiting the size of the models to 40x40x40mm.
- » Constraining the overarching form of the prototypes to cuboids.
- » Exploring the potential of 'softness or hardness', or 'texture or smoothness'.

Development: Collection 2

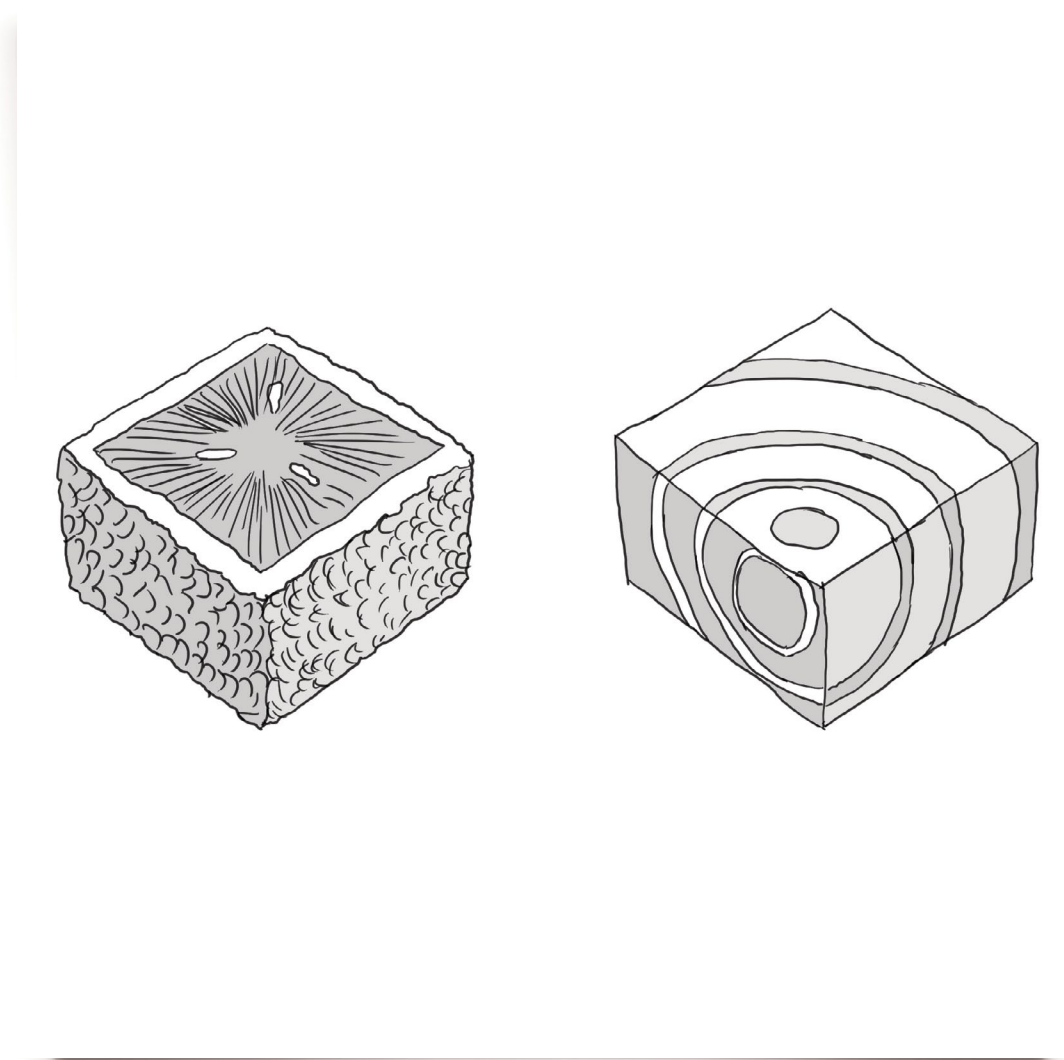
Using the Morphological Analysis as a basis, a selection of ideas were developed for each of the strategies. These ideas were all developed out of the ideation focussed on exploring the potential of the strategies and how to articulate them within the imposed constraints. The ideas and sketches for cubes fitting into each of the strategies were as follows:



Visible Novelty: Combination with Transparent Materials (VN1)

- » *"Intangible Depth"* - (VN1P1) - Use an under-the-surface gradient in PPP materials to alter depth perception of a transparent material.
- » *"Collapsing Construct"* - (VN1P2) - Use a textured cavity to create the look of a filled centre, which will readily collapse when touched.

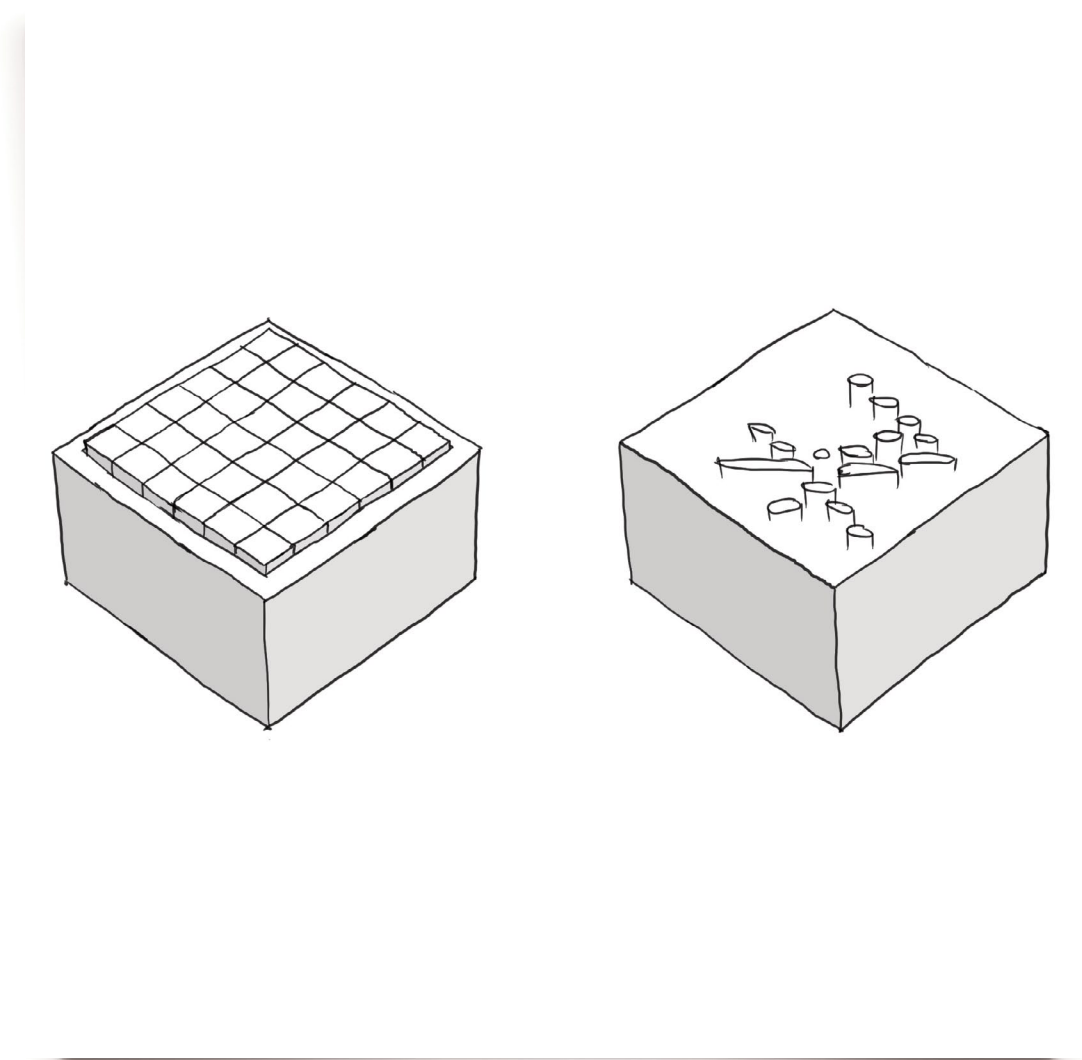
Figure 3.3 - Sketch concepts for the Visible Novelty: Combination with Transparent Materials strategy.



Visible Novelty: New Appearance for Known Product or Material (VN2)

- » “Citrus Resistance” - (VN2P1) - Use variance in PPP material to create a squishable form referencing a citrus fruit.
- » “Dynamic Onion” - (VN2P2) - Use intense layering of PPP materials to achieve an onion-like object with variations in materials properties.

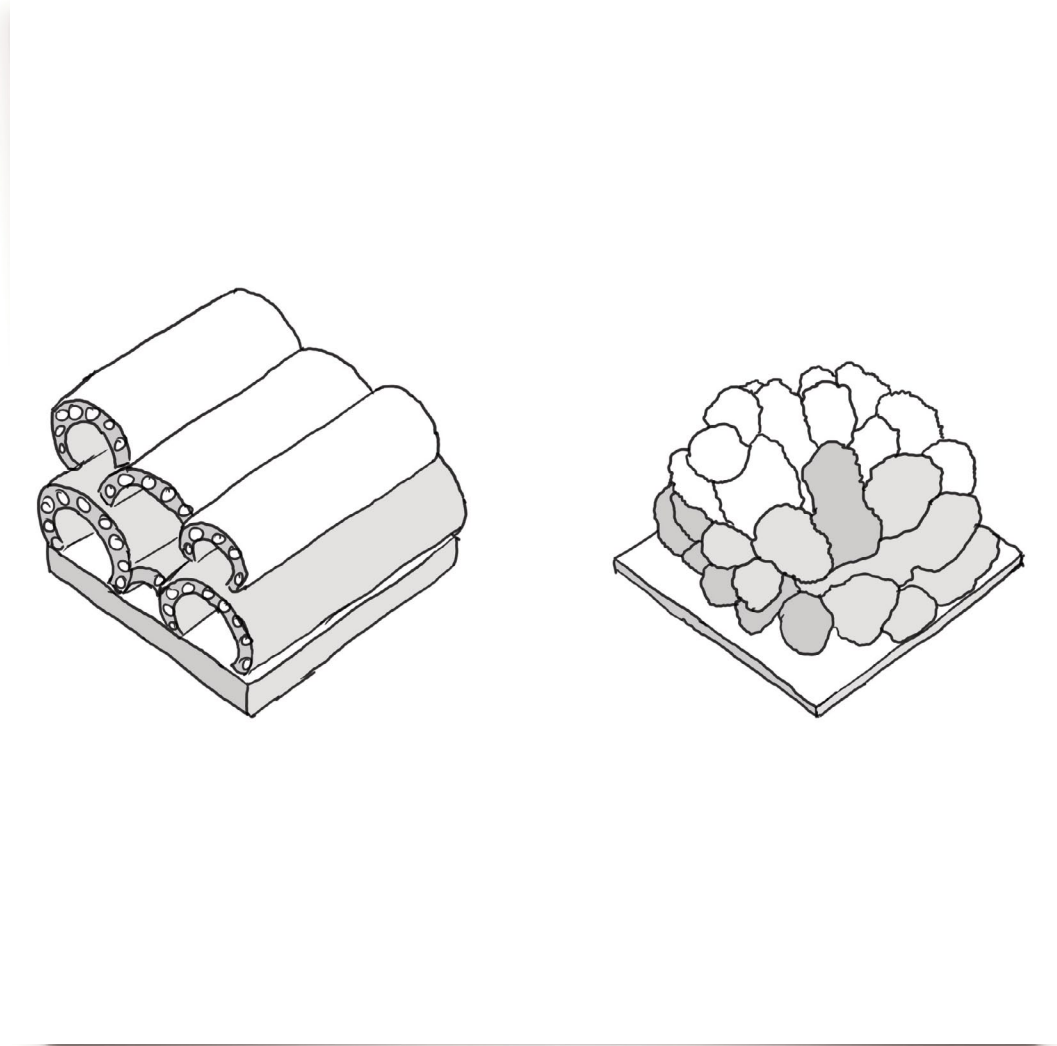
Figure 3.4 - Sketch concepts for the Visible Novelty: New Appearance for Known Product or Material strategy.



Visible Novelty: Hidden Material Characteristics (VN3)

- » “Compression Mosaic” - (VN3P1) - Hide soft material structures underneath harder components, in order to create a flexible hard surface.
- » “Hidden Red Peak” - (VN3P2) - Hide a disjointed series of pieces that only form an image when viewed from a certain angle.

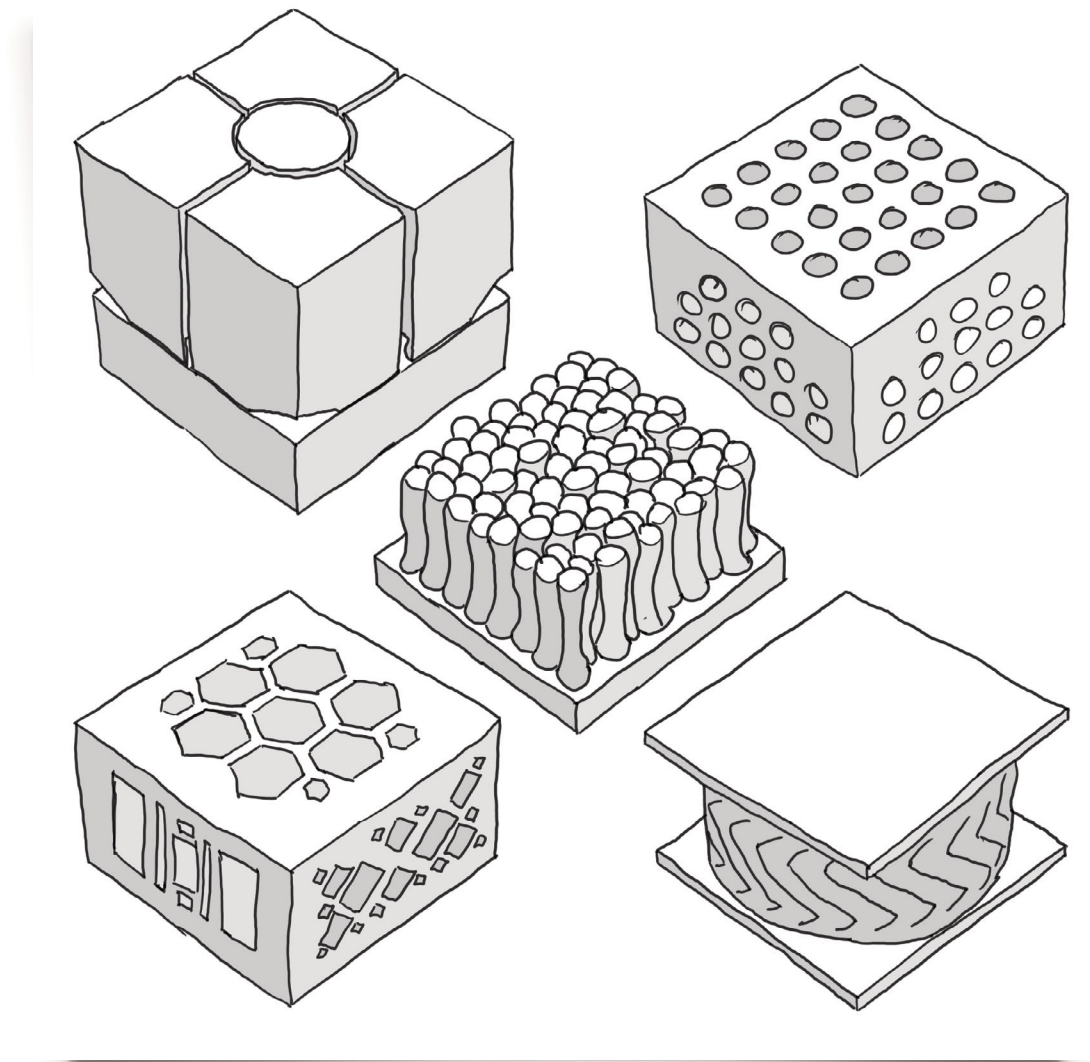
Figure 3.5 - Sketch concepts for the Visible Novelty: Hidden Material Characteristics strategy.



Visible Novelty: New Material with Unknown Characteristics (VN4)

- » “Collapsing Tubes” - (VN4P1) - Create a structure that does not make an explicit reference to anything but abstract tube forms, and makes use of soft and hard PPP materials.
- » “Dendritic Coral” - (VN4P2) - Creates a reference to coral-like structures, a structure that most people do not get to touch, only look at. Make object that is soft with hard detailing.

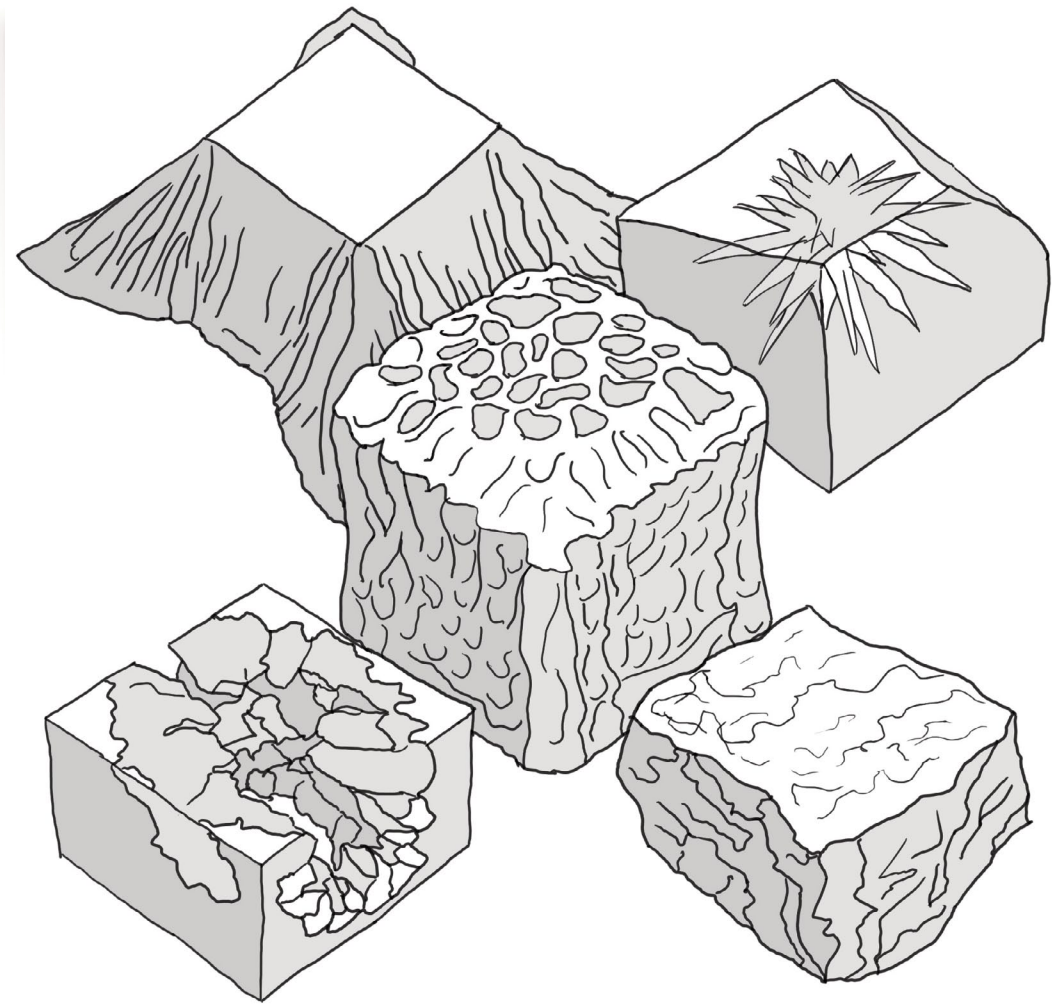
Figure 3.6 - Sketch concepts for the Visible Novelty: New Material with Unknown Characteristics strategy.



Hidden Novelty: Hidden Material Characteristics (HN1)

- » “Hidden Articulation” - (HN1P1) - Object could be made in ABS FDM and explore the potential of internal mechanisms and explosive motion.
- » “Hidden Light Tubes” - (HN1P2) - Create a cube that uses the clear PPP material to allow light to pass through the model.
- » “Tentacle Grasses” - (HN1P3) - Explores the potential of the PPP material blending in order to create a very intense tactile experience.
- » “Textural Variance” - (HN1P4) - Explore the ability to suggest softness where there is rigidity, by layering the softer PPP materials over a hard core.
- » “Twisting Expectation” - (HN1P5) - Create an object that translates an inputted motion into another motion entirely, through PPP material variance.

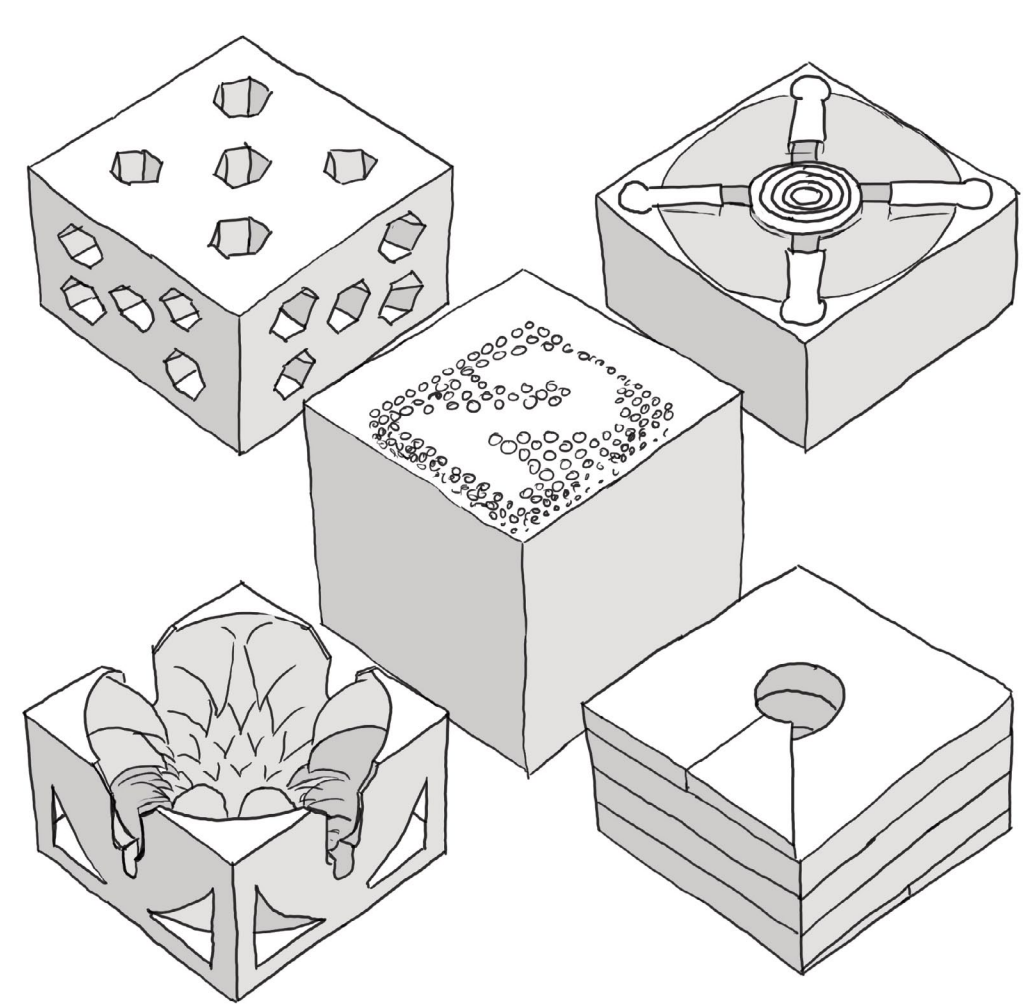
Figure 3.7 - Sketch concepts for the Hidden Novelty: Hidden Material Characteristics strategy.



Hidden Novelty: New Material that looks like Familiar Material (HN2)

- » “Fabric Falsification” - (HN2P1) - Using the texture of ABS printing and fabric simulations in order to visually suggest softness and familiarity.
- » “Frozen Reflection” - (HN2P2) - Create a structure using PPP printing that looks very similar to an ice cube but ends up actually being soft and warm.
- » “Liquid Hesitance” - (HN2P3) - Exploring the potential of ABS FDM printing to look like a thick, pasty liquid through simulations, attempting familiarity.
- » “Rubberised Geode” - (HN2P4) - Referencing crystal structures through the form as well as the optical quality of TangoPlus. The crystalline structure would actually be soft.
- » “Stress Stone” - (HN2P5) - Explore making PPP material variants look like stone. Explicitly explores form as well as surface texture.

Figure 3.8 - Sketch concepts for the Hidden Novelty: New Material that looks like Familiar Material strategy.



Hidden Novelty: Visual Illusion (HN3)

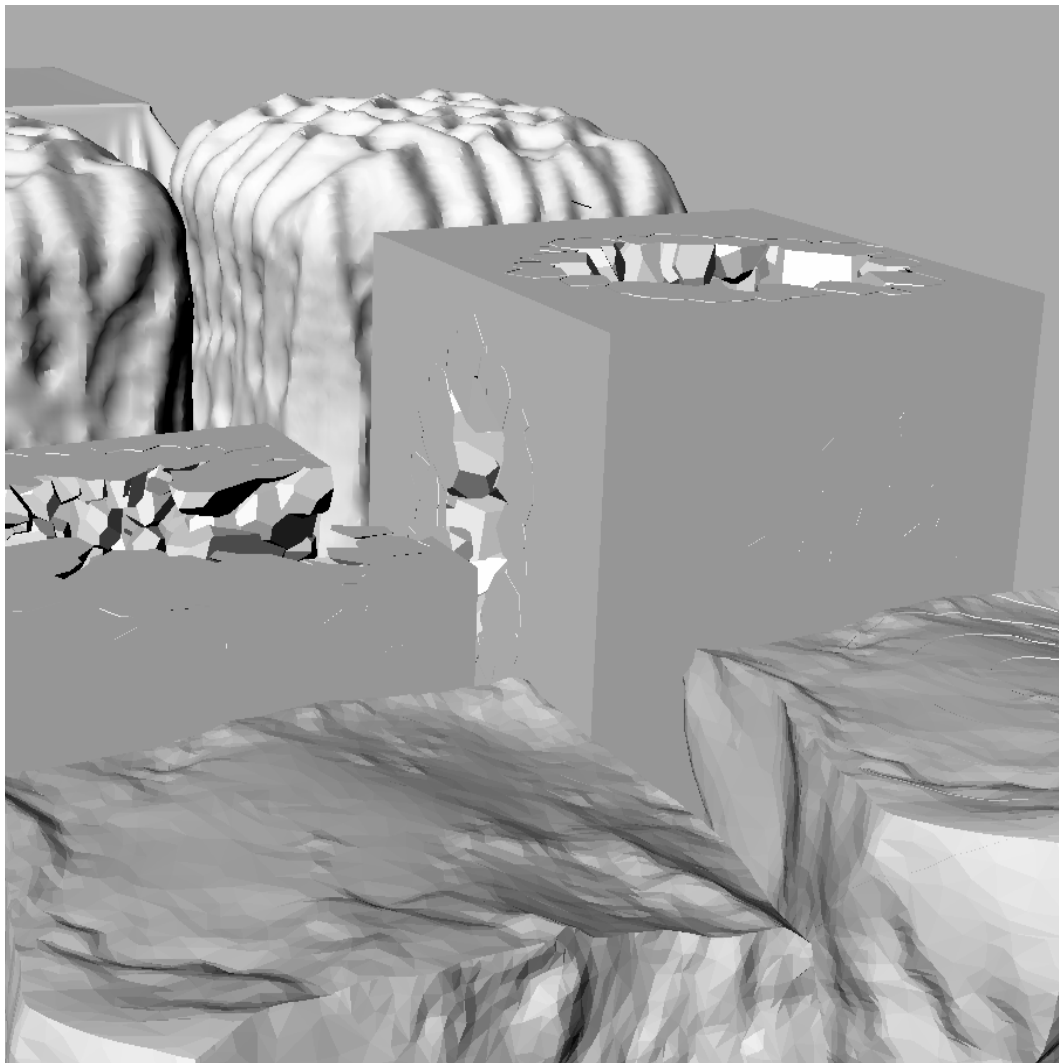
- » “Disconnected Light Tubes” - (HN3P1) - Create a cube with light tubes that are connected in abnormal ways, encouraging curiosity and exploration.
- » “Dynamic Button” - (HN3P2) - Create a single moving structure using PPP that reveals new components when a button is pressed.
- » “Illusion Die” - (HN3P3) - Explore the possibility of different points of view revealing different symbols to the user.
- » “Rubberised Thorns” - (HN3P4) - Create a cube that references hard, dangerous forms and have them revealed to be soft and pleasant.
- » “Spiral Collapse” - (HN3P5) - Create a form that looks like a textured cube, but that is actually revealed to be a dynamic and smooth spiralling structure.

Figure 3.9 - Sketch concepts for the Hidden Novelty: Visual Illusion strategy.

Approaches To Surprise 3D Printing Qualities	VN: Combination with Transparent Materials	VN: New Appearance for Known Product or Material	VN: Hidden Material Characteristics	
	Intangible Depth	Citrus Resistance Dynamic Onion	Compression Mozaic Hidden Red Peak	
	Intangible Depth	Citrus Resistance -Dynamic Onion	Compression Mozaic Hidden Red Peak	
	Collapsing Construct	Citrus Resistance Dynamic Onion	Compression Mozaic	
	Intangible Depth	Citrus Resistance Dynamic Onion	Hidden Red Peak	
Build internal structures or mechanisms.				
Build simultaneously with different materials showcasing distinct properties.				
Create gradients in material from hard to soft.				
Create gradients in material from almost clear to almost opaque.				
Create complex structures and textures with ease.				

Figure 3.10 - Morphological Analysis intersecting Ludden’s strategies with the potential qualities of 3D printing.

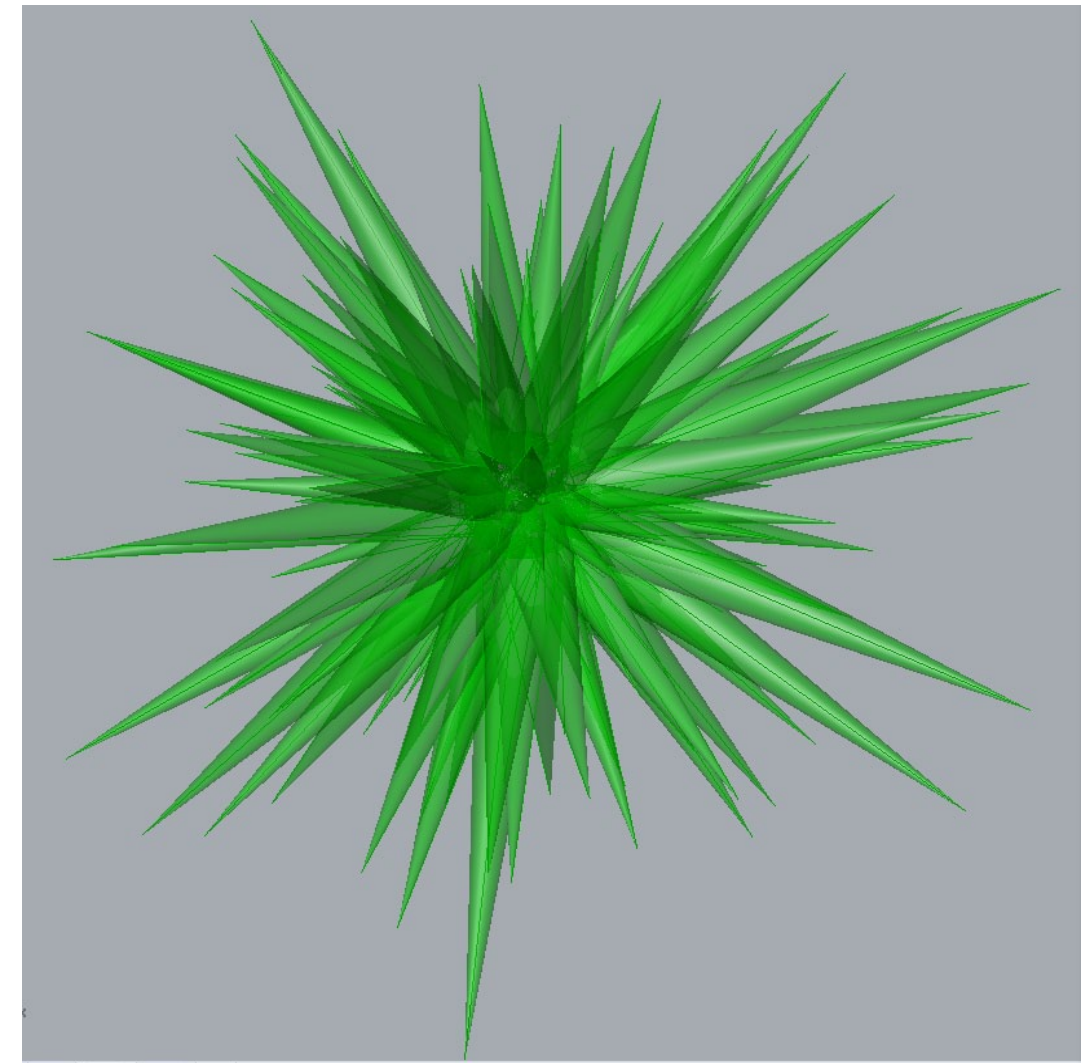
VN: New Material with Unknown Characteristics	HN: Hidden Material Characteristics	HN: New Material that looks like Familiar Material	HN: Visual Illusion
Collapsing Tubes	Hidden Articulation Twisting Expectation	Frozen Reflection Rubberised Geode	Disconnected Light Tubes Dynamic Button Illusion Die
Collapsing Tubes Dendritic Coral	Hidden Light Tubes Tentacle Grasses Textural Variance Twisting Expectation	Frozen Reflection Rubberised Geode Stress Stone	Disconnected Light Tubes Dynamic Button Illusion Die Spiral Collapse
Dendritic Coral	Tentacle Grasses Twisting Expectation	Rubberised Geode Stress Stone	Dynamic Button Illusion Die Spiral Collapse
Collapsing Tubes Dendritic Coral	Hidden Light Tubes Twisting Expectation	Frozen Reflection Rubberised Geode Stress Stone	Disconnected Light Tubes Illusion Die Rubber Thorns
Dendritic Coral	Tentacle Grasses Twisting Expectation	Fabric Falsifications Liquid Hesitance Stress Stone	Rubber Thorns



The previous table (figure 3.10) built on the Morphological Analysis (figure 3.3), identifying which of the 3D printing qualities each of the cubes most specifically targeted. Most of the cubes targeted more than one of the 3D printed qualities and as a result sat in multiple spots of the table. This table served as a clarifying tool comparing the 3D printed qualities with the sketch concept outputs of the Morphological Analysis.

After sketching, the process moved into 3D CAD modelling. The program used for design development was Rhinoceros (Referred to in this thesis as Rhino); a computer-based surface modelling program that excels at a rapid, iterative approach and can yield high resolution and exceedingly complex forms (figure 3.11). The employment of Rhino also allowed the use of a plug-in called Grasshopper. Grasshopper uses a visual coding interface that employs multiple

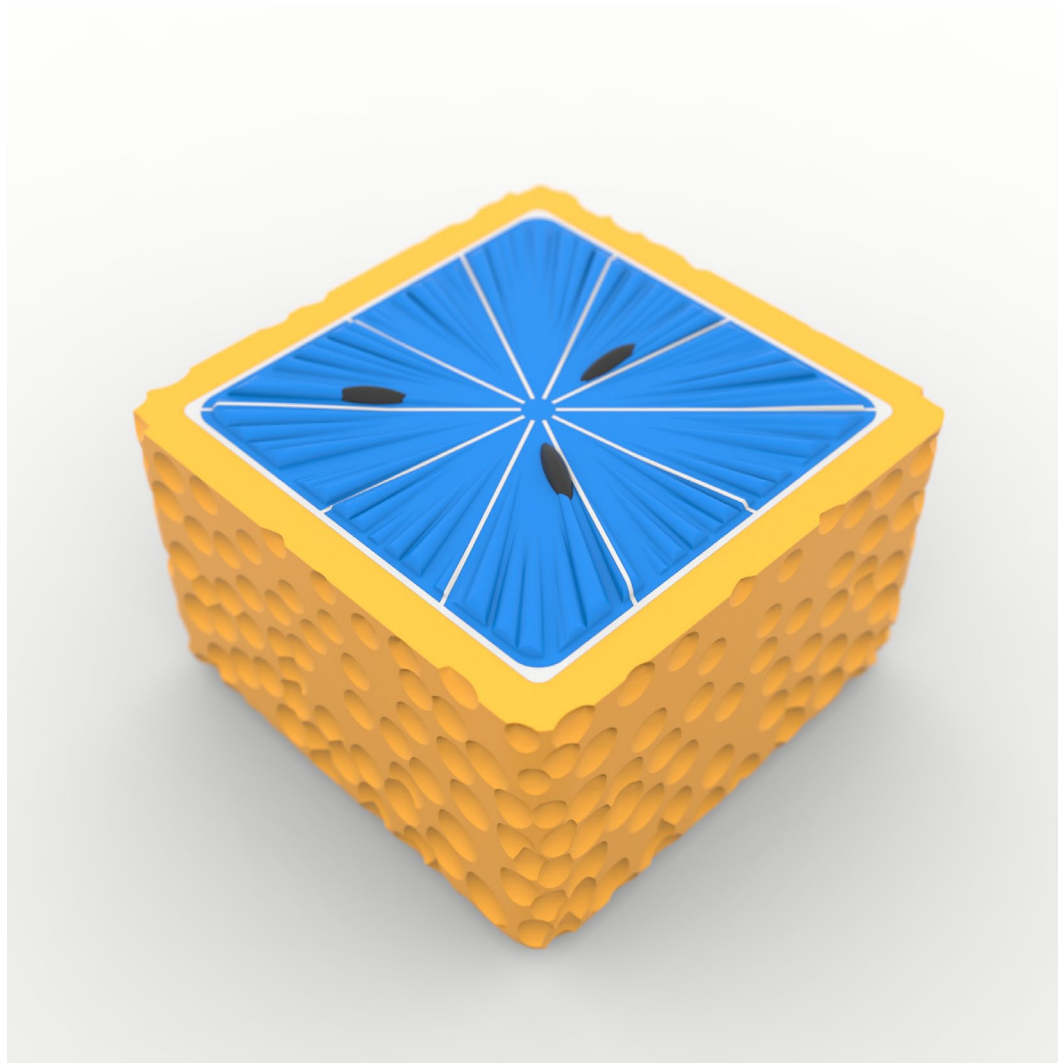
Figure 3.11 - Rhinoceros was an incredibly important tool for the development of the cubes, allowing rapid iteration and experimentation.



smaller functions in order to create a parametric system. A parametric system allows the designer to make changes to the fundamental starting conditions or rules of a design and have the final design output update to reflect these changes (Yassine, 2012, p. 543).

The use of a parametric system was key for the development of some of the cubes (figure 3.12), as it allowed for massive complexity to be built into the models. Certain cubes had aspects of their design based off initial parameters which allowed small, incremental changes to the designs to be facilitated easily and quickly without much effort. Grasshopper additionally made it easy to generate flocks of objects based off the same starting conditions (such as in a texture), by incorporating small alterations to each, ensuring that each form was unique and reducing the unnatural uniformity of the flock. This diversity

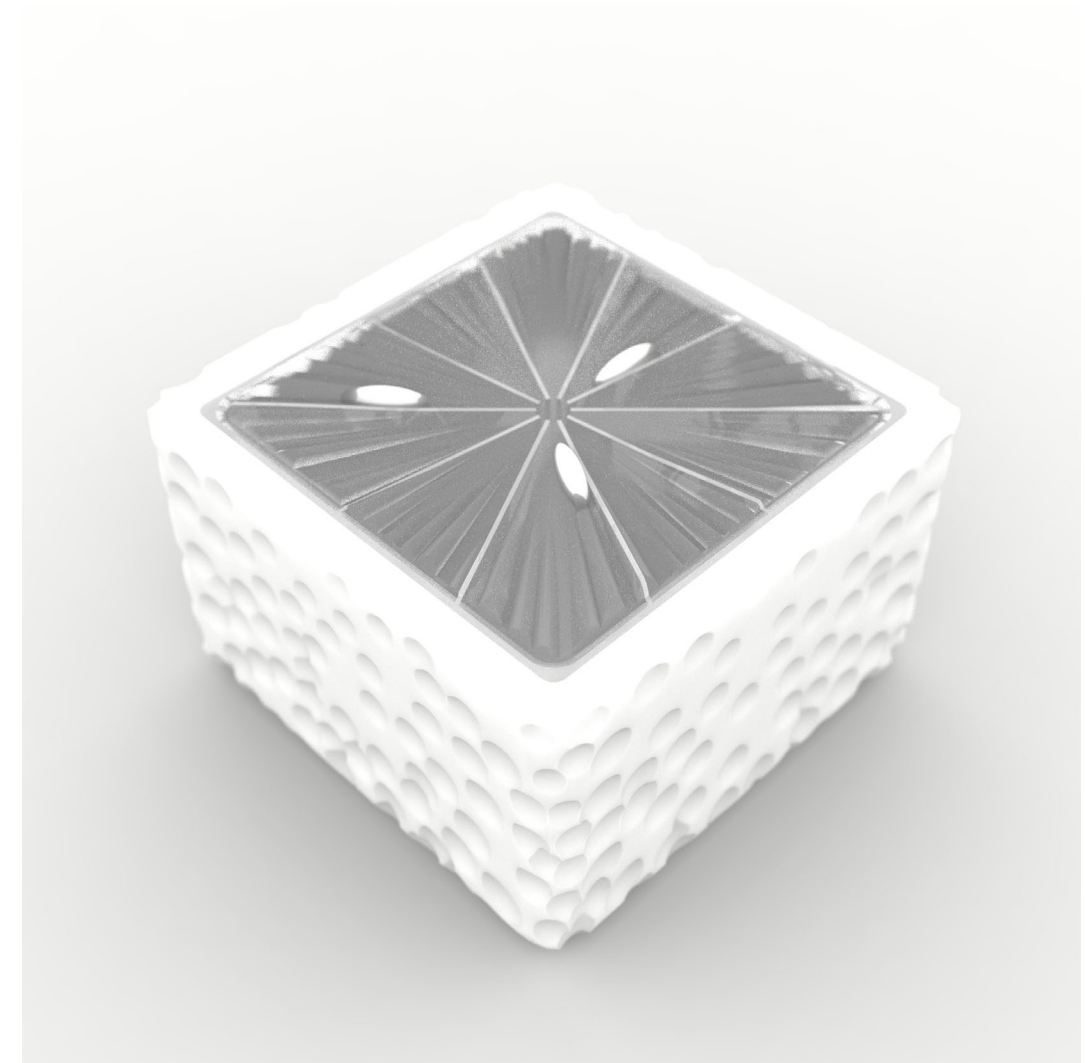
Figure 3.12 - Process images showing the employment of Grasshopper for exceedingly complex geometry that would eventually find its way into Frozen Reflection.



was akin to the natural variance of individual plants or animals within the same species, and would have been challenging and time-consuming to CAD model traditionally.

Incorporating the multi-material capabilities of the Connex PPP printer was an aspect of the process that had to be considered at various stages of CAD modelling. In order to define multiple materials in a 3D print, the user has to produce separate 3D models that are all part of an assembly: A collection of files that all contribute to a single continuous print. These models occupy the same area in virtual space; often sitting inside and in between each other, with their surfaces in direct contact (figure 3.13 & 3.14).

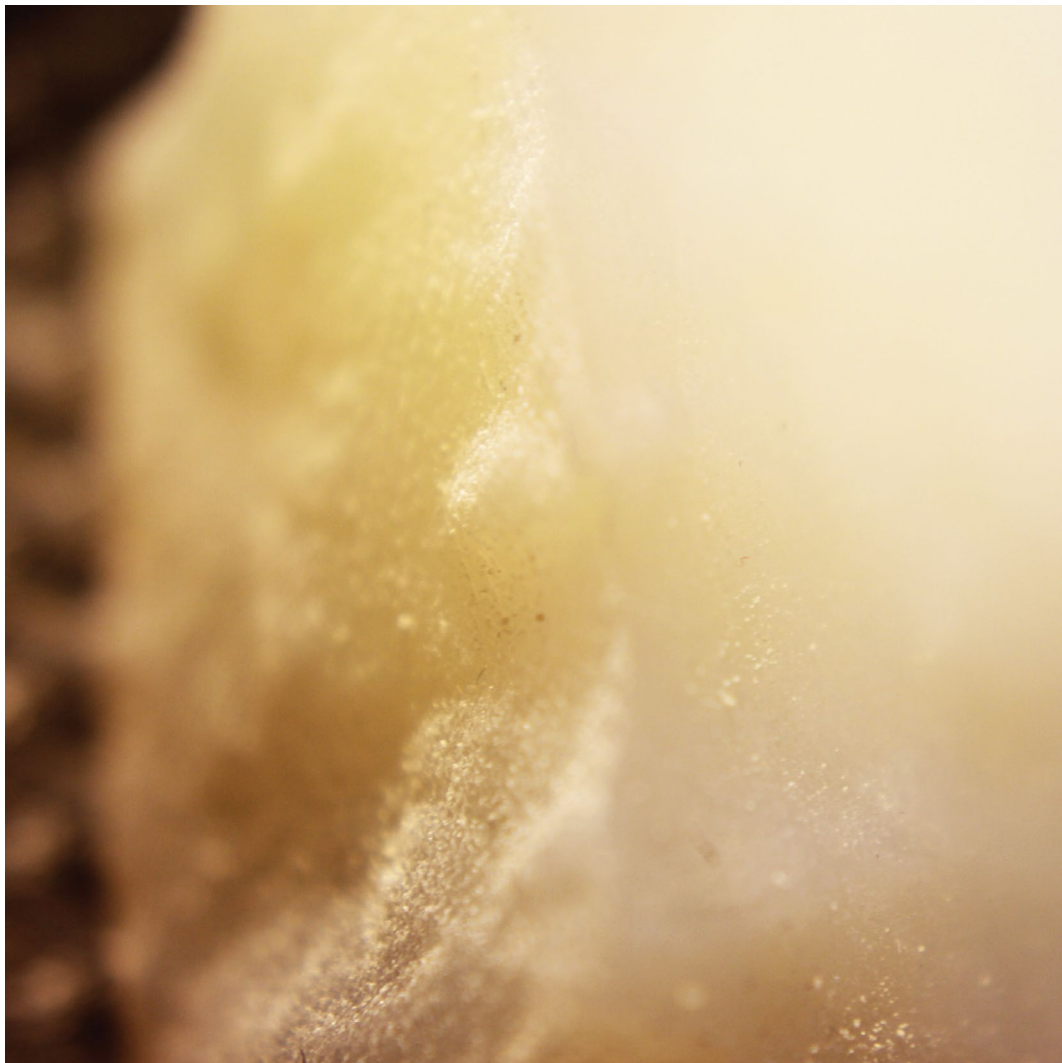
Figure 3.13 - False-colour renders showing the complexity of designing in volumes for multi-material PPP printing.



In order to effectively leverage the capabilities of the printer, these boundary surfaces are accurate to thousandths of a millimetre. If there is a gap between the surfaces of the different parts in an assembly, then this void will be filled with support material and the models will not form a continuous solid volume and can fall apart.

This can however also be an exceedingly useful quality, because if exploited properly, with carefully defined tolerances, it can allow the print to incorporate moving joints. This enables manufacturing of structures that are impossible with any other manufacturing techniques. By combining the different materials and their blends, it allows the creation of materials with some unique optical and tactile qualities (figure 3.15).

Figure 3.14 - This render showcases the more realistic difference in materials.



Development: User Testing Procedure

Once the models were complete, they were tested with users. The purpose of the testing process was to evaluate the prototype’s potential to elicit a VTI, gauge emotional responses, and collect outside perspectives. This user testing was focussed around the point of first encounter. Dissecting the components of a VTI was done by looking first at the participant’s visual encounter, and their subsequent tactile interaction.

The testing process followed a procedure similar to Evaluative Research or Product Testing (Kittur, Chi, & Suh, 2008, pp. 453-456). This, in combination with a semi-structured interview let the participants verbalise their thoughts

Figure 3.15 - Close-up material shots showing the difference in visual qualities between the blends of VeroWhite and TangoPlus.

Participant _

Prototype _ (_N_P_)

1. What does the prototype look like it will feel like?

Soft

○ ○ ○ (↕) ○ ○ ○

neither

both

Hard

Textured

○ ○ ○ (↕) ○ ○ ○

neither

both

Smooth

2. Having tactually explored the prototype, what does it feel like?

Soft

○ ○ ○ (↕) ○ ○ ○

neither

both

Hard

Textured

○ ○ ○ (↕) ○ ○ ○

neither

both

Smooth

3. Were your answers to question 1 and 2 different? Tell the researcher your thoughts about the prototype.

4. How would you emotionally define your experience with this prototype?

Anger

Hate

Contempt

Disgust

Fear

Negative Surprise

Disappointment

Shame

Regret

Guilt

Sadness

Compassion

Relief

Admiration

Love

Contentment

Positive Surprise

Pleasure

Joy

Pride

Amusement

Interest

None

Other

5. If you answered "Other" to question 4, what emotion(s) did you feel?

Figure 3.16 - Questionnaire used for User Testing, showing the use of a scale for assessing visual and tactile appraisals, as well as the use of the GWOE.

DESIGN / TEST RESULTS

and opinions regarding their interactions and subjective experiences with the prototypes. This was supplemented with self-reporting; which took the form of Questionnaires (Robsons & McCartan, 2016) that included a scale for subjectively assessing perception of softness or hardness, as well as smoothness or texture. The questionnaire also incorporated the Geneva Wheel of Emotions (Scherer, 2005, pp. 720-725) for each cube. The purpose of the GWoE was to allow for a self-reported numerical assessment of the participants emotional responses. The tool was modified to include “Positive Surprise” and “Negative Surprise” on the wheel, as a way of gaining a self-reporting angle on the participants sense of their own surprise.

In order to effectively test with participants, I specifically recruited participants who had little to no contact with 3D printing. By ensuring my participants were unfamiliar with the process, I could gather data that could be representative of people who were unfamiliar with 3D printing. Recruitment was done verbally as well as through social media. All related ethics documents can be found in Appendix Item 1.

This section discusses the data collection procedure, as well as the final outputs (Collection 2).

User Testing & Data Collection

The user testing investigated user’s visual perception, tactile perception, and their emotional response to the prototypes. The process after the consent signing and reading of information forms was as follows:

1. The participant sat across the table from the researcher. The researcher had all the prototypes under a shroud, so that the participant could not see them or their shape (a box was used).
2. One prototype was slid out from beneath the shroud on a piece of paper and placed in front of the participant. At no point was the participant told the name of any of the prototypes. Moving the model on the paper was done to ensure that the participant would not see anyone touch it before they did. The participant was not allowed to touch it initially, but they were allowed to move around, altering their perspective of the object.
3. The participant was asked to report on their visual appraisal by filling out Question 1 (*What does the prototype look like it will feel like?*) in the questionnaire.
4. The prototype was pushed over to the participant and they were allowed to pick up and tactually inspect the prototype. Any exclamations or verbal responses upon inspecting the prototype were noted.
5. The participant was asked to fill out Question 2 (*Having tactually explored the prototype, what does it feel like?*) in the questionnaire and report verbally on their thoughts for Question 3 (*Were your answers in question 1 and 2 different? Tell the researcher your thoughts about the prototype.*). The participants verbal responses were noted.

6. The participant was asked to fill out Question 4 (*How would you emotionally define your experience with this prototype?*) in the questionnaire, which used the GWoE for gathering responses to the prototype. They were allowed to pick up and inspect the model again if they needed to refresh their memories.
7. After completing the questionnaire for that prototype, the prototype was placed back on the paper and returned beneath the shroud.
8. The participant and researcher repeated this process for all of the 23 prototypes.
9. After the study was complete, there was an opportunity for the participant to ask any questions about the prototypes, see all the prototypes again, and receive information on the thesis itself.

Once all the data from all the participants was collected, all the numerical data was entered into a spreadsheet. There, the data was laid out according to the questions in the questionnaire as well as the responses to the GWoE. The responses from the 10 different participants were then aggregated by averaging the responses across each of the questions. The mean of the participants' responses for each emotion on the GWoE (Question 4) were calculated, in order to create an 'average' emotional response for each prototype. Answers for the 'other' component of the question (Question 5) were also collected and collated. Once the average emotional responses had been collated, the components of the GWoE were split into two groups: cumulative positive valence emotions and cumulative negative valence emotions. Each of these groups represented their respective halves of the GWoE; the right side being positive and the left side being negative. This gave a general sense of whether the average response to each prototype was more positive or negative. These values were simply all of the GWoE averages of that half of the circle added together. These values had a possible maximum of 66, with each of the individual emotional values having a possible maximum of 6.

The responses to the questions regarding softness, hardness, smoothness and texture were then compared. The first question (Question 1); answered based solely on a visual appraisal, was compared to the responses given based on the tactile appraisal (Question 2) after the participant was allowed to interact with the prototype. If there was no incongruity and the material was as expected, then the responses should have been similar. The numerical difference between these two answers were noted as 'points of change'. For example; if a participant visually thought the prototype was 2 points from center towards hard (recorded as +2), and then found the prototype was 3 points from center towards soft (recorded as -3), this was registered as a change from +2 to -3. This was resultantly calculated as a change of '-5 points of change' on the 'soft/hard' perception shift. Both the 'both' and 'neither' responses were recorded as 0. The more points of change, the stronger the shift from the visual perception to the tactile perception, and the stronger the visual-tactile-incongruity.

Final Outputs & Data Representation

In order to provide a better overview of the final physical outputs of Phase 1 as well as a comprehensible view of the prototype-specific data derived from the user testing, the two sections have been merged. A photo of each 3D printed prototype is presented alongside the data for that prototype to allow for more legibility. Each of these spreads will be accompanied by three questions highlighting details on each prototype as well as noteworthy verbal quotes from the user testing. The questions that asked of each prototype were:

- » What was the approach to the VTI Strategy?
- » What was the tangible interaction?
- » Were there any qualities revealed by light?

The data that is presented is:

- » The Geneva Wheel of Emotions; showing the average emotional response for that prototype. (Represented in a polar diagram; a natural fit for the GWoE)
- » The average soft/hard perception shift of the participants for that prototype. (Represented in a small bar chart, showing the pre- and post-interaction perception)
- » The average textured/smooth perception shift of the participants for that prototype. (Represented in a small bar chart, showing the pre- and post-interaction perception)

Included with the data and photos are some of the comments made by the participants.

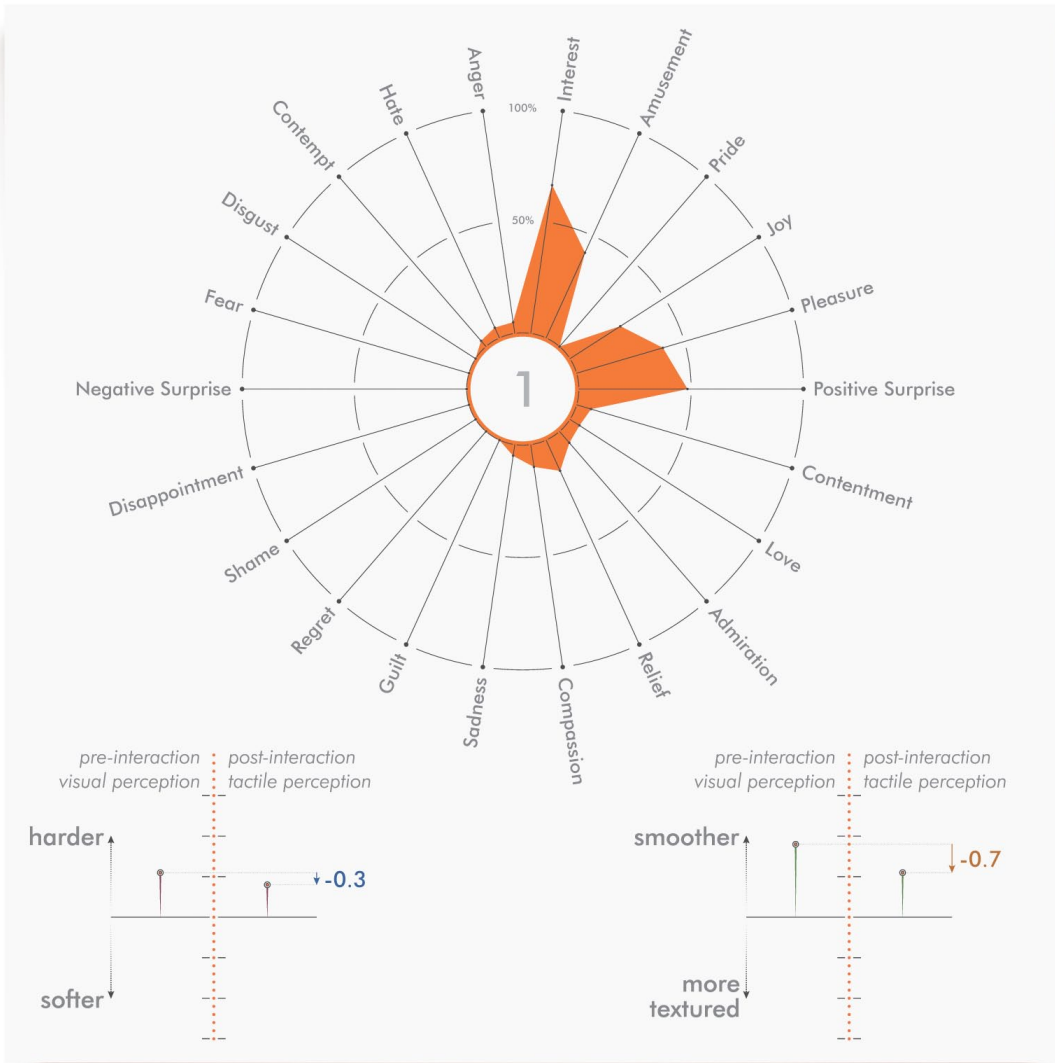


Figure 3.17 - The full Collection Two.



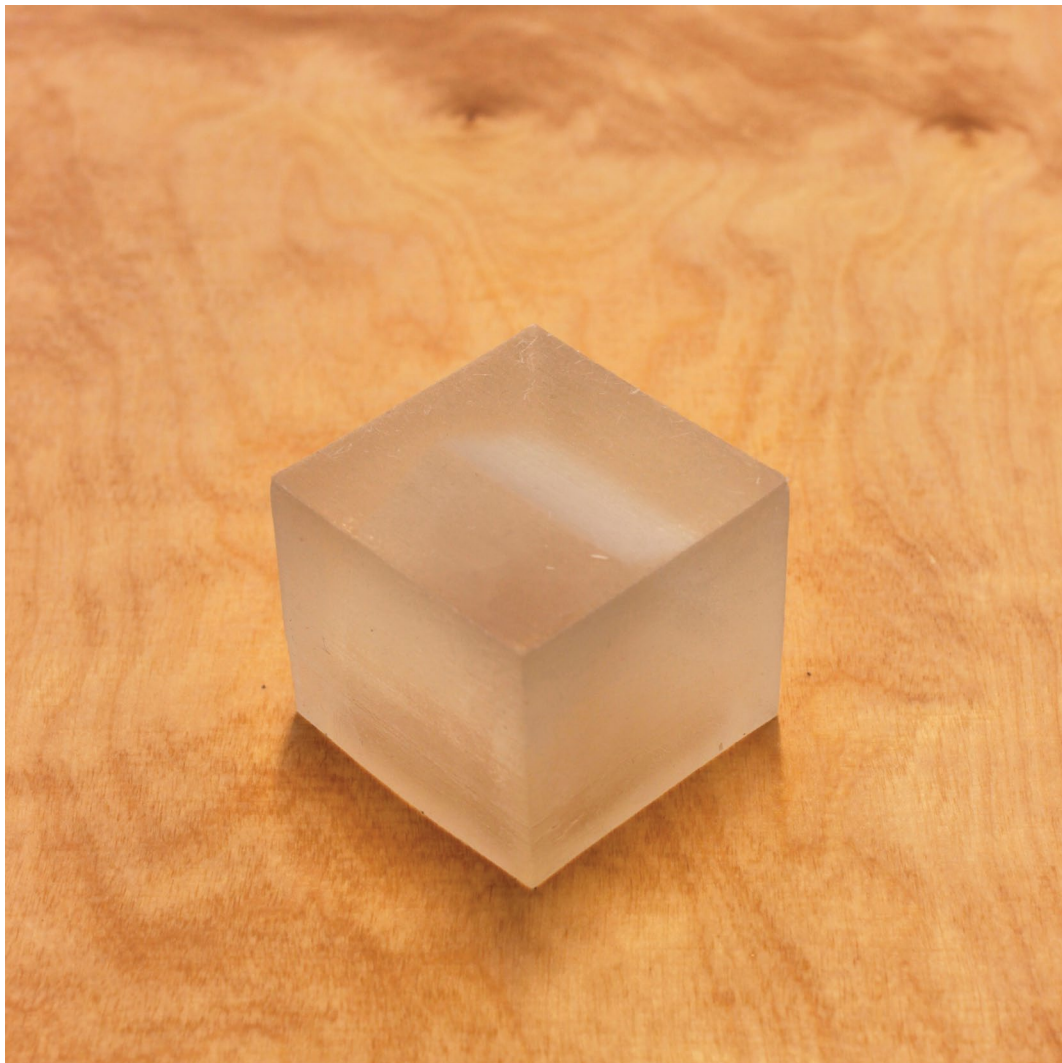
- Visible Novelty: Combination with Transparent Materials (VN1)**
Intangible Depth - (VN1P1)
- 1. To explore the effect a gradient of transparent material could have on depth perception.
 - 2. The transparent soft sections can be squeezed by the user as a way of gauging the shape of the filled space.
 - 3. Due to the shape of the two transparent sections, when a light is moved along the model, the way that the light permeates the model changes dramatically. The user can use the shadows from their hands to gauge the shape of the transparent sections.

Figure 3.18 - VN1P1: Intangible Depth



- "It's heavier than expected, and I thought it was going to be concave, not flat!"*
(Participant 2)
- "Oh my... I thought it was going to be completely solid!"*
(Participant 5)
- "It looked hard, but it's so squishy!"*
(Participant 7)
- "I thought I saw texture, but it's smooth."*
(Participant 10)

Figure 3.19 - VN1P1 failed to reveal a significant emotional response, and did not elicit a notable VTI.



**Visible Novelty: Combination with Transparent Materials (VN1)
Collapsing Construct - (VN1P2)**

- 1. To explore the potential for a textured transparent material to imply a filled space.
- 2. Due to the space in the middle of the model not actually being filled by anything, when squeezed by the user the structure collapses inwards with ease.
- 3. The texture on the inside of the experiment was designed to catch the light in a way that made it look like there was a solid object inside the form. The texture made the inner edge of the form more reflective, suggesting another kind of surface.

Figure 3.20 - VN1P2: Collapsing Construct



"It's hollow! I thought there was something inside it."
(Participant 1)

"It's like a rubber ball-like toy I used to have as a kid."
(Participant 3)

"Oh! I thought it was going to be solid!"
(Participant 5)

"It looked sharp and hard-edged!"
(Participant 6)

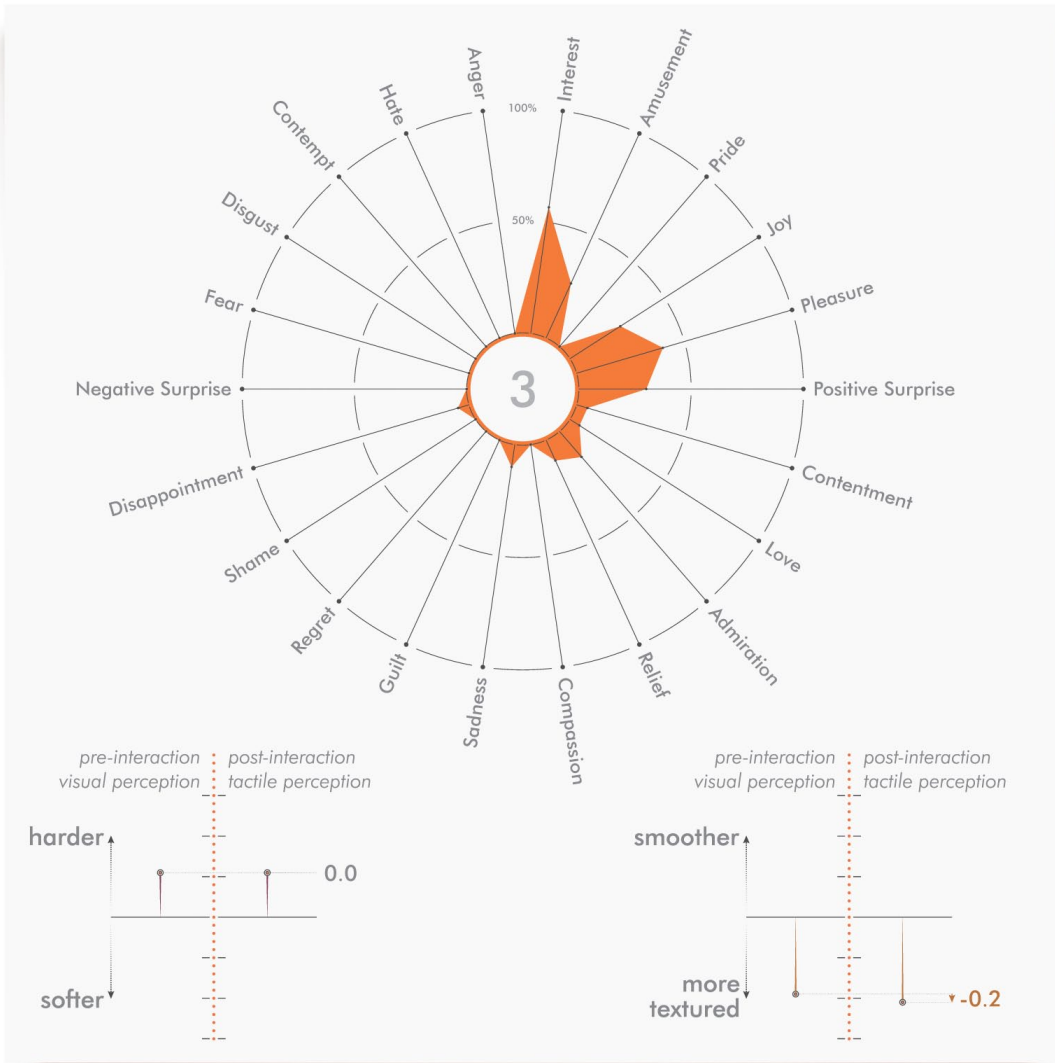
Figure 3.21 - VN1P2 was found by all participants to be softer than anticipated, and the emotional response was largely positive.



Visible Novelty: New Appearance for Known Product or Material (VN2)
Citrus Resistance - (VN2P1)

- 1. To explore how texture and variable hardnesses could make an object feel like citrus fruit.
- 2. When squeezed or touched, the 'feel' is very similar to that of a lemon. The various sections of the model use different hardnesses and this can be 'felt out' by the user.
- 3. Due to the various combinations of materials used, the light permeates the model to varying degrees when lit from different angles. The light also reflects strongly off some of the more opaque parts.

Figure 3.22 - VN2P1: Citrus Resistance



"Oh...I see. It's like a lemon. The top texture is really nice."
(Participant 1)

"It squeezes like a lemon! But it's so rubbery..."
(Participant 3)

"The texture is really interesting along the top..."
(Participant 6)

"The outer layer is so pitted! It makes it really solid too."
(Participant 10)

Figure 3.23 - VN2P1 elicited a lacklustre emotional response, and did not elicit a notable VTI.



Visible Novelty: New Appearance for Known Product or Material (VN2)
Dynamic Onion - (VN2P2)

- 1. To explore how a visual use of variable 3DP materials could make an object look like an onion, but feel completely different.
- 2. While looking very similar to an onion, the feel is completely different. The various layers alternate between hardnesses and create interesting points of flex.
- 3. Due to the concentric layering of the various materials, when illuminated along the side of the model the light curves through the clearer parts of the model while only partially permeating the more opaque sections.

Figure 3.24 - VN2P2: Dynamic Onion



"It's got a really weird texture...I can see the ridges along the side"
(Participant 4)

"I really like these see-through sections."
(Participant 5)

It's hard and flimsy in really weird ways..."
(Participant 10)

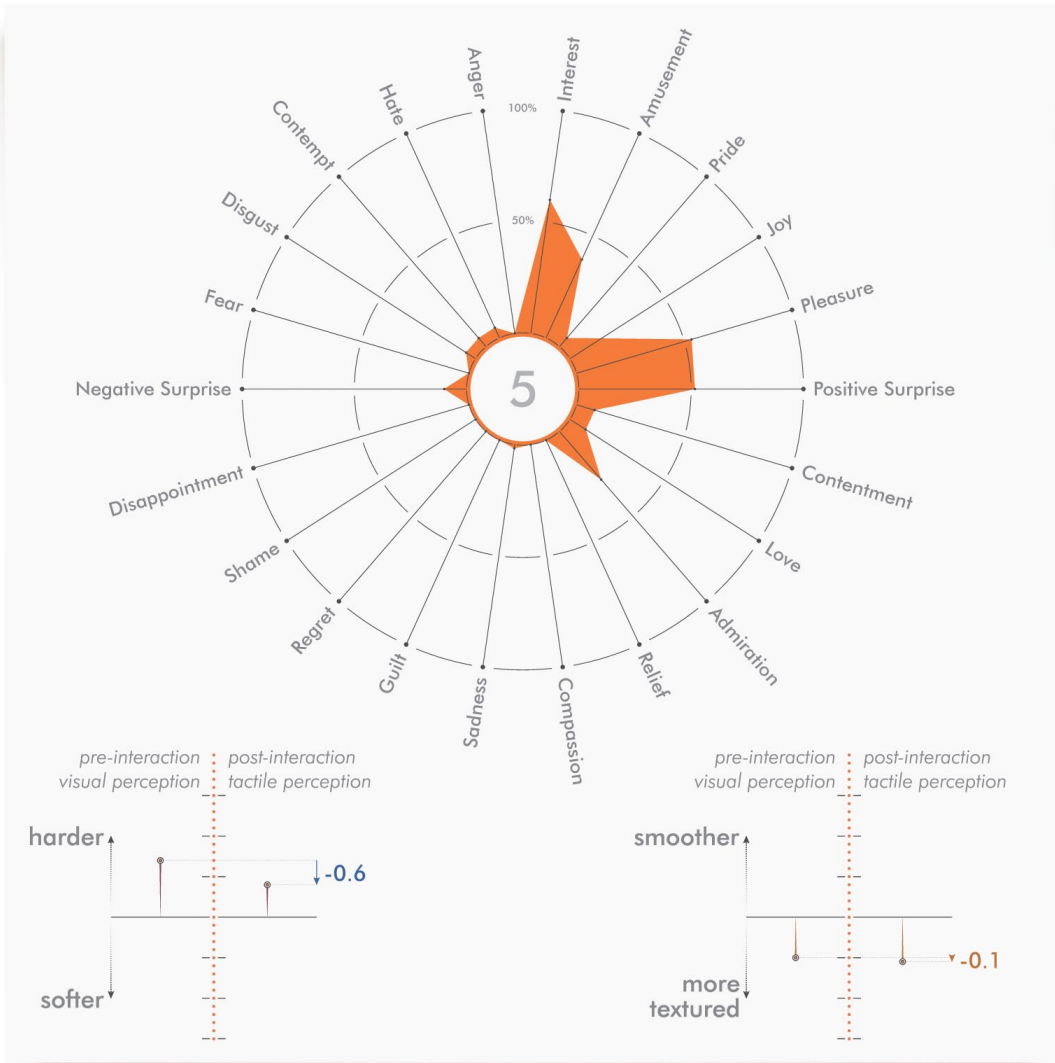
Figure 3.25 - VN2P2 elicited a largely lacklustre emotional response, and did not elicit a notable VTI.



Visible Novelty: Hidden Material Characteristics (VN3)
Compression Mosaic - (VN3P1)

- 1. To explore how material properties could be hidden in order to give other materials properties they do not have.
- 2. The tile-like structures of the model are hard, but the individual tiles all rest on a soft bed, giving the collection of tiles a sense of softness.
- 3. The internal spaces of the model being filled by a material of a different opacity means that by using light you can reveal some of the internal geometries of the design, as well as being able to change the light permeation with pressure.

Figure 3.26 - VN3P1: Compression Mozaic



“Ugh. It’s frustrating. It’s like it’s almost squishy but not quite.”
(Participant 1)

“Is it hollow? It feels like it’s hollow.”
(Participant 2)

“This one is really interesting. How far can I squeeze it? It’s hard but soft as well!”
(Participant 8)

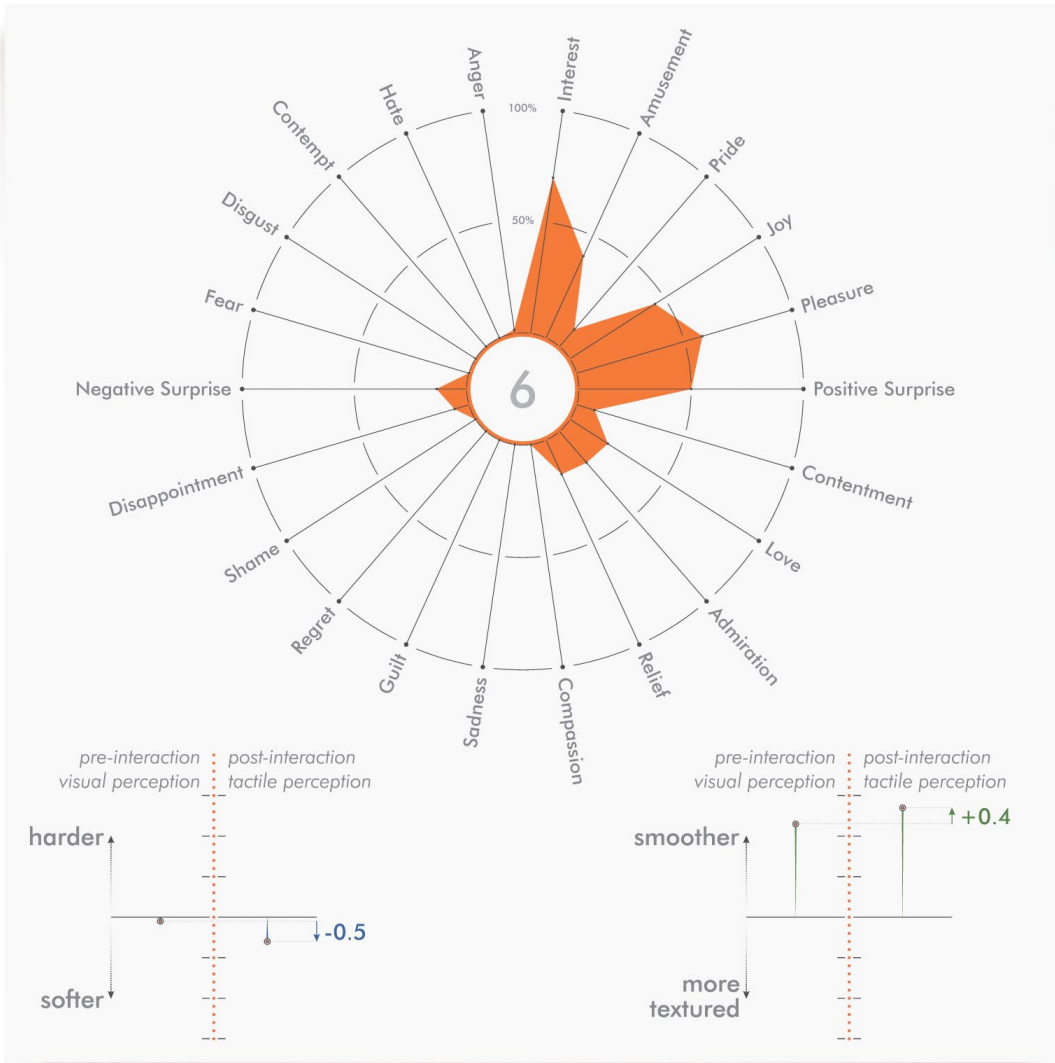
Figure 3.27 - VN3P1 was a favourite for some, but most were not particularly taken by it, and it did not elicit a notable VTl.



Visible Novelty: Hidden Material Characteristics (VN3)
Hidden Red Peak - (VN3P2)

- 1. To explore how an image or symbol could be hidden in such a way that it was only visible from one specific angle.
- 2. The individual hard white sections are embedded within a large section of soft material, allowing the pieces to be pushed around and felt by the user.
- 3. When carefully illuminated with a point light source from the right angle, the model can almost function as a projection slide, allowing a soft outline of the hidden symbol to be shown.

Figure 3.28 - VN3P2: Hidden Red Peak



“It’s softer than I thought it would be, and I can almost feel the parts inside!”
(Participant 2)

“What’s the deal with the parts inside? It looks like some sort of shape.”
(Participant 6)

“Oh wow! Is that Red Peak?? That’s amazing. The parts move around as I squish it.”
(Participant 8)

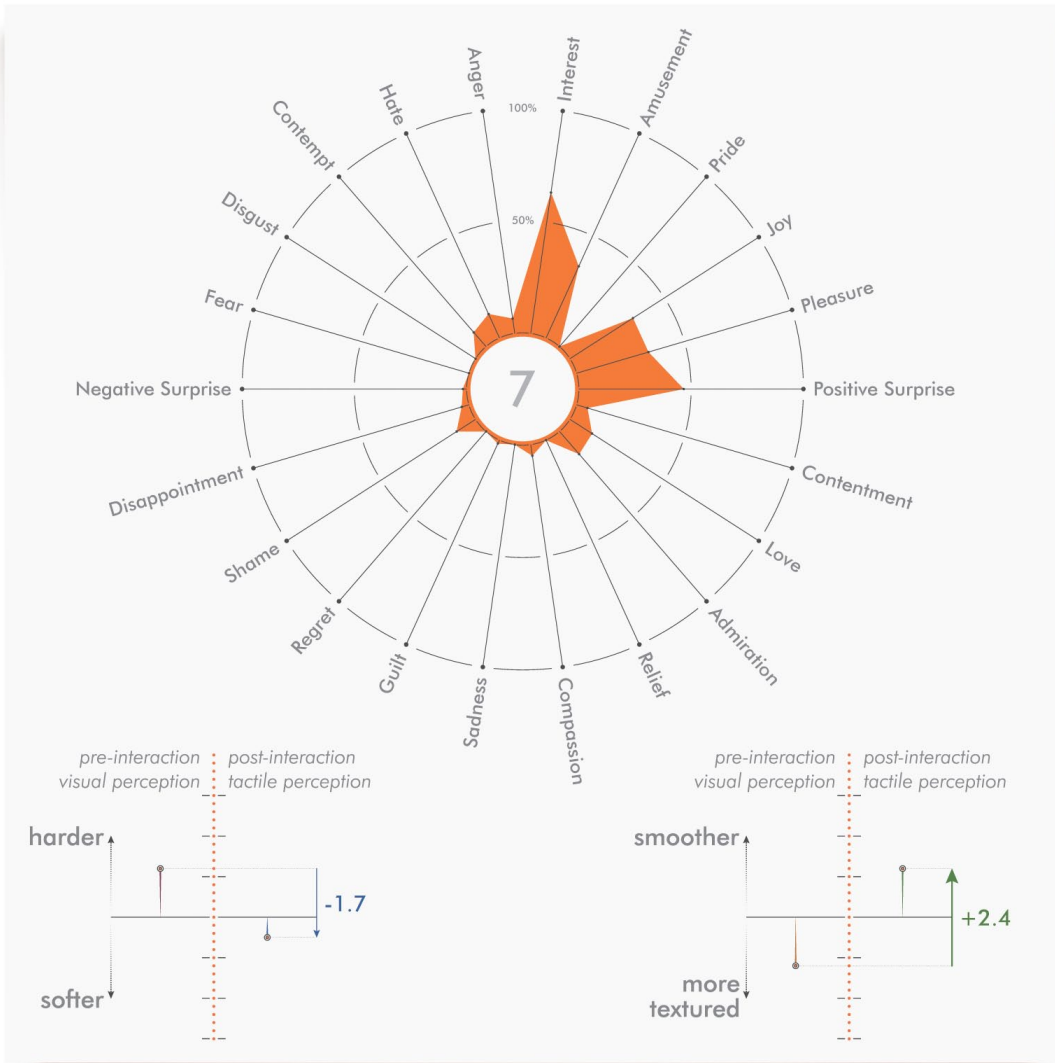
Figure 3.29 - VN3P2 elicited a reasonably positive response, and did not elicit a notable VTI



Visible Novelty: New Material with Unknown Characteristics (VN4)
Collapsing Tubes - (VN4P1)

- 1. To explore how the varying use of two different materials could affect how compressible a structure is.
- 2. Different tubes are more or less resistant to being squashed, depending on the density of the rods of white material.
- 3. Collapsing the tubes means that the way the light passes through the model changes, also the hard white sections tend to retain the light and glow, while the clear lets the light pass through.

Figure 3.30 - VN4P1: Collapsing Tubes



"What. It doesn't look smooth but it really is..."
(Participant 1)

"Those ridges look so sharp though...and the whole thing squishes down too!"
(Participant 2)

"It looks like pasta! I really expected to feel the texture on the sides."
(Participant 4)

"Ooh it's so weird! The way the different parts squash down is really cool."
(Participant 10)

Figure 3.31 - VN4P1 elicited a lacklustre emotional response, and most participants found it smoother than anticipated.



Visible Novelty: New Material with Unknown Characteristics (VN4)
Dendritic Coral - (VN4P2)

- 1. To explore how the textured use of a second material could affect the perceived hardness of a structure.
- 2. The surface of the structure is covered by thousands of dots of hard material while the structure itself is soft. This creates a sense of the surface being harder than it really is and giving it an intense texture.
- 3. Light actually makes the structure more easy to visually understand, because it picks up the small dots of hard material quite well.

Figure 3.32 - VN4P2: Dendritic Coral



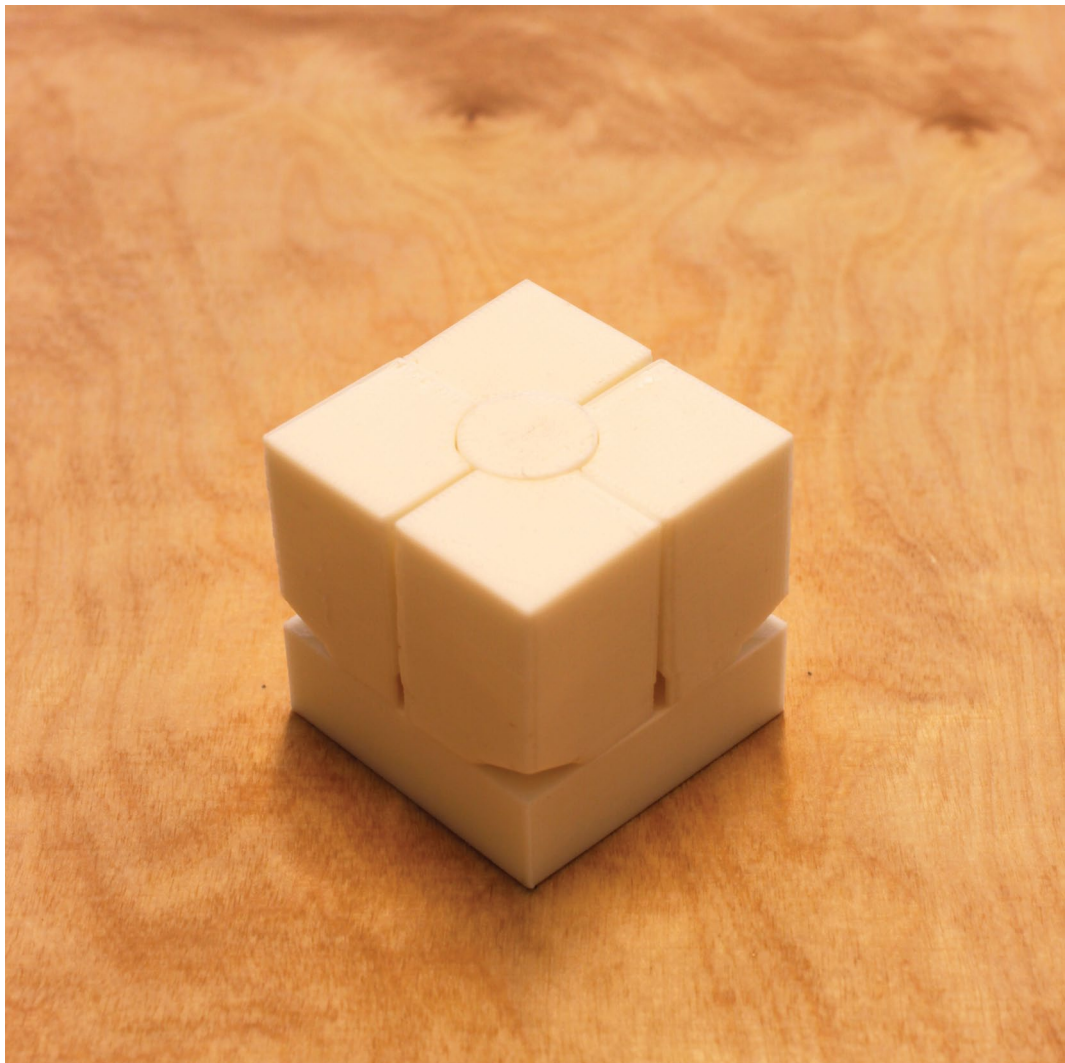
"Oh man this is so satisfying to play with. It's so rough!"
(Participant 1)

"It looks like coral...but it's soft!"
(Participant 2)

"It kind of reminds me of a sea anenome...the thing from Finding Nemo?"
(Participant 4)

"It's like a gummy sweet. It's got this weird double texture going on."
(Participant 10)

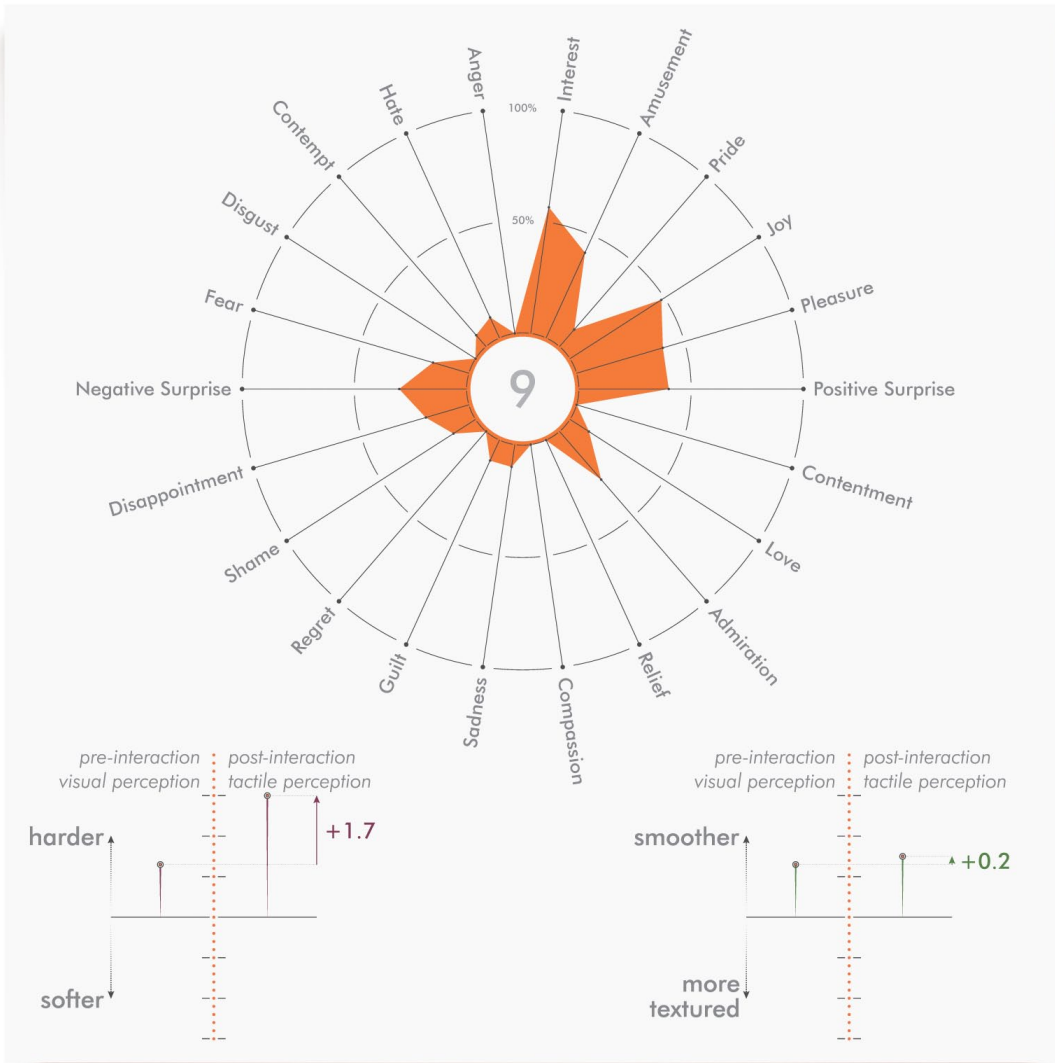
Figure 3.33 - VN4P2 elicited the most positive response out of any of the prototypes, and did not elicit a notable VTI.



Hidden Novelty: Hidden Material Characteristics (HN1)
Hidden Articulation - (HN1P1)

- 1. To explore how extensive mechanical operation could be hidden.
- 2. The button in the middle invites the user to touch it, and when they press it, the internal mechanisms engage and make the design explode and fall apart.
- 3. The ABS is very opaque compared to the models made through PPP, and casts heavy shadows.

Figure 3.34 - HN1P1: Hidden Articulation



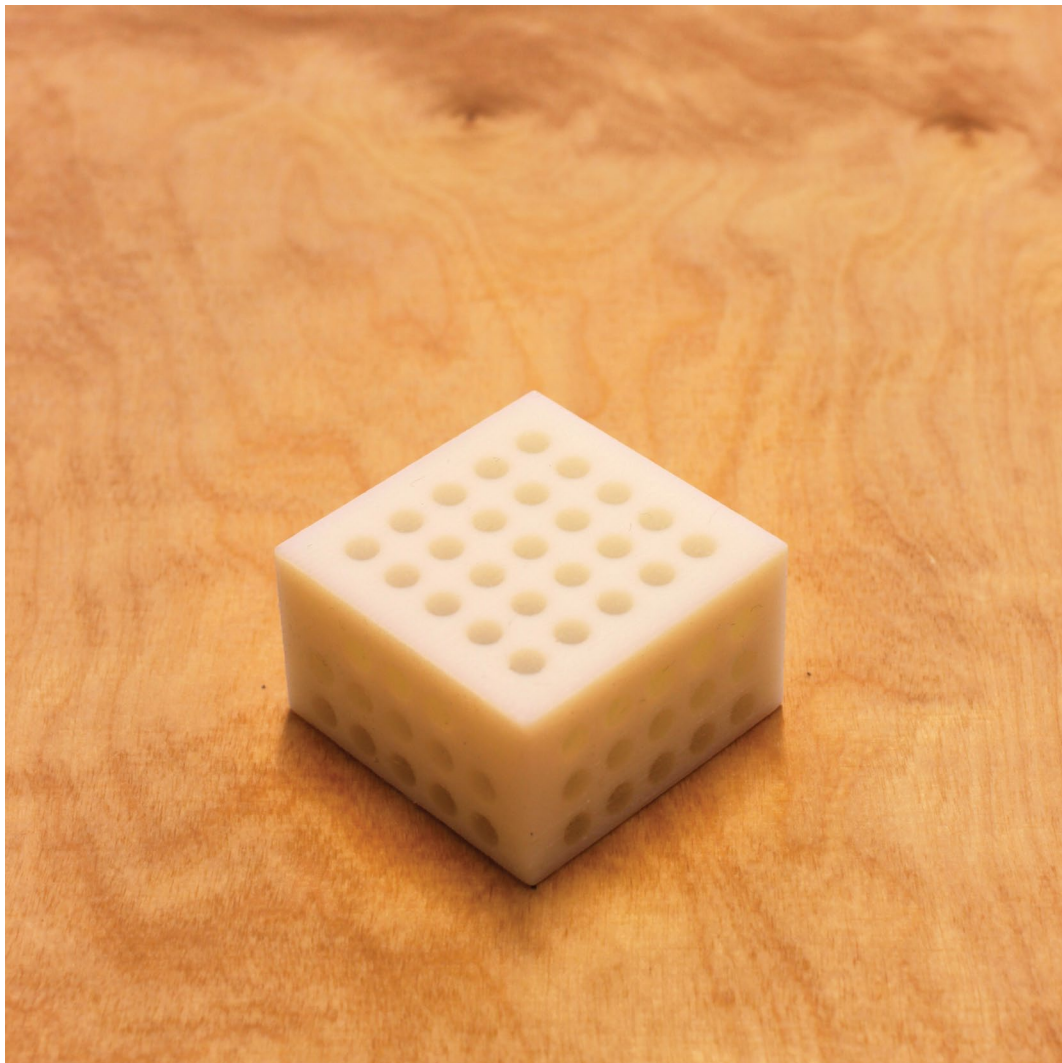
"This one makes me really nervous. I don't know why, I just really don't like it."
(Participant 2)

"It looks like tofu. But I'm sure it's not tofu hahaha."
(Participant 3)

"Oh my god I hate this one. That scared me."
(Participant 6)

"I love that how intricate the parts are."
(Participant 7)

Figure 3.35 - HN1P1 elicited the most negative emotional response out of any of the prototypes, and did not elicit a notable VTI.



Hidden Novelty: Hidden Material Characteristics (HN1)
Hidden Light Tubes - (HN1P2)

- 1. To explore how the transparent material could effectively be designed to transmit light.
- 2. The large panel of transparent soft material on the underside had division points where the hard material begins to form into the tubes visible on the other sides, forming a textured soft surface.
- 3. The light emanated throughout the model, but was most apparent and bright where the ends of the tubes met the surface.

Figure 3.36 - HN1P2: Hidden Light Tubes

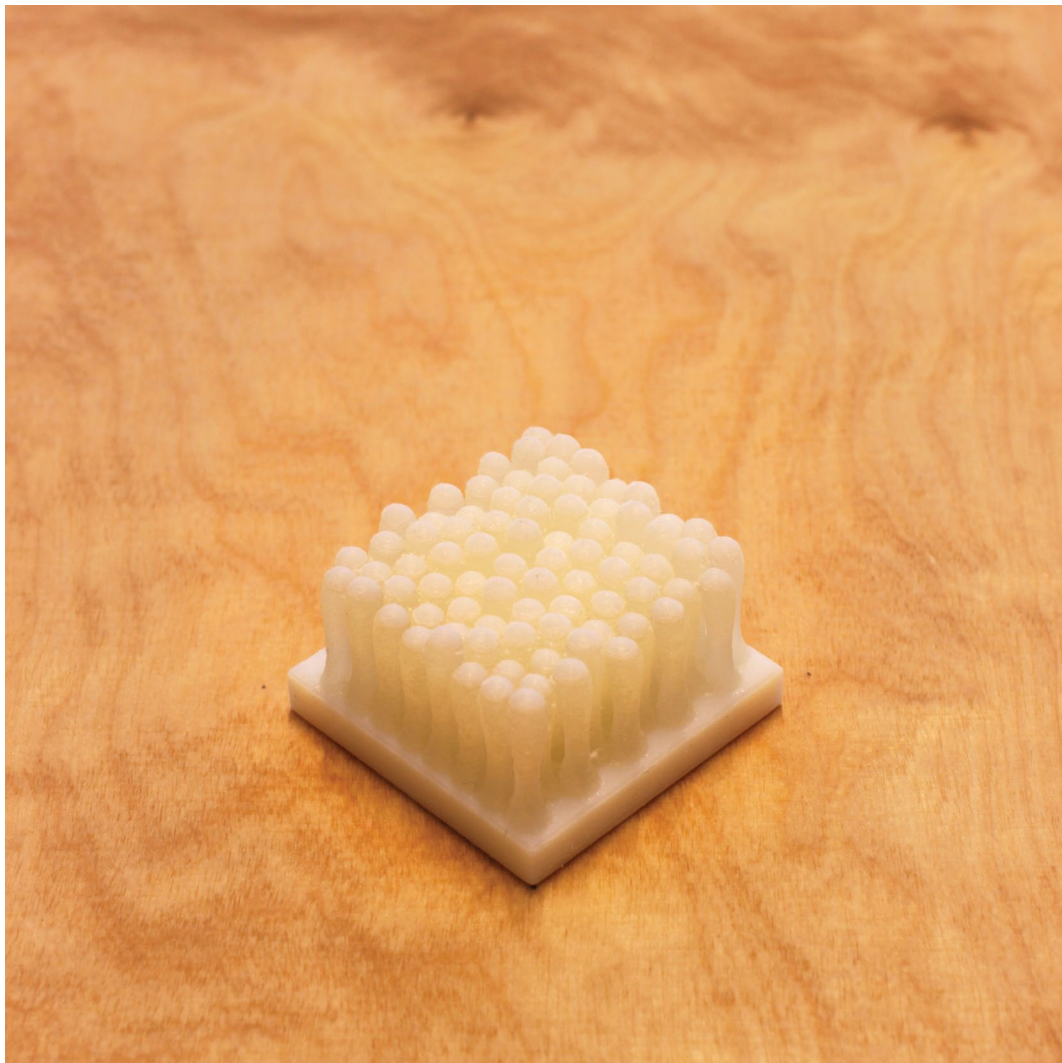


"Oh, weird! I thought the holes were hollow. But they're filled with soft stuff."
(Participant 2)

"If I hold this one up to the light, the patterns are so interesting!"
(Participant 6)

"I so don't trust you anymore, these keep catching me off-guard."
(Participant 10)

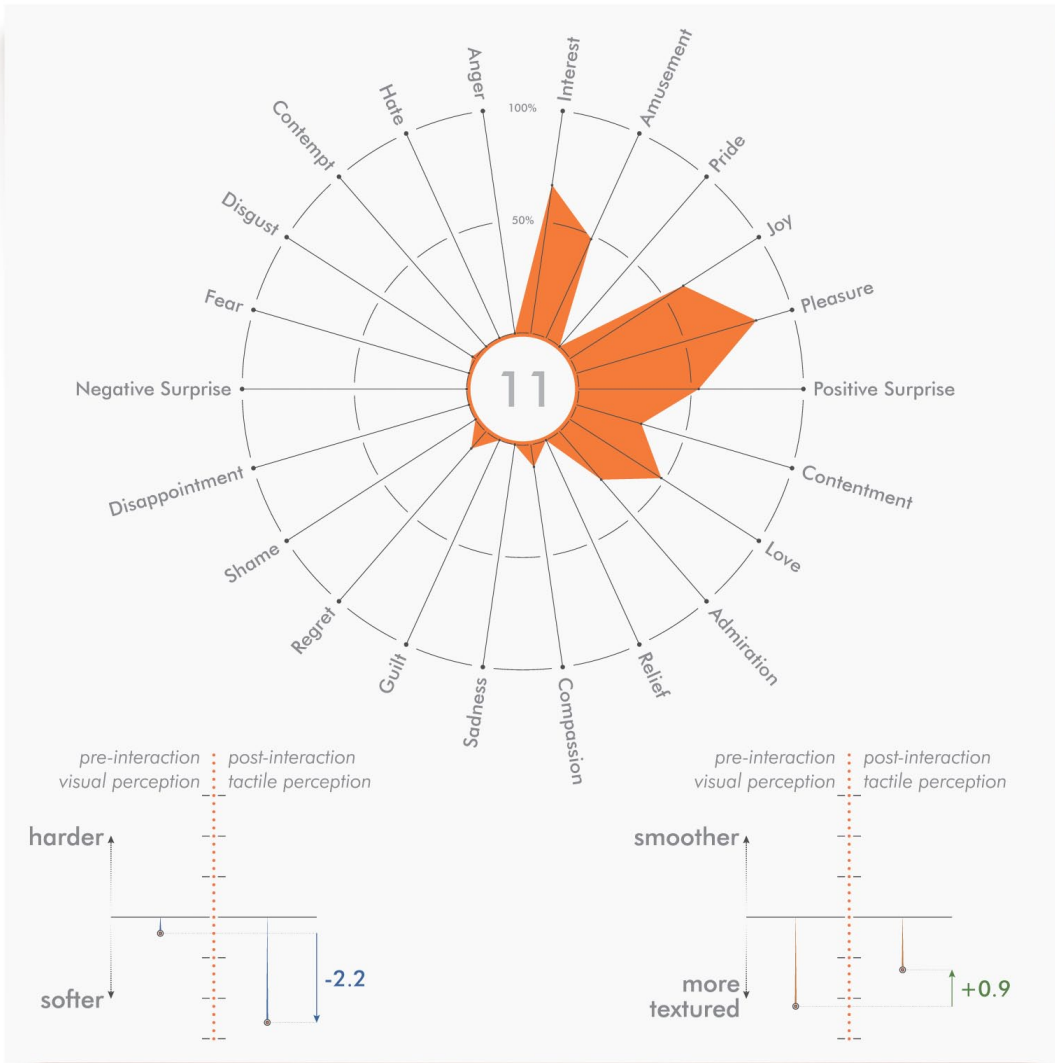
Figure 3.37 - HN1P2 elicited a lacklustre emotional response, and did not elicit a strong VTI.



Hidden Novelty: Hidden Material Characteristics (HN1)
Tentacle Grasses - (HN1P3)

- 1. To explore how a multitude of smaller multi-material forms could form a unique and odd tactile interaction.
- 2. The tactile experience is complex, as the tips of the tentacles are harder, creating a diverging sense of rigidity amongst all the flexibility.
- 3. The tips of the tentacles do not transmit light as readily as the rest of the tentacles, but the overall form has an organic glow when illuminated, akin to beeswax.

Figure 3.38 - HN1P3: Tentacle Grasses



"I love this one. Love love love it. It's so much fun to play with."
(Participant 1)

"They're like little mushrooms. It's weirdly organic. I'm having fun with this one."
(Participant 2)

"Imagine if this was a mattress! That would be lots of fun."
(Participant 6)

"It moves in such a strange way!"
(Participant 10)

Figure 3.39 - HN1P3 elicited a tremendously positive emotional response, and most participants found it to be softer than anticipated.



Hidden Novelty: Hidden Material Characteristics (HN1)
Textural Variance - (HN1P4)

- 1. To explore how a thin layer of softer materials could affect perception.
- 2. The shallowness of the layers means that the soft materials are not particularly soft, as they are backed by the hardest material.
- 3. The softer clearer materials generally allow more light through, but overall no particular light qualities are found.

Figure 3.40 - HN1P4: Textural Variance

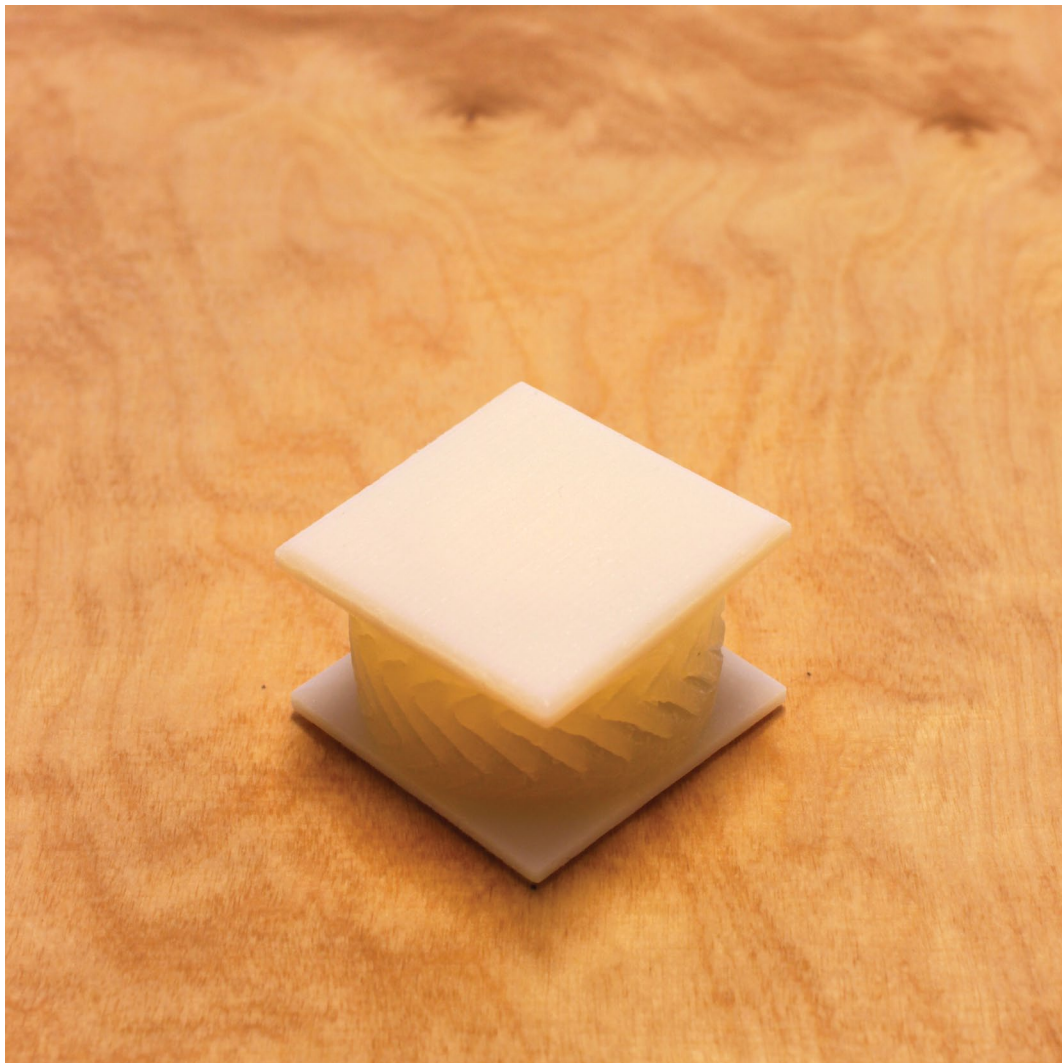


"I was expecting the darker parts to be softer..."
(Participant 1)

"The patterns are really neat. It's a shame they aren't softer though."
(Participant 5)

"It's definitely way harder than I expected it to be."
(Participant 10)

Figure 3.41 - HN1P4 elicited the weakest emotional response, and did not elicit a notable VTI.



Hidden Novelty: Hidden Material Characteristics (HN1)
Twisting Expectation - (HN1P5)

- 1. To explore how an unexpected aspect could be built into a standard interaction.
- 2. The design of the form causes it to expand when twisted. This is orchestrated through a pressure outwards caused by the angular spiral cuts in the outer rim.
- 3. The middle mechanisms are revealed in low detail through shining a light through the side of the experiment, as well as the pressure changing the light permeation.

Figure 3.42 - HN1P5: Twisting Expectation

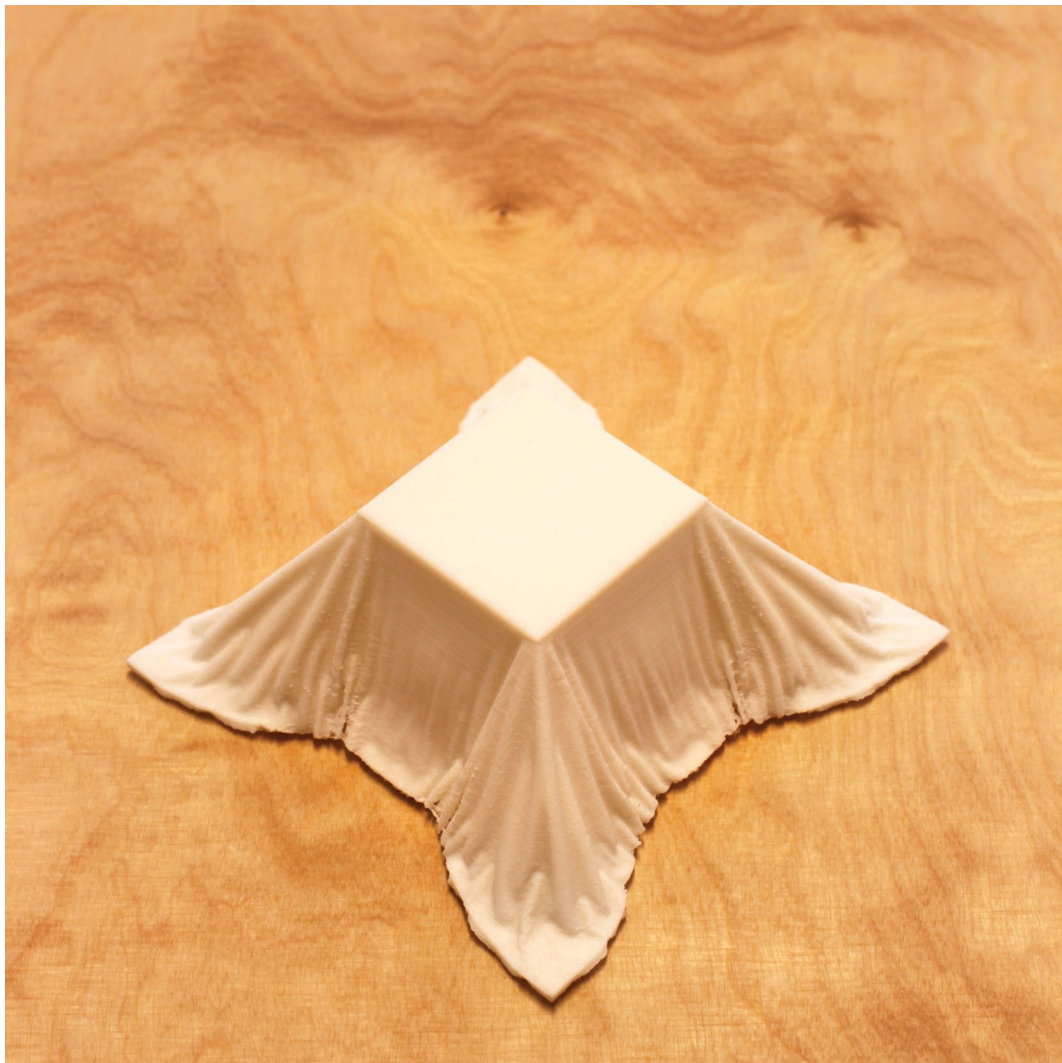


"I like that I can see through the sides of the it. Kind of neat, seeing the internals."
(Participant 1)

"Oooh wow it moves. That's really clever, the way it expands."
(Participant 3)

"That twisting expansion is awesome. You should make this one bigger."
(Participant 7)

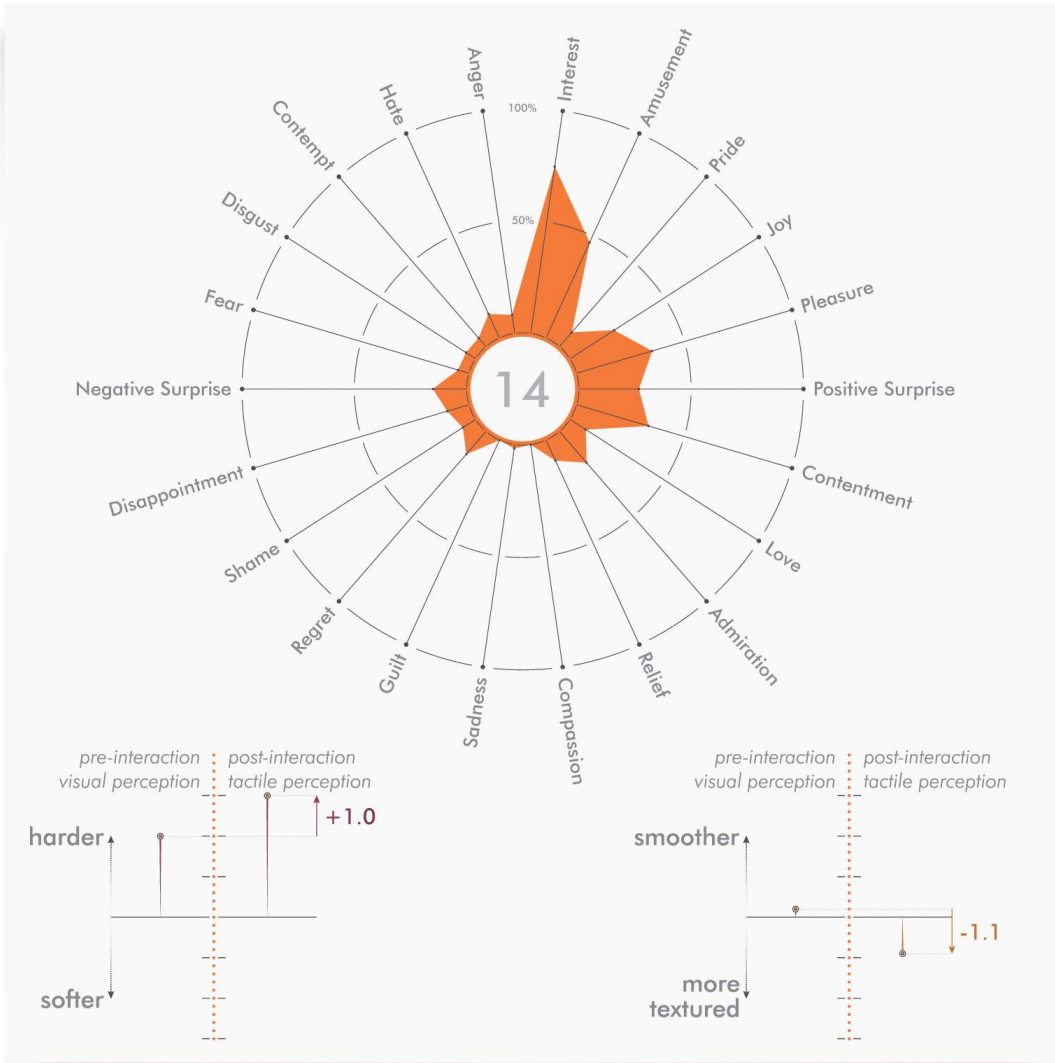
Figure 3.43 - HN1P5 elicited a very positive emotional response, and did not elicit a notable VTI.



Hidden Novelty: New Material that looks like Familiar Material (HN2)
Fabric Falsification - (HN2P1)

- 1. To explore how a soft fabric could be visually emulated with something hard.
- 2. The ABS has a rough surface texture that lends itself to creating the illusion of a fabric. It is not soft and the entire structure holds its shape.
- 3. The ABS is slightly translucent, forming darker patches where the surface is thicker, just like real fabric.

Figure 3.44 - HN2P1: Fabric Falsification



"This one is really beautiful, but it's not as playful as I'd like it to be."
(Participant 1)

"Oh. It's just hard. That's disappointing."
(Participant 4)

"I thought there was going to be something underneath it, and I thought it was going to be soft!"
(Participant 5)

"It's hard, isn't it. Thought so. I like the texture though!"
(Participant 9)

Figure 3.45 - HN2P1 elicited a strong negative emotional response, and did not elicit a notable VTI.



Hidden Novelty: New Material that looks like Familiar Material (HN2)
Frozen Reflection - (HN2P2)

- 1. To explore how the look of ice could be visually emulated.
- 2. The experiment is made of a soft transparent material and the centre is made of the white hard material. This allows the user to explore the feel of the central section through a softly muted touch.
- 3. The middle form casts intriguing shadows around the rest of the experiment when illuminated.

Figure 3.46 - HN2P2: Frozen Reflection



"I love that I can feel the points of the middle part through the soft shell."
(Participant 2)

"It kind of looks like a glass prism!"
(Participant 4)

"Those sharp edges are really nice. It's interesting to explore."
(Participant 7)

"I'm kind of annoyed that I can't feel the inside better."
(Participant 10)

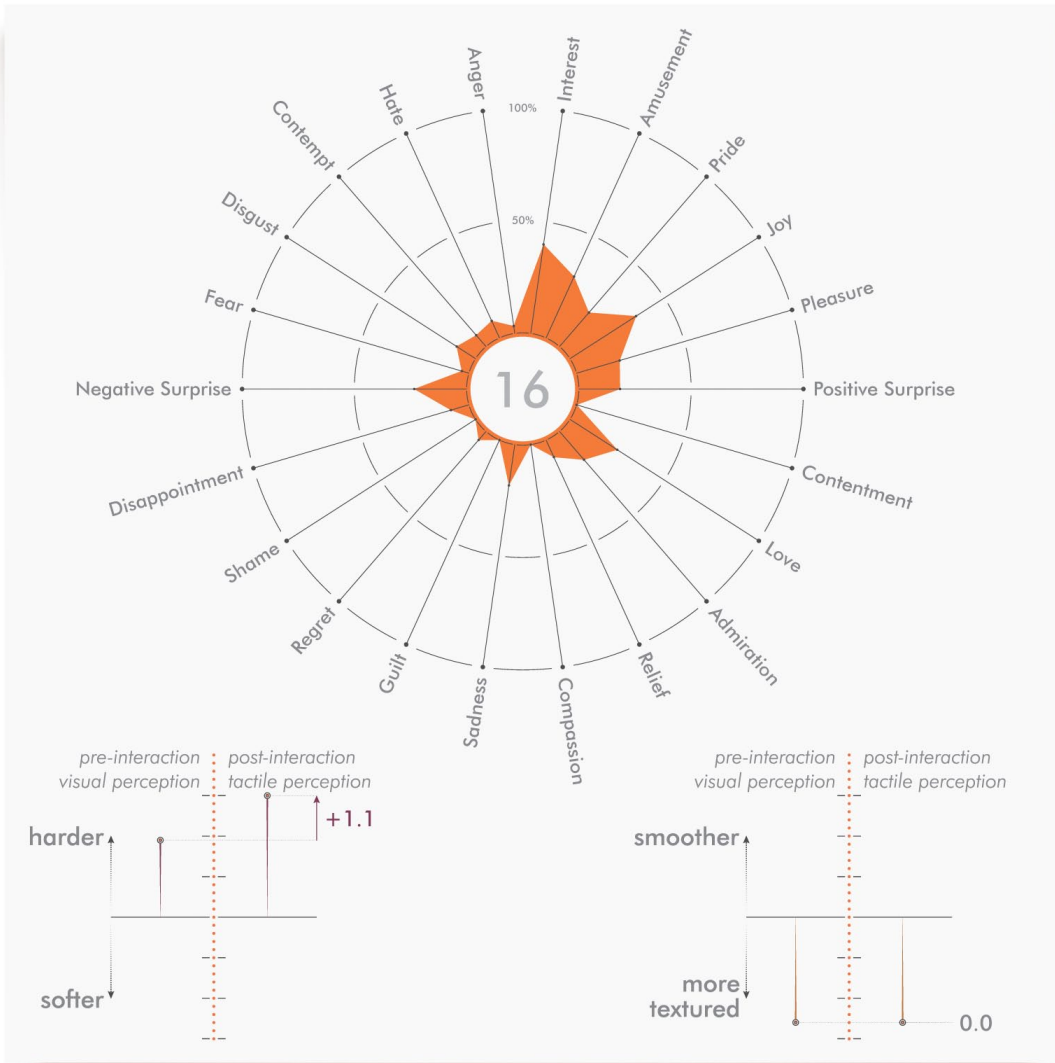
Figure 3.47 - HN2P2 elicited a positive emotional response, and did not elicit a notable VTI.



Hidden Novelty: New Material that looks like Familiar Material (HN2)
Liquid Hesitance - (HN2P3)

- 1. To explore how something wet could be emulated with something dry.
- 2. The material has been treated in a way that made it appear wet and soft when it was actually dry and hard.
- 3. The model is solid ABS, so no interesting transparencies were experienced. The surface reflected light slightly.

Figure 3.48 - HN2P3: Liquid Hesitance



- "It's kind of spooky. I don't like how rough the texture is."*
(Participant 1)
- "It kind of reminds me of Gaudi's work, you know, the cathedral?"*
(Participant 5)
- "I think I would have enjoyed it more if it was soft."*
(Participant 6)
- "This one is less interesting than the others."*
(Participant 9)

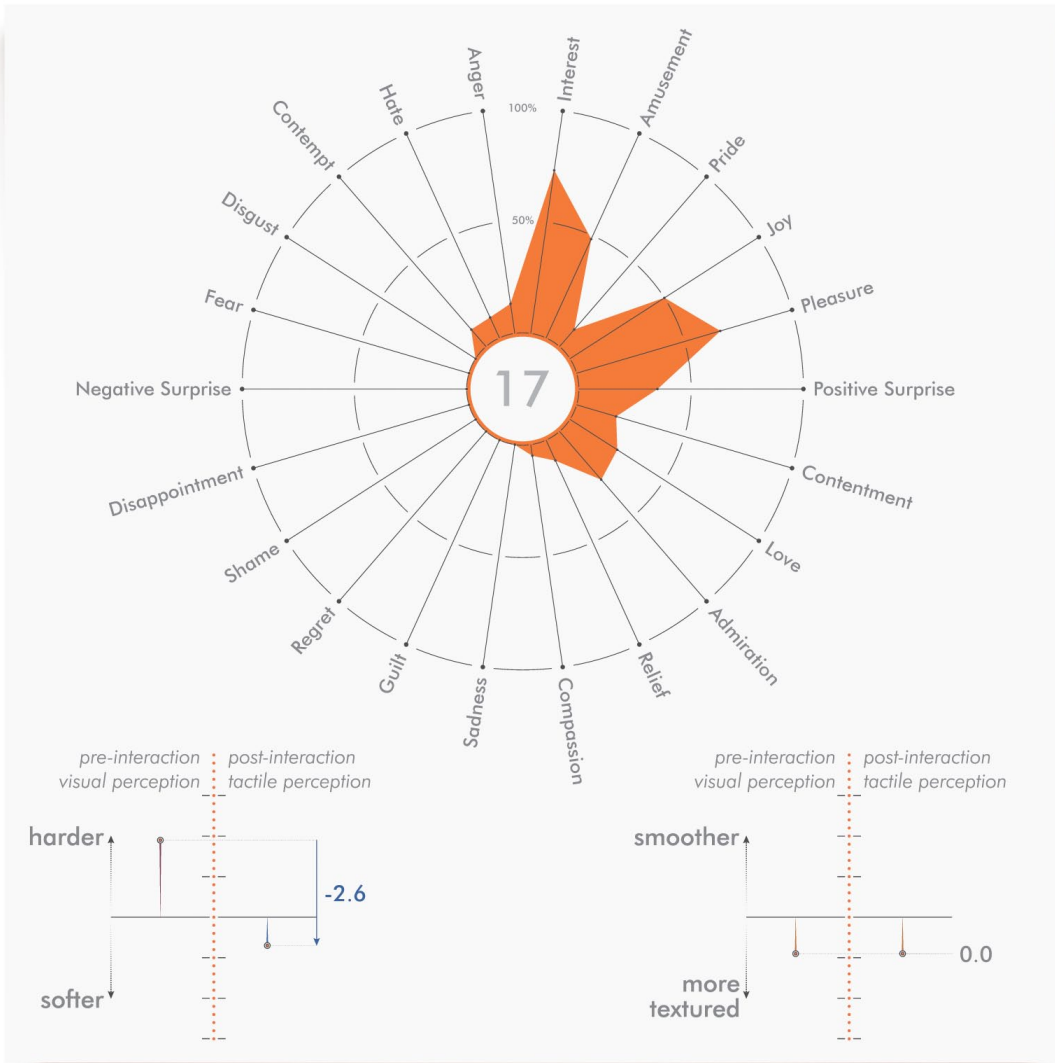
Figure 3.49 - HN2P3 elicited a strong negative emotional response, and did not elicit a notable VTI.



Hidden Novelty: New Material that looks like Familiar Material (HN2)
Rubberised Geode - (HN2P4)

- 1. To explore how soft materials could be made to look hard through referencing recognisable forms that are normally hard.
- 2. The structure is made of a hard white outer material and a soft clear material for the crystalline structures. These formed a small cave-like structure, but the crystalline structures are all soft and pliant.
- 3. The various shards of crystal offer some interesting visual and optical qualities, refracting light all throughout the model.

Figure 3.50 - HN2P4: Rubberised Geode



"This one is so cool. Can I keep it?"
(Participant 1)

"I love that it's both soft and hard. I didn't expect it to be that soft though!"
(Participant 4)

"No way. I was so sure it was hard. It looks like a crystal!"
(Participant 5)

"It looks like a slice of crystal."
(Participant 9)

Figure 3.51 - HN2P4 elicited a largely positive emotional response, and most participants found it softer than anticipated.



Hidden Novelty: New Material that looks like Familiar Material (HN2)
Stress Stone - (HN2P5)

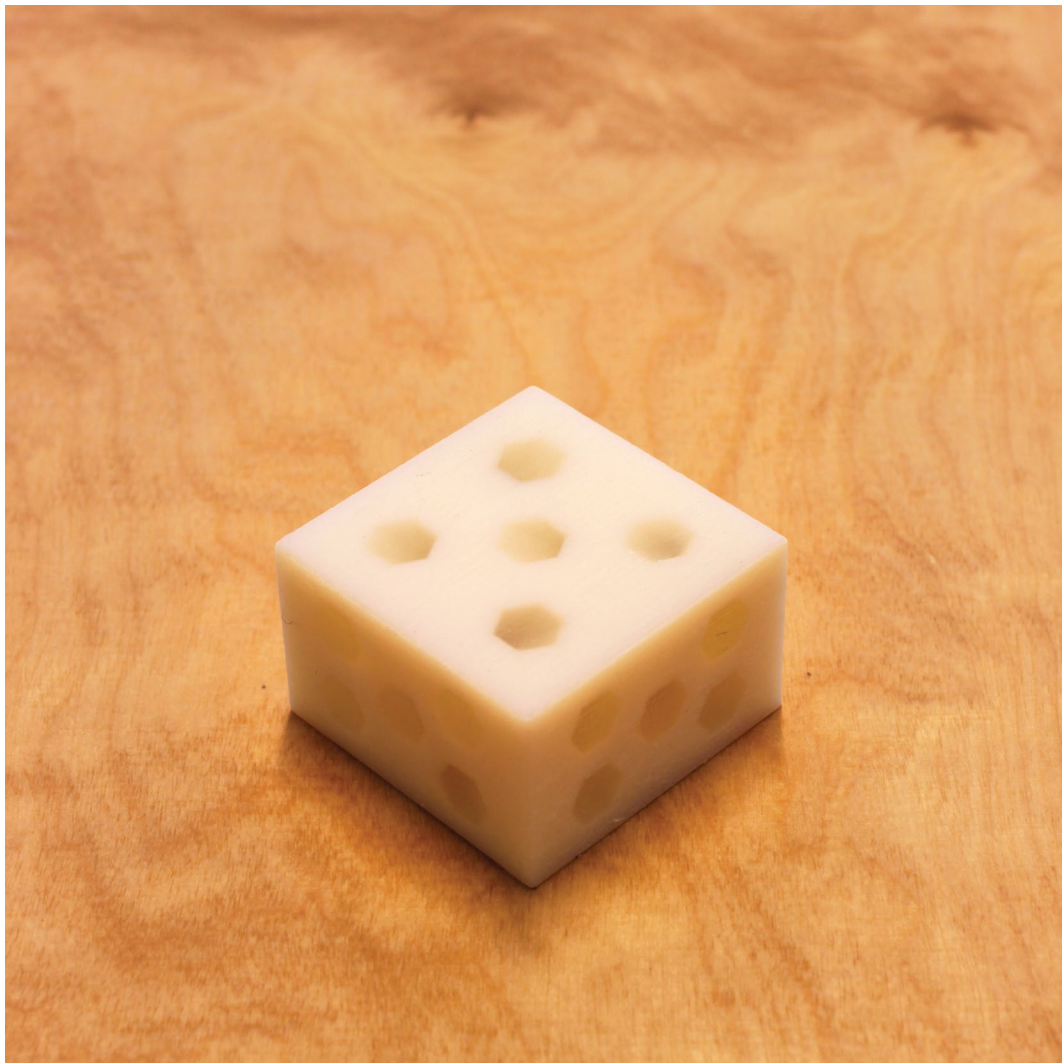
- 1. To explore how to replicate the hard look of a stone, but make it out of soft material combinations.
- 2. Radiating out from the middle of the shape, each successive “shell” of the model has a slightly softer material. This allows the user to squeeze the experiment at different points and get different tactile experiences.
- 3. The various shells have different transparencies, allowing the light to pass through differently, visually highlighting the unique segments.

Figure 3.52 - HN2P5: Stress Stone



- “This one is so beautiful...it looks like wax!”
(Participant 1)
- “There’s like a weird subtle shift in the material on this one. Like it gets softer towards the edges.”
(Participant 2)
- “It looked like it was going to be quite rough, but it’s quite smooth really!”
(Participant 4)
- “It’s like a rough-cut gemstone. This one is really lovely.”
(Participant 10)

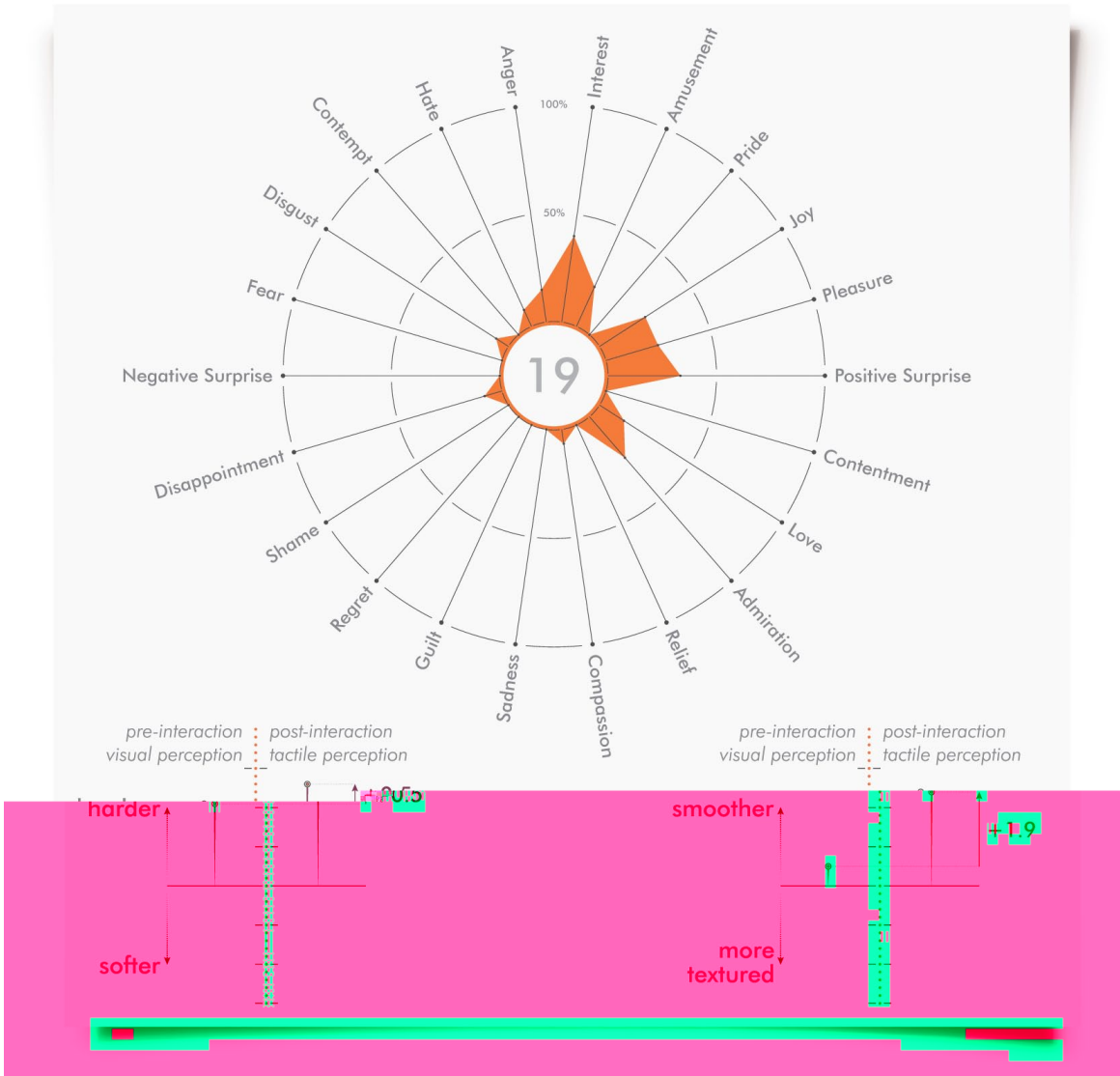
Figure 3.53 - HN2P5 elicited a positive emotional response, and did not elicit a notable VTI.



Hidden Novelty: Visual Illusion (HN3)
Disconnected Light Tubes - (HN3P1)

- 1. To explore how light could be transmitted to different places inside the cube, encouraging exploration.
- 2. The tangible interaction in this experiment encourages exploration of the overall form, as well as feeling the softness of the tubes.
- 3. When light is shone on the model, light is transmitted quite efficiently through the tubes to the other end.

Figure 3.54 - HN3P1: Disconnected Light Tubes



"This one is harder and smoother than I thought it was going to be."
(Participant 2)

"I expected more texture...the holes didn't look filled!"
(Participant 4)

"Oh that's so weird the way the light links between points!"
(Participant 6)

"Those holes looked so real. I'm not trusting you any more."
(Participant 10)

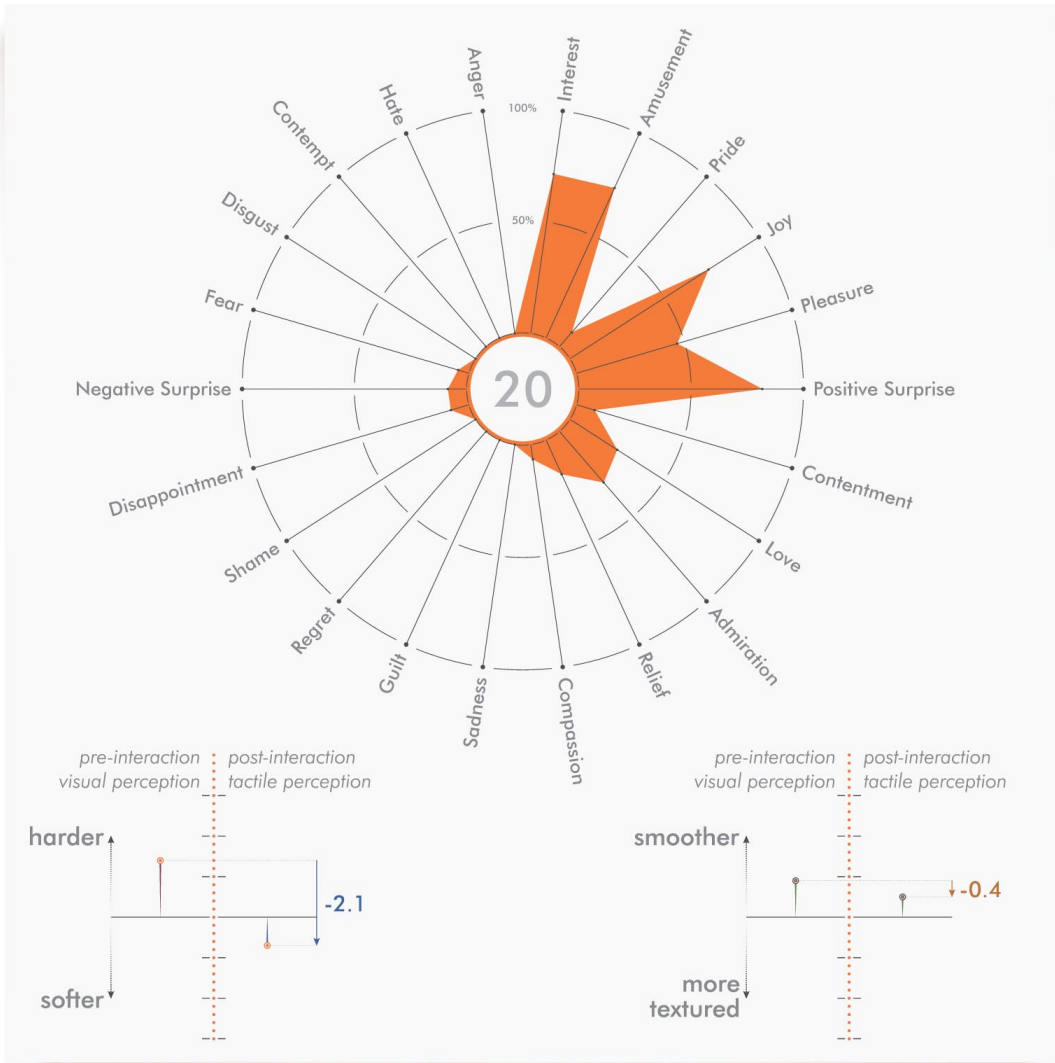
Figure 3.55 - HN3P1 elicited a very muted emotional response, and did not elicit a notable VTI.



Hidden Novelty: Visual Illusion (HN3)
Dynamic Button - (HN3P2)

- 1. To explore how the pressing of a button could be visually enhanced using physical structures.
- 2. The button press is met by a gradual pressure increase until it hits a hard stop. Small outer sections lift from their housings, visually reflecting the button depression.
- 3. Light highlights the various working parts of the design, as well as the different materials they are made from.

Figure 3.56 - HN3P2: Dynamic Button



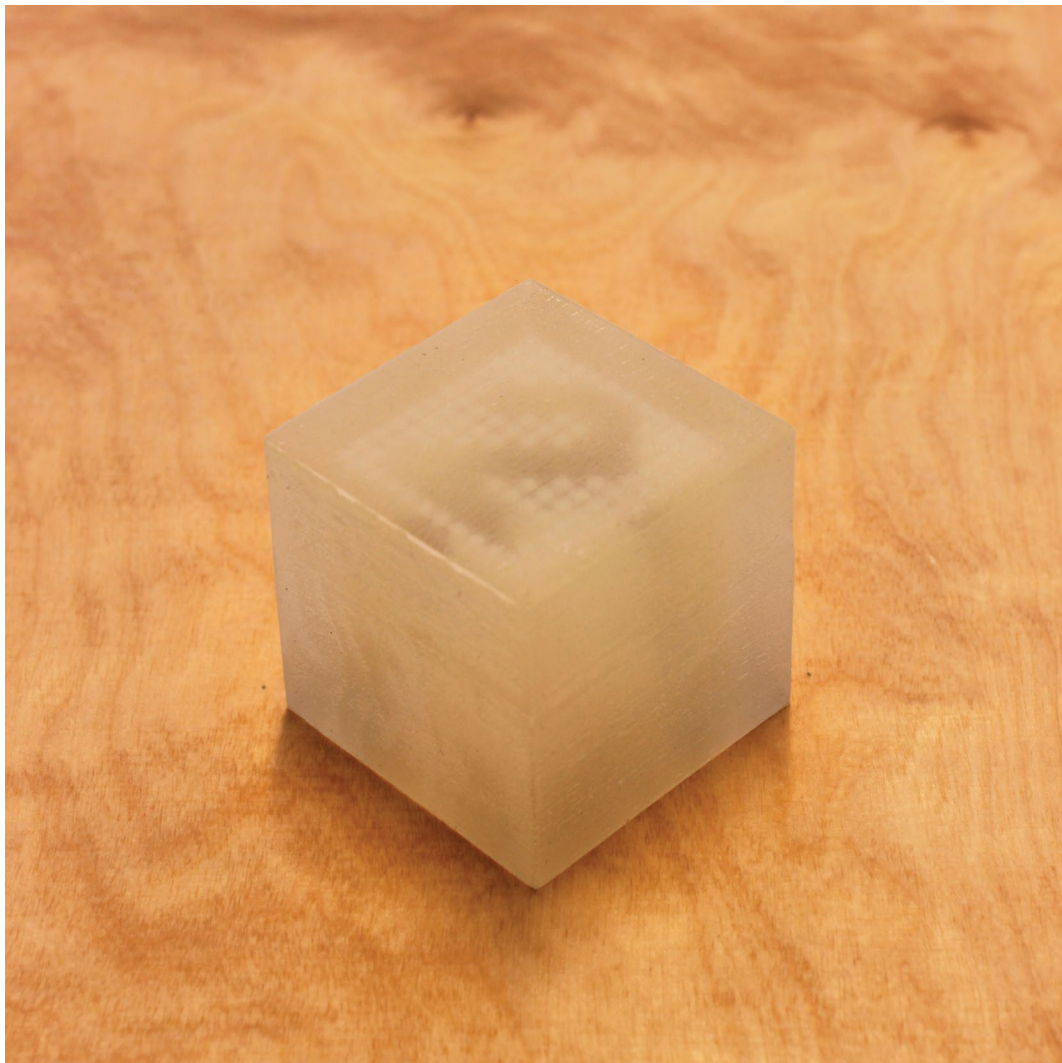
"The way it moves is really interesting, I didn't expect those parts to raise up."
(Participant 2)

"This is such a cool button. I want to see this turn something on."
(Participant 6)

"This makes me think of Star Wars, hahaha. Like it should activate something important."
(Participant 9)

"I almost missed that there was a button element to press."
(Participant 10)

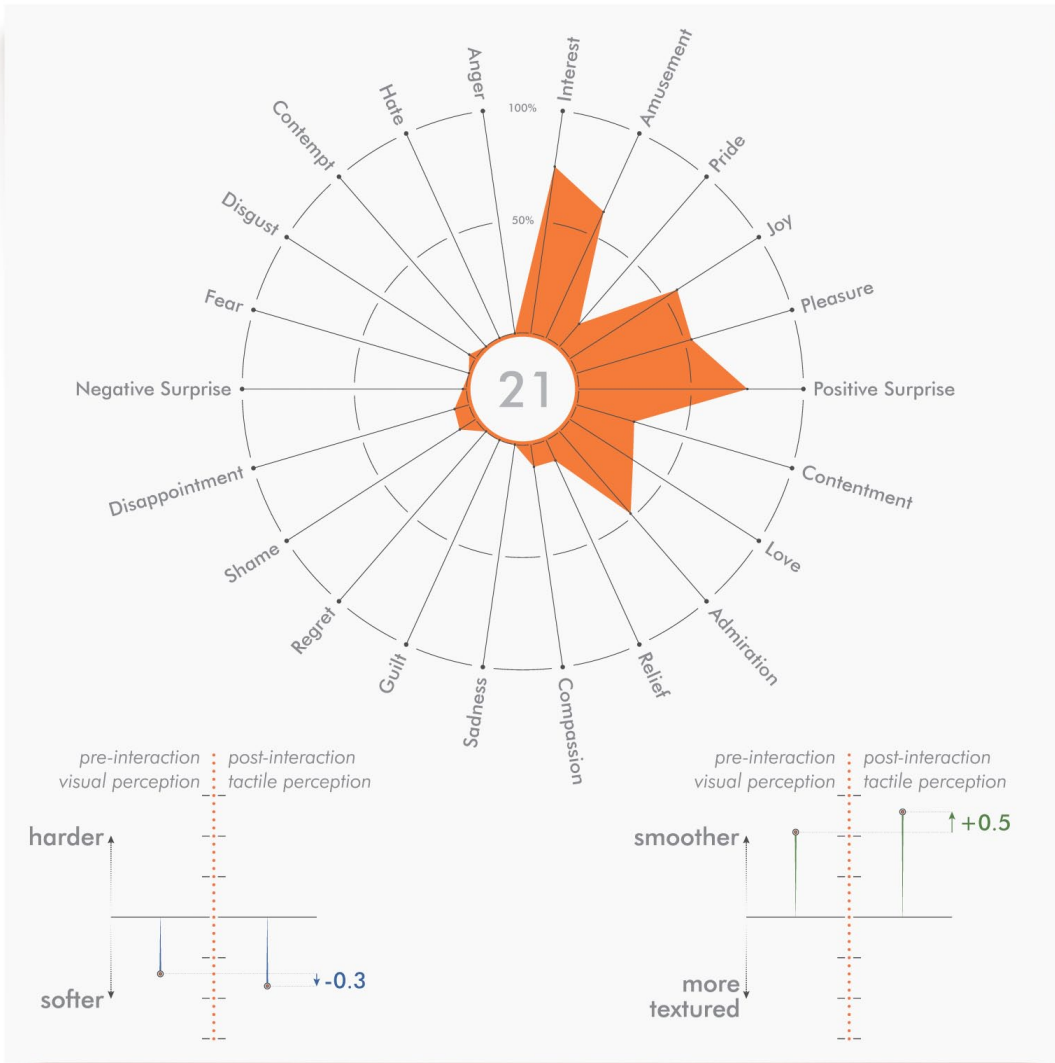
Figure 3.57 - HN3P2 elicited a strong positive emotional response, and most participants found it to be softer than anticipated.



Hidden Novelty: Visual Illusion (HN3)
Illusion Die - (HN3P3)

- 1. To explore how different numbers can be visible from different angles.
- 2. The user can squeeze the experiment, and feel a hard central section, created by the 3D grid of hard white spheres.
- 3. When light is shone through the model, the white spheres almost appear to project a holographic-like image.

Figure 3.58 - HN3P3: Illusion Die



"Oh, I can see things through it! There's numbers there!"
(Participant 4)

"I see...it's a dice! It's so lovely and squishy."
(Participant 7)

"It would have been awesome if it had all 6 numbers!"
(Participant 9)

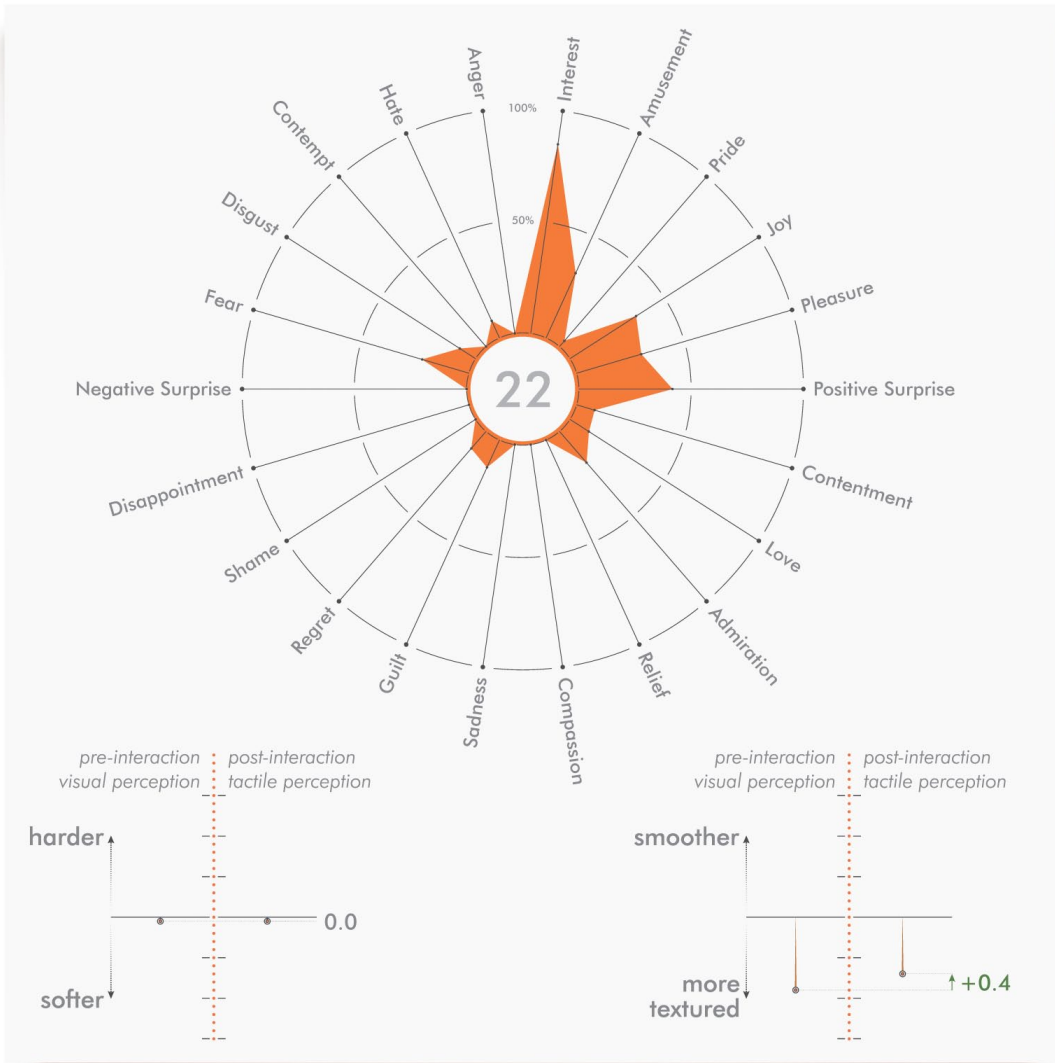
Figure 3.59 - HN3P3 elicited a strong positive emotional response, and did not elicit a notable VTI.



Hidden Novelty: Visual Illusion (HN3)
Rubberised Thorns - (HN3P4)

- 1. To explore how something sharp could be emulated by a soft material.
- 2. The outer part of the experiment forms a hard structure, while the inner section is all made of the soft materials. The thorns provide a soft caress, rather than something sharp.
- 3. The thorns pick up more of the light, glowing slightly and showing the distinct separation of the sections.

Figure 3.60 - HN3P4: Rubberised Thorns

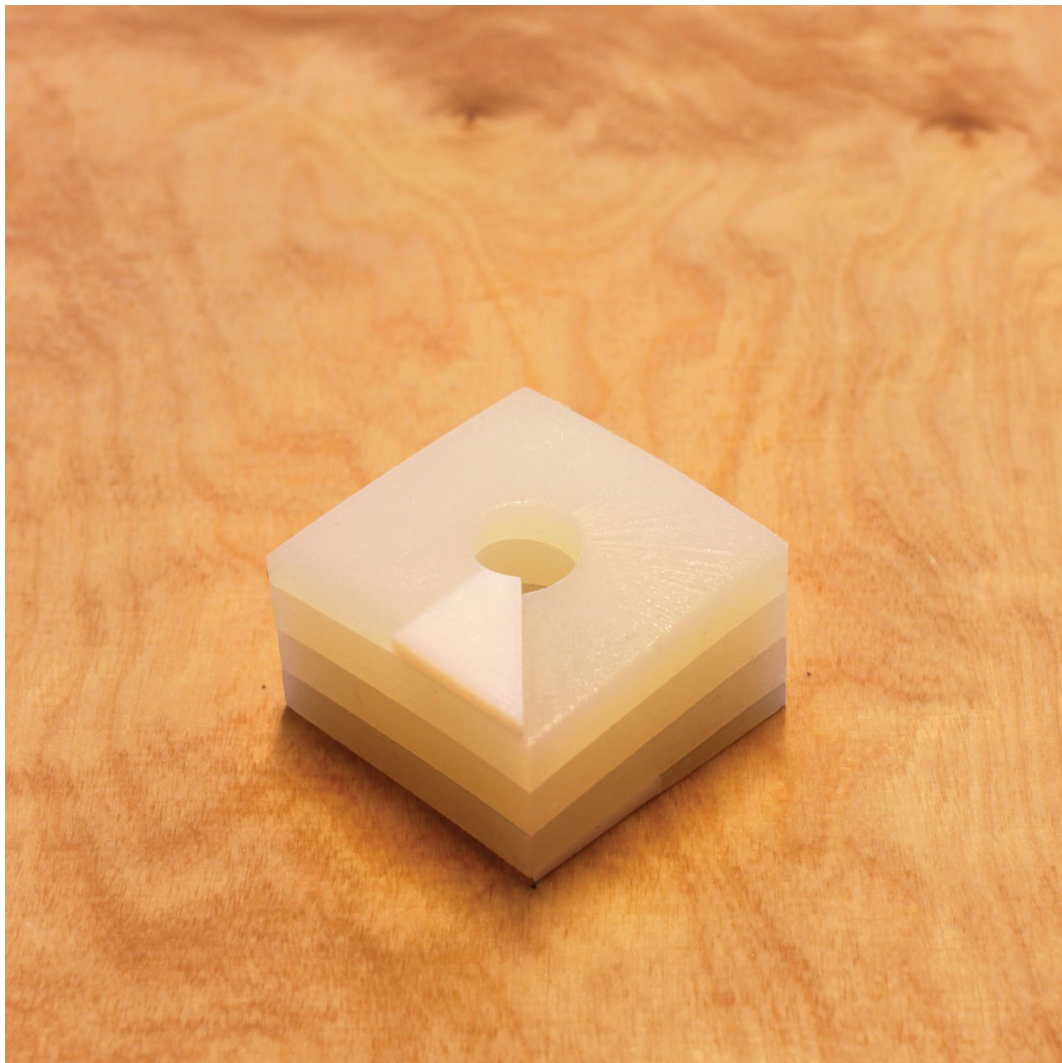


"I feel like I shouldn't like this. I feel guilty for liking this one."
(Participant 1)

"It kind of reminds me of a squid's beak!"
(Participant 6)

"This one is really fun on the inside."
(Participant 10)

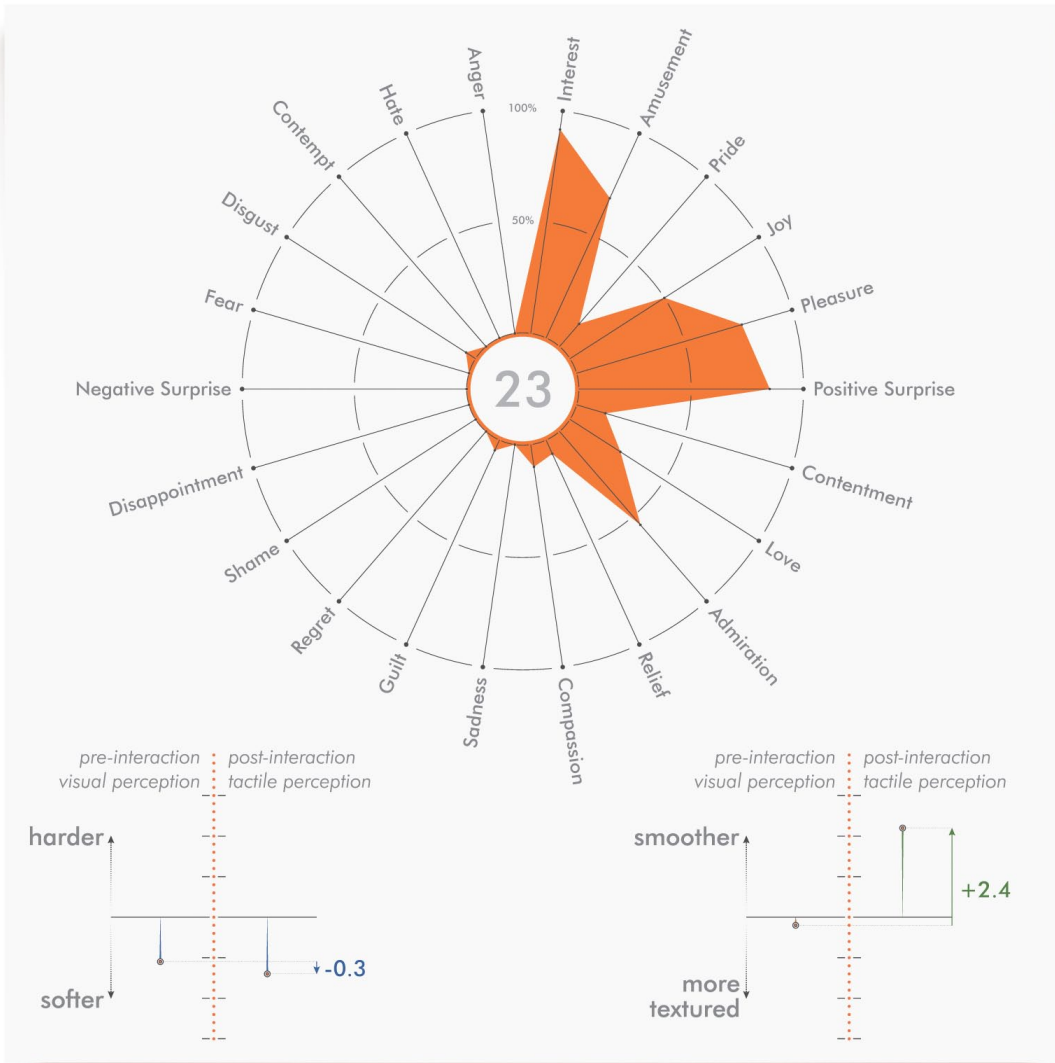
Figure 3.61 - HN3P4 elicited a fairly muted emotional response, and did not elicit a notable VTI.



Hidden Novelty: Visual Illusion (HN3)
Spiral Collapse - (HN3P5)

- 1. To explore how stretching and collapse could be explored through 3D Printing.
- 2. As the experiment is picked up and moved, the various parts of the model move, revealing that it is made of a soft pliant material that is willing to flex and stretch.
- 3. Light almost appears to travel along the spiral when the model is stretched out. There is a possibility of incorporating a pattern that is only visible when the model is stretched.

Figure 3.62 - HN3P5: Spiral Collapse



"This one is like a super-cool slinky."
(Participant 1)

"This one is way smoother than I thought it was going to be. And it's so soft!"
(Participant 2)

"It moves so much! I love how far I can stretch it."
(Participant 6)

"Was this one popular with others? I think this one is my favourite."
(Participant 8)

Figure 3.63 - HN3P5 elicited one of the strongest positive emotional response, and was found to be smoother than anticipated by most users.

Experiment Number & Strategy Code	Name of Prototype	Notable VTI achieved
#1 - VN1P1	Intangible Depth	
#2 - VN1P2	Collapsing Construct	Tactually found to be softer than visually perceived.
#3 - VN2P1	Citrus Resistance	
#4 - VN2P2	Dynamic Onion	
#5 - VN3P1	Compression Mozaic	
#6 - VN3P2	Hidden Red Peak	
#7 - VN4P1	Collapsing Tubes	Tactually found to be smoother than visually perceived.
#8 - VN4P2	Dendritic Coral	
#9 - HN1P1	Hidden Articulation	
#10 - HN1P2	Hidden Light Tubes	
#11 - HN1P3	Tentacle Grasses	Tactually found to be softer than visually perceived.
#12 - HN1P4	Textural Variance	
#13 - HN1P5	Twisting Expectation	
#14 - HN2P1	Fabric Falsification	
#15 - HN2P2	Frozen Reflection	
#16 - HN2P3	Liquid Hesitance	
#17 - HN2P4	Rubberised Geode	Tactually found to be softer than visually perceived.
#18 - HN2P5	Stress Stone	
#19 - HN3P1	Disconnected Light Tubes	
#20 - HN3P2	Dynamic Button	Tactually found to be softer than visually perceived.
#21 - HN3P3	Illusion Die	
#22 - HN3P4	Rubber Thorns	
#23 - HN3P5	Spiral Collapse	Tactually found to be smoother than visually perceived.

Mean perception shift for soft/hard (in points of change)	Mean perception shift for textured/smooth (points of change)	Cumulative Positive Valence Emotions (Max: 66)	Cumulative Negative Valence Emotions (Max: 66)
-0.3	-0.7	16	1.1
-3.2	-0.9	23.7	0.6
0	-0.2	12.9	0.9
0.8	0.4	15.8	0.8
-0.6	-0.1	16.2	1.6
-0.5	0.4	20.2	1.3
-1.7	2.4	14.8	2.6
0.6	0.2	29.9	1.2
1.7	0.2	16.5	6.9
1.6	0.8	16.6	0.6
-2.2	0.9	25.7	0.7
0.8	0.3	10.8	0.8
-0.7	-0.4	23.8	0.4
1	-1.1	17.1	4.9
0.3	-0.7	20.4	0.3
1.1	0	12.8	5.2
-2.6	0	22.2	2
0.6	0.9	16.9	0.2
0.5	1.9	11.3	2.3
-2.1	-0.4	26.5	1.3
-0.3	0.5	27.8	1.2
0	0.4	15.8	3.7
-0.3	2.4	29.8	0.6

Data Aggregation, Translation & Analysis

In order to gain a better overview over the data from the responses. I collated all 230 questionnaires, 10 for each cube. The way this data was aggregated into a spreadsheet is detailed prior with details of the user testing process.

Experiment Number & Strategy Code: Strategy number and prototype number.
Name of Prototype: Name assigned to prototype, served to make them more recognisable.
VTI Achieved: Was one or both of the perception shifts substantial, and if so which ones? (This was noted at 2+ points of change in either direction, and was for indication only)

Figure 3.64 - Collected and averaged responses from all participants on all prototypes.

Averaged perception shift for soft/hard: Difference between average initial visual perception and subsequent tactile perception for soft/hard. Shown in points of change. Positive numbers indicated participants found the prototype to be harder than visually perceived, and vice versa.
Averaged perception shift for textured/smooth: Difference between average initial visual perception and subsequent tactile perception for textured/smooth. Shown in points of change. Positive numbers indicated participants found the prototype to be smoother than visually perceived, and vice versa.
Cumulative Positive Valence Emotions: All averaged positive emotion values on the GWoE added together, with a maximum possible value of 66.
Cumulative Negative Valence Emotions: All averaged negative emotion values on the GWoE added together, with a maximum possible value of 66.

Figure 3.64 contd. - The larger the number, the stronger the colour.

DISCUSSION & CONCLUSION

Data Interpretation

The cubes that were found to be most successful demonstrated a variety of different qualities. Some of the cuboids had averaged responses that demonstrated an overwhelmingly positive response. These cubes included Dendritic Coral, Spiral Collapse, and Illusion Die. However, of these 3, only the data from Spiral Collapse indicated a strong presence of a VTI.

Interestingly, the three prototypes (Hidden Articulation, Fabric Falsifications and Liquid Hesitance) that were not made using PPP and only used standard FDM ABS printing all reported the highest negative emotional responses and most of the weakest positive responses. Some of the users also verbally reported disappointment with the lack of material complexity in these models, stating phrases like “Oh, it’s just hard. That’s disappointing.” (Participant 4 on Fabric Falsifications), “This one is less interesting than the others” (Participant 9 on Liquid Hesitance) and “I think I would have enjoyed it more if it was soft” (Participant 6 on Liquid Hesitance). This, coupled with positive responses for some of the prototypes that utilised the most diverse range of material possibilities suggested an affinity for the multi-material prints. A lot of participants expressed enjoyment with the softness of some of the PPP prototypes. The top 5 prototypes in terms of positive emotional responses that also showcased substantial perception shifts were: *Spiral Collapse*, *Dynamic Button*, *Tentacle Grasses*, *Collapsing Construct* and *Rubberised Geode*. These prototypes explored the strategies Ludden (2008) developed in quite particular ways:

» HN3P5 - *Spiral Collapse* explored the potential of creating the visual illusion of texture being more intense than it really was. The shape of the layers and the way they sat on top of each other made the form look very textured, yet the entire form was actually very smooth. The stacked, slinky-like spiral also had the ability to expand, catching many of the participants off-guard. This made the surprise effect twofold; the first surprise being the

unexpected smoothness and softness, while the second surprise developed out of the spring-like interaction.

- Perception (Max: 3 or -3): The average visual perception of this prototype listed it as slightly more textured than smooth (-0.2), but the tactile perception found it very smooth (2.2).
 - Perception Shift (Max: 6 or -6): This represented a realisation that the prototype was smoother than anticipated (2.4).
 - Emotional Response (Max: 66): The average emotional response to this prototype was overwhelmingly positive, cumulatively listing (29.8) on the positive side of the GWoE, yet only (0.6) on the negative side.
 - The three emotions that were recorded most strongly included (Max: 6): Interest (5.5), Positive Surprise (5.1), and Pleasure (4.6).
- » HN3P2 - *Dynamic Button* was a more visual exploration; exploring the potential of a surface interlaced with hidden structures to give a visual feedback when pressed. Like *Spiral Collapse*, also exploring the potential of visual illusion, it revealed the hidden structures as it caved inwards when pressed, causing a lot of participants to find it softer than anticipated. The movement of the small reacting structures was quite small, but all the participants noticed it and verbally made a comment on it.
- Perception (Max: 3 or -3): The average visual perception of this prototype listed it as reasonably hard (1.4), but the tactile perception found it slightly soft (-0.7).
 - Perception Shift (Max: 6 or -6): This represented a realisation that the prototype was softer than anticipated (-2.1).
 - Emotional Response (Max: 66): The average emotional response to this prototype was overwhelmingly positive, cumulatively listing (26.5) on the positive side of the GWoE, yet only (1.3) on the negative side.
 - The three emotions that were recorded most strongly included (Max: 6): Positive Surprise (4.9), Amusement (4.4), and Joy (4.4).

- » HN1P3 - *Tentacle Grasses* explored the potential of hiding material characteristics and confusing the viewer with diverse material variations. This was achieved by halving the tentacles into harder and softer sections. This also gave them a large amount of dynamic motion when touched. A lot of participants explained that they were “*having a lot of fun with this one*” (Participants 2, & 9) or that it “*moves in a really surprising way*” (Participants 2 & 10).
 - Perception (Max: 3 or -3): The average visual perception of this prototype listed it as slightly more soft than hard (-0.4), but the tactile perception found it exceedingly soft (-2.6).
 - Perception Shift (Max: 6 or -6): This represented a realisation that the prototype was softer than anticipated (-2.2).
 - Emotional Response (Max: 66): The average emotional response to this prototype was very positive, cumulatively listing (25.7) on the positive side of the GWOE, yet only (0.7) on the negative side.
 - The three emotions that were recorded most strongly included (Max: 6): Pleasure (5.0), Interest (4.0) and Joy (3.6).
- » VN1P2 - *Collapsing Construct* was specifically intended to reference a solid, static, sharply-edged shape. By texturing the hollow inside of the shape, the prototype was made to look like there was a hidden object inside the form. All the participants were surprised to find that the form was actually soft and hollow, and the degree at which the form collapsed elicited some wonderful “*Oh!*” (Participants 2, 4, 5, & 9) exclamations from the participants.
 - Perception (Max: 3 or -3): The average visual perception of this prototype listed it as slightly more hard than soft (0.7), but the tactile perception found it exceedingly soft (-2.5).
 - Perception Shift (Max: 6 or -6): This represented a realisation that the prototype was a lot softer than anticipated (-3.2).

- Emotional Response (Max: 66): The average emotional response to this prototype was very positive, cumulatively listing (23.7) on the positive side of the GWOE, yet only (0.6) on the negative side.
- The three emotions that were recorded most strongly included (Max: 6): Positive Surprise (5.5), Interest (4.9), and Pleasure (3.7).
- » HN2P4 - *Rubberised Geode* also made use of intense intentional referencing to understood forms. This intentional referencing to a well-understood object with hard form language and similar refractive properties appeared to throw a lot of the participants off. Participant 5 was convinced they had the answer, expressing utter disbelief “*No way. I was so sure it was hard. It looks like a crystal!*”.
 - Perception (Max: 3 or -3): The average visual perception of this prototype listed it as very hard (1.9), but the tactile perception found it slightly more soft than hard (-0.7).
 - Perception Shift (Max: 6 or -6): This represented a realisation that the prototype was softer than anticipated (-2.6).
 - Emotional Response (Max: 66): The average emotional response to this prototype was very positive, cumulatively listing (22.2) on the positive side of the GWOE, yet only (0.6) on the negative side.
 - The three emotions that were recorded most strongly included (Max: 6): Interest (4.4), Pleasure (4.0), and Joy (3.0).

Significance & Implications

The use of recognisable forms and referential structures appeared a common theme in comments by the participants in response to why their visual appraisal was wrong. “*I thought it was going to be like a crystal*” (Participant 5 on *Rubberised Geode*). “*It looked sharp and hard-edged*” (Participant 6 on *Collapsing Construct*). Similarly, the introduction of intriguing, unknown forms encouraged interaction, inviting curiosity and experimentation. Not knowing

quite what to expect left the participants in a position where surprising them would be easier. The responses, data and designs led to the refining of key approaches from the strategies detailed by Ludden (2008). These approaches were specifically defined to work within the qualities possible with 3D printing, yet allow enough freedom to design freely. These approaches, developed specifically out of four of the five aforementioned stand-out designs as well as the insights drawn from the other prototypes were:

- » Approach One: *Visually referencing recognisable forms, objects and structures, but making them tactually different.*
Adapted from Ludden’s ‘Hidden Novelty: New Material that looks like Familiar Material’ and ‘Visible Novelty: New Appearance for Known Product or Material’.
 - **Rubberised Geode**, Collapsing Construct, Dynamic Button
- » Approach Two: *Using material variances and unfamiliar forms to encourage interaction.*
Adapted from Ludden’s ‘Hidden Novelty: Hidden Material Characteristics’ and ‘Visible Novelty: New Material with Unknown Characteristics’.
 - **Tentacle Grasses**, Frozen Reflections, Dynamic Onion
- » Approach Three: *Suggesting surfaces have texture when they are actually smooth, through the use of an illusion.*
Adapted from Ludden’s ‘Hidden Novelty: Visual Illusion’ and ‘Visible Novelty: Combination with Transparent Materials’.
 - **Spiral Collapse**, Disconnected Light Tubes, Collapsing Tubes
- » Approach Four: *Using internal structures to challenge the initial visual perception of the material properties.*
Adapted from Ludden’s ‘Hidden Novelty: Hidden Material Characteristics’ and ‘Visible Novelty: Combination with Transparent Materials’.
 - **Collapsing Construct**, Compression Mosaic, Dynamic Button

The prototypes highlighted were the most successful prototypes in terms of the strength of the VTI elicited. These would serve as focal points for the development of the approaches and led into the next phase.

Limitations

There were several limitations and issues with the user testing that became apparent after some of the user testing sessions. These will be addressed here before the next round of user testing placed at the end of Phase 2. One of the limitations included the lack of randomisation between the participants. This issue, coupled with comments from the participants led to the realisation that users became familiar with the materials used over the course of the 23 prototypes. This potentially could have been addressed in the following ways; randomise the order of the prototypes so that the familiarity with the materials would not consistently be impacting the same few prototypes, or reduce the number of prototypes that each participant was exposed to.

Another alteration that might have assisted in getting clearer responses was putting question 1 (Asking for a visual material assessment of hardness/softness and smoothness/texture) and question 2 (A tactile material assessment of the hardness/softness and smoothness/texture) on different pages. This would have been useful in getting participants to re-assess their sensory inputs rather than answering the question in relation to their previous response, or while still being able to see it. In order to supplement this, it would likely also be useful to interleave question 1 and 2 with question 3, the question pertaining to the GWoE. This way the participant’s emotional responses could immediately be collected post-interaction, as well as distracting them from comparing their answers to the material assessment question. This may have also helped to gather more accurate first-exposure emotional responses and more divergent material assessments.

Aspects that will be factored into the user testing for the next phase:

- » Randomise the order of the prototypes between participants in order to reduce the effect of material familiarity.
- » Split material assessment questions across different pages in order to ensure that participants are answering the questions independently as opposed to in relation to each other.
- » Place the GWoE as the first question after the interaction in order to get more accurate post-interaction emotional responses.
- » Ask some more open-ended questions in the questionnaire in order to gather more quotes and feedback.

The next phase details the development of a series of lights that utilise the identified approaches and respond to the full research question:

How can the unique qualities that 3D printing offers generate surprise through visual-tactile incongruities in lighting design?

4

DESIGN PHASE 2

INTRODUCTION & QUESTION

The previous chapter finished with the development of four approaches: *Visually referencing recognisable forms, objects and structures, but making them tactually different; Using material variances and unfamiliar forms to encourage interaction; Suggesting surfaces have texture when they are actually smooth, through the use of an illusion; and Using internal structures to challenge the initial visual perception of the material properties.* These four approaches were supplemented with the four most successful prototypes; based on the user testing, surprise responses and feedback. Design Phase 1 also provided a wealth of knowledge on designing for PPP printing, all of which was immeasurably useful to the development of this chapter. Existing lighting designs in the background highlighted the relevance of beauty as an invitation for interaction, as well as the importance of pertinent and comprehensible tactile interactions. Some of the designs in Phase 1 also began to exemplify the importance of layering surprise, an aspect that the literature revealed as an avenue to further the person-product relationship.

This phase employed the four approaches as starting points for the design of four interactive lights based on VTI-inducing 3D printing. The shortcomings of the user testing in Design Phase 1 were addressed in this phase as well. This phase expanded the research question out to include lighting, addressing the question with design solutions that are situated at the intersection between tactile interactivity, VTIs, 3D printing and surprise. This involved considering aspects like the quality of light, electronics design, material consideration, and functionality. The question this design phase responds to is:

How can the design of lighting elicit surprise through the use of visual-tactily incongruous 3D printing?

This phase follows a Research through Design approach, again structured like a miniature thesis. The design process was followed by user testing, which served to investigate the potential of the designs to generate surprise. This was also done to address the approaches put forward at the end of Design Phase 1. The designs developed serve as expressions of these approaches.

METHODS & CRITERIA

This chapter followed a similar overarching structure to Design Phase 1; continuing the Research through Design process, with adapted methods and updated considerations. This chapter responds specifically to the aim of: *‘design, build and test interactive lighting that aims to elicit surprise through the use of VTIs and 3D printing’.*

Objective 1: Design and develop lights that incorporate 3D printed tactile interactivity and surprise.

- » *Concept Mapping* (Ausubel, 1963; Martin & Hanington, 2012, p. 38)
This method was used to develop a broader understanding of a complicated design space involving 3D printing, tactile interactions and lighting design. This also served to identify specific electronics that could be used in the design of the interactions.
- » *Morphological Analysis* (Zwicky, 1967)
This method was used in combination with sketching to explore the success of the best prototypes from Design Phase 1 and investigate them as starting points for the interactions built into the lights.
- » *Research Through Design* (Burdick, 2003, p. 82; Martin & Hanington, 2012, p. 146)
This was used as the core approach for designing the lights and the relevant electronics. It involved sketching, iterative ideation and prototyping, as well as CAD modelling, parametric design, prototyping and 3D printing. This design phase also employed the following set of updated criteria identified at the end of Design Phase 1:
 - *Designs should each explore one of the approaches developed in response to the exploration of Ludden’s (2008) strategies in Phase 1.*
 - *Designs should explore the range of qualities and capabilities of PPP.*
 - *Designs should employ evocative interactions and activation controls.*
 - *Designs should be visually coherent between each other.*

MATERIALITY & FAMILIARITY

- Objective 2: Test the designs’ abilities to generate surprise with participants and analyse responses.**
- » *Evaluative Research / User Testing* (Kittur, Chi, & Suh, 2008, pp. 453-456)
An adapted version of the previous evaluative user testing was conducted to test the lights, facilitating the collection of qualitative and self-reported information. The testing incorporated *Interviews* (Kuniavsky, 2003; Martin & Hanington, 2012, p. 140), *Questionnaires* (Robson & McCartan, 2016) and the *Geneva Wheel of Emotions* (Scherer, 2005, pp. 720-725) (Will be referred to in this thesis as the GWoE) as well as modified *Likert Scales* (Matell & Jacoby, 1971) for participants to self-report on their emotional and usability thoughts on the physical prototypes. The GWoE was modified to include surprise (unpleasant and pleasant).
 - » *Data Analysis* (Mogey, 1999)
The adapted versions of the questionnaires included some new data values and responses to track. Calculating the mean was still used as the primary data analysis technique. The questionnaires included modified Likert scales, like the first user tests, but also with some new questions as well which required a slightly different approach.

One of the areas that was touched on in the background research review that was not explicitly considered in the previous design phases was the importance of MAYA; Raymond Loewy’s (1951) principle of “Most Advanced, Yet Acceptable” (pp. 277-286). This principle suggested that in order to develop successful products, designers ought to include elements of familiarity in their designs alongside innovative, novel concepts. The way this was interpreted in the design process was to situate the novel and unfamiliar 3D printed materials amongst materials that were recognisable and familiar.

This initially emerged out of the realisation that the designs in Phase 1 were hampered by the lack of focus towards a specific outcome, as they existed solely as abstract objects. A way to ground those objects was to set them against something more familiar. This was addressed after the user testing through the photography in Design Phase 1. Rather than opting for a traditional approach to product photography, where the models were situated against a clean, untextured backdrop, I instead decided to situate the prototypes against a natural, textured timber background. This was done in order to effectively communicate the transparencies present as well as to test how situating the 3D printed material amongst those sorts of materials might work.

This aspect was intended as an element of the design that the user could be absolutely certain about. By juxtaposing the 3D printed component with a natural material that looks and feels familiar, the aim was to create an object that fulfilled both ends of the spectrum in terms of familiarity to unfamiliarity.



The chosen wood, due to its pale coloration and ability to complement the 3D prints, was ash (figure 4.1). This timber, combined with the specific interaction and outcome of the lights, would seek to focus the familiarity more specifically for the users.

Figure 4.1 - "Rubberised Geode" against a slab of ash.

DESIGN PROCESS

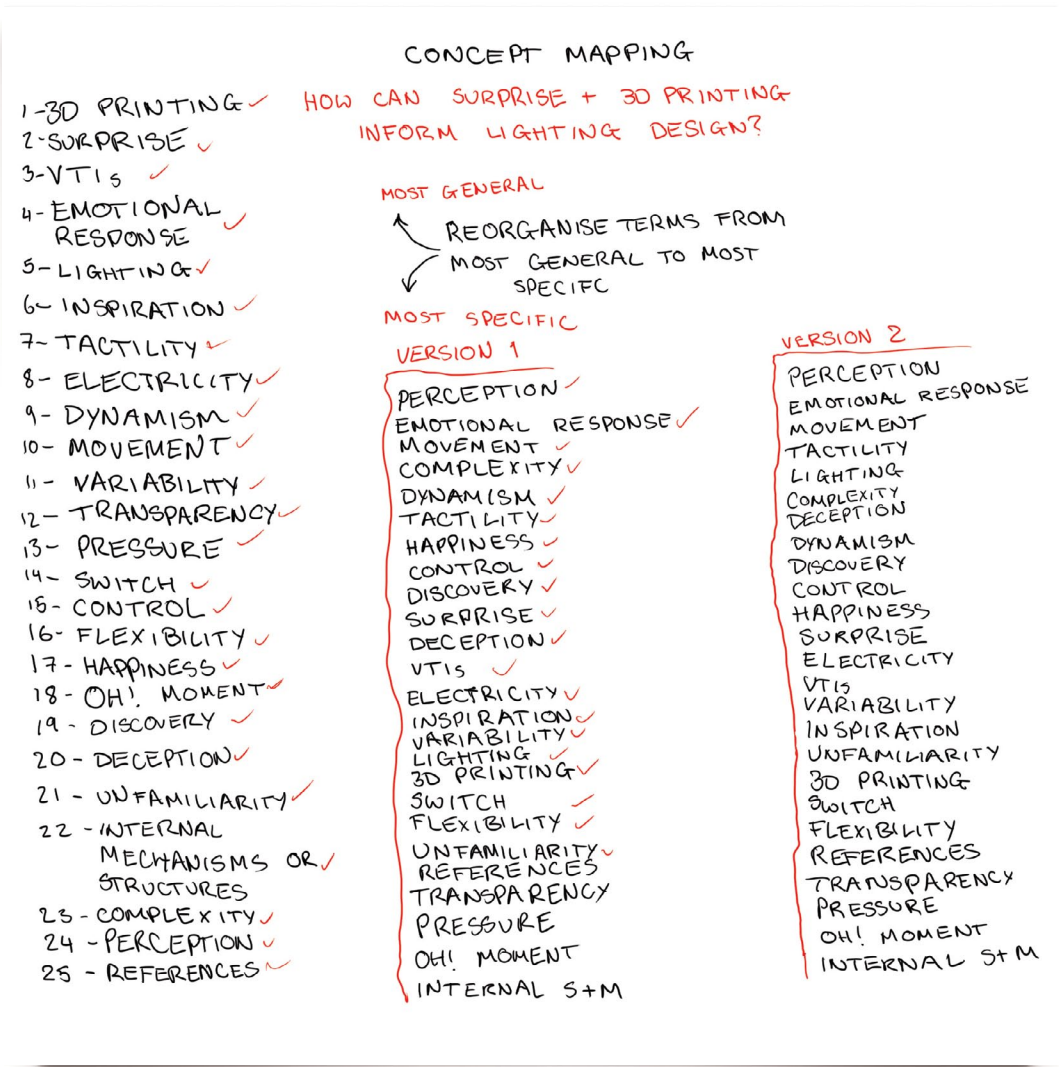
Similarly to Design Phase 1, the process initiated with a relation-building process (Concept Mapping) that aimed to pull ideas and meaning into the pool of thought that facilitated the development of ideas. This formed the basis for a Morphological Analysis that was used specifically as an idea-developing strategy. Once these two sections were completed, the process moved into the exploration through sketching, CAD modelling, rendering and 3D printing.

Concept Mapping

Three separate concept maps were developed, each focusing on slightly more specific areas relating to the design phase. The concept maps sought to draw together various disconnected regions, pulling sense from the region and developing a broader understanding of a complicated space.

Concept maps get the researcher to create a list of 15-25 words that pertain to the question posed. After the list is assembled, it is re-organised from most general to most specific (figure 4.2). This is usually done twice in order to get a more accurate ordering.

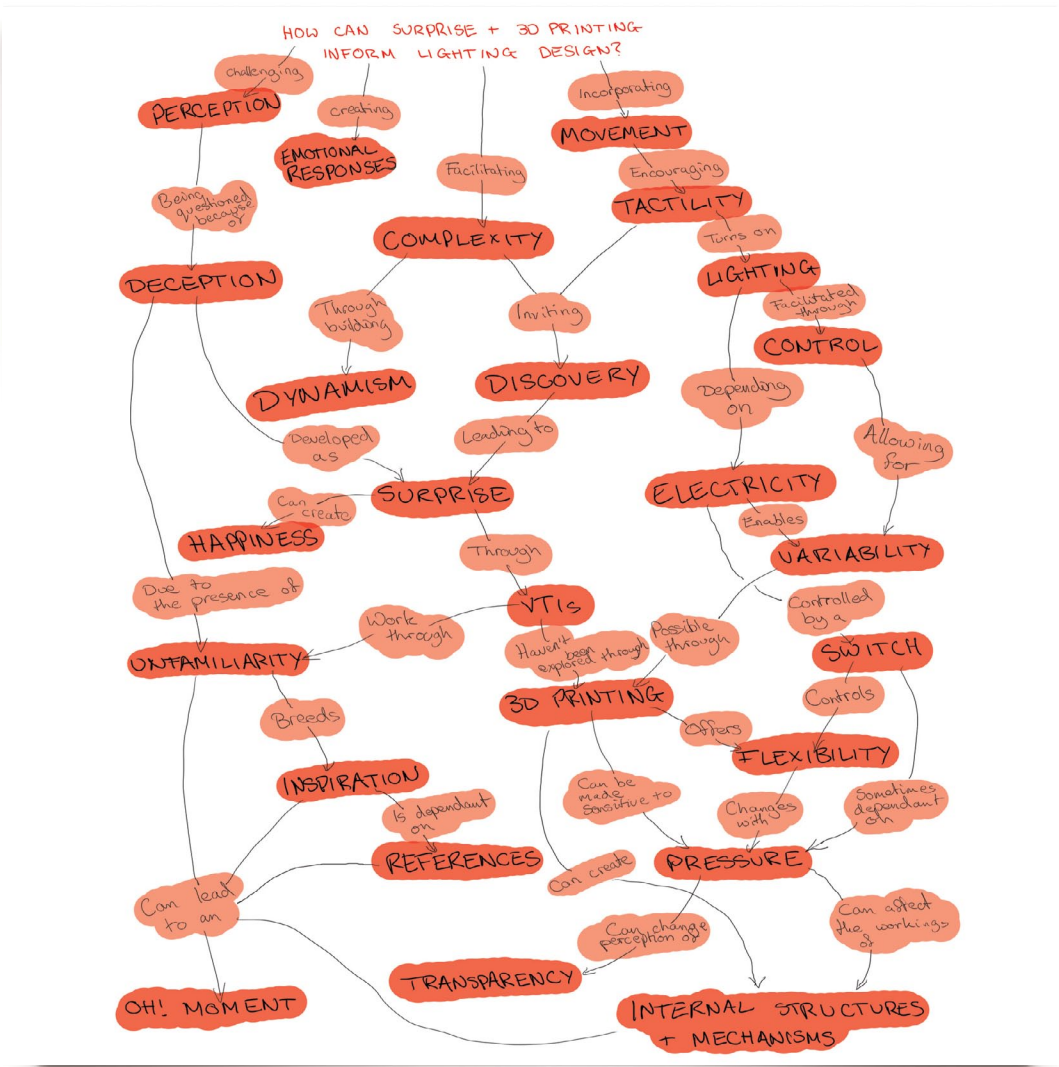
Subsequently, these words are arranged across a digital page (so that they could be re-organised and moved as needed) and connecting words were drawn (figure 4.3). These words drew connections between distinct terms, developing a web that highlighted and created emergent connections.



1. How can surprise & 3D printing inform lighting design?

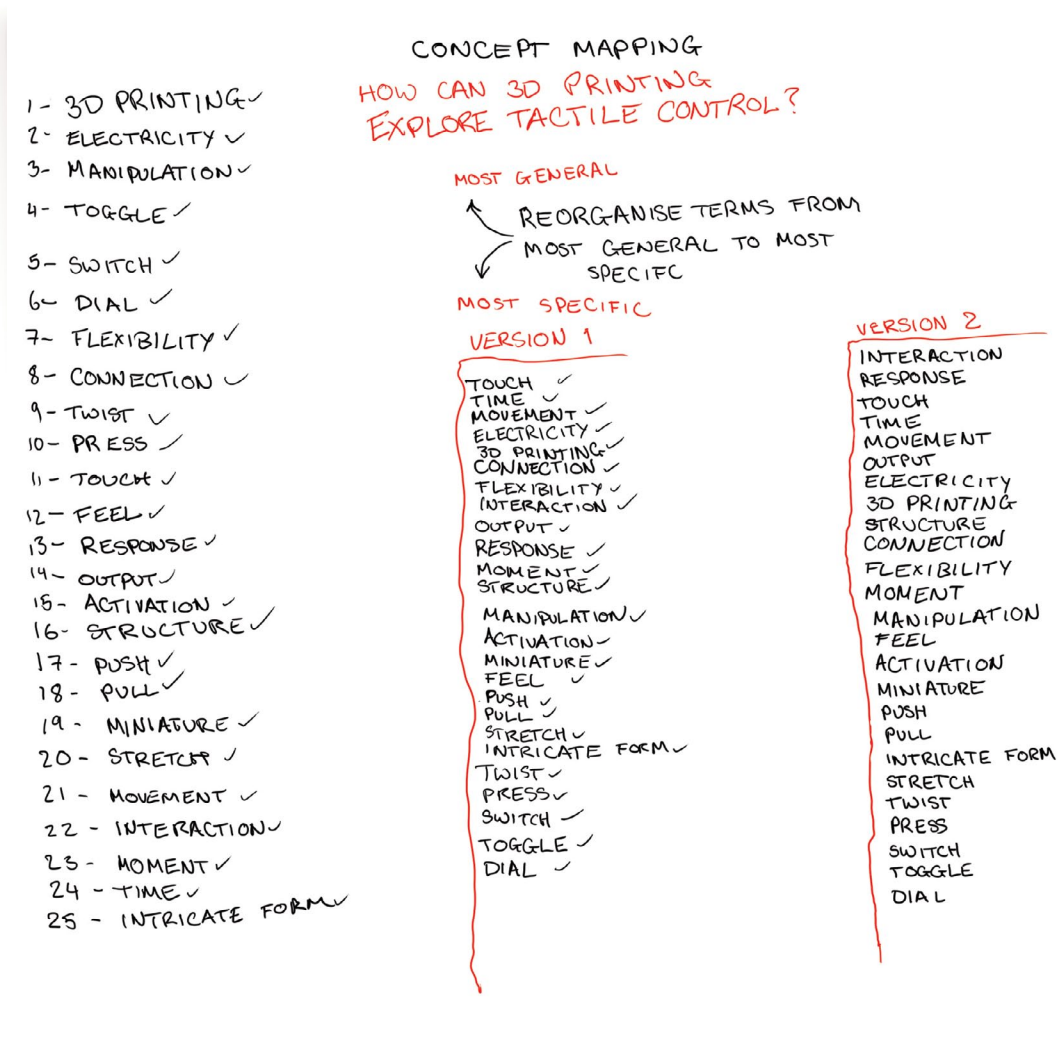
This concept map sought to develop a more cohesive understanding of the larger space that this design phase is operating in, by interlacing and weaving the two areas into each other.

Figure 4.2 - How can surprise & 3D printing inform lighting design? (Mapping Setup)



This concept map facilitated the connection between some distinct areas, highlighting the importance of tactility, discovery, control, and variability. To lighting designers, these areas may vary in importance, but PPP 3D printing and VTIs offered an opportunity to bring them together through a series of designs.

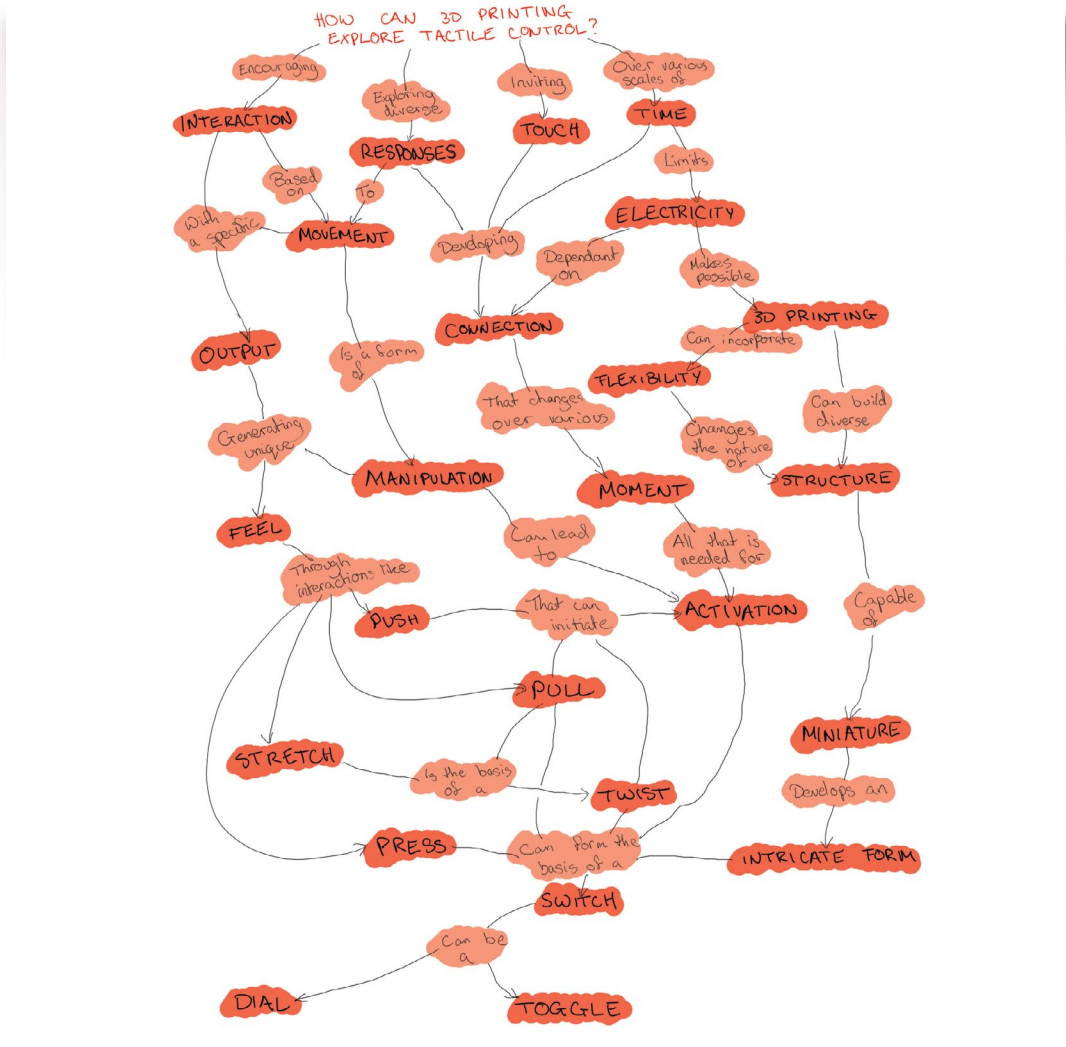
Figure 4.3 - How can surprise & 3D printing inform lighting design? (Map with connecting words)



2. How can 3D printing explore tactile control?

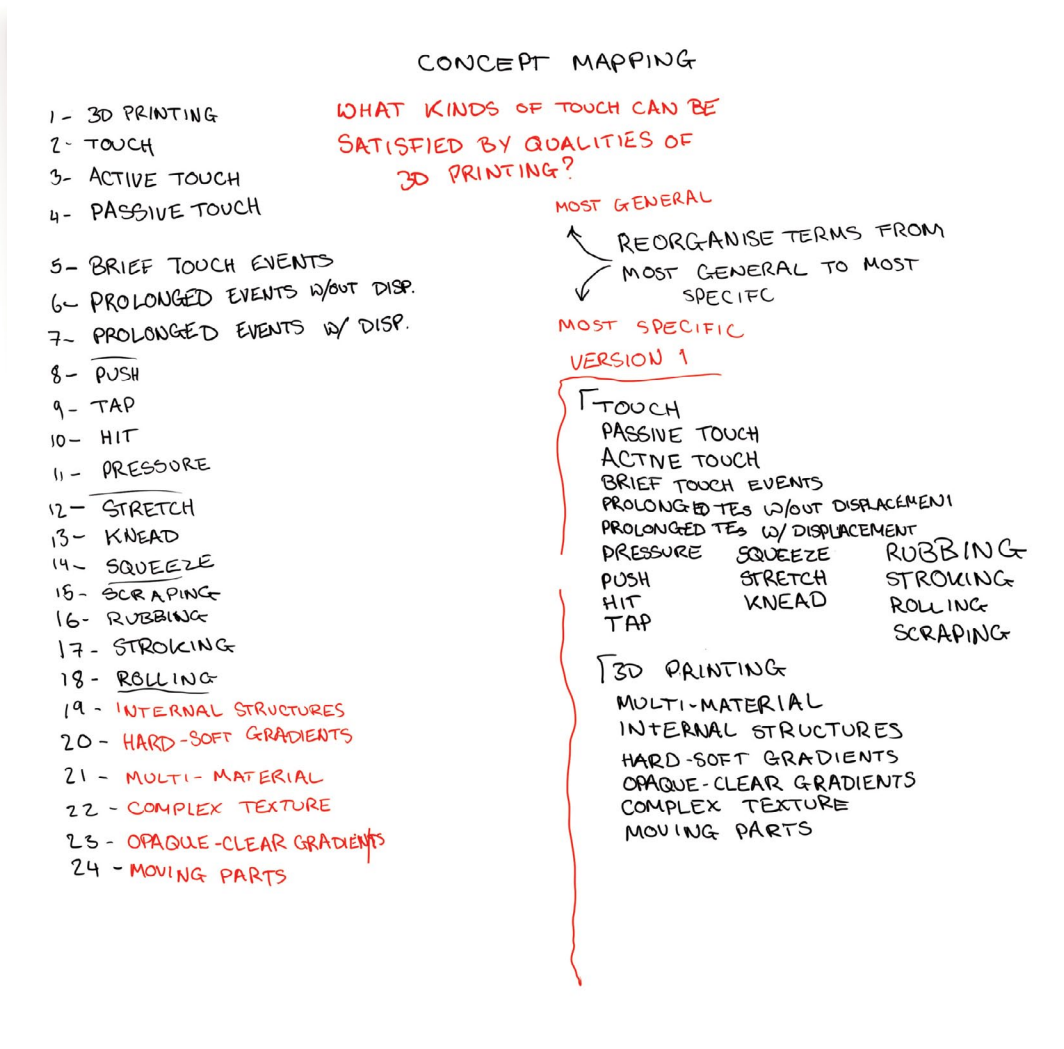
This second concept map explored the potential for 3D printing to engage with tactile control. This involved bringing together different ways an object could be touched, and looking at pathways that could be explored with 3D printing to facilitate tactile control of an electronic object.

Figure 4.4 - How can 3D printing explore tactile control? (Mapping Setup)



By combining various connection words, it became clearer what kinds of tactile interactions 3D printing could engage with and became evident that a further concept map was needed in order to look specifically at “kinds of touch” in relation to 3D printing.

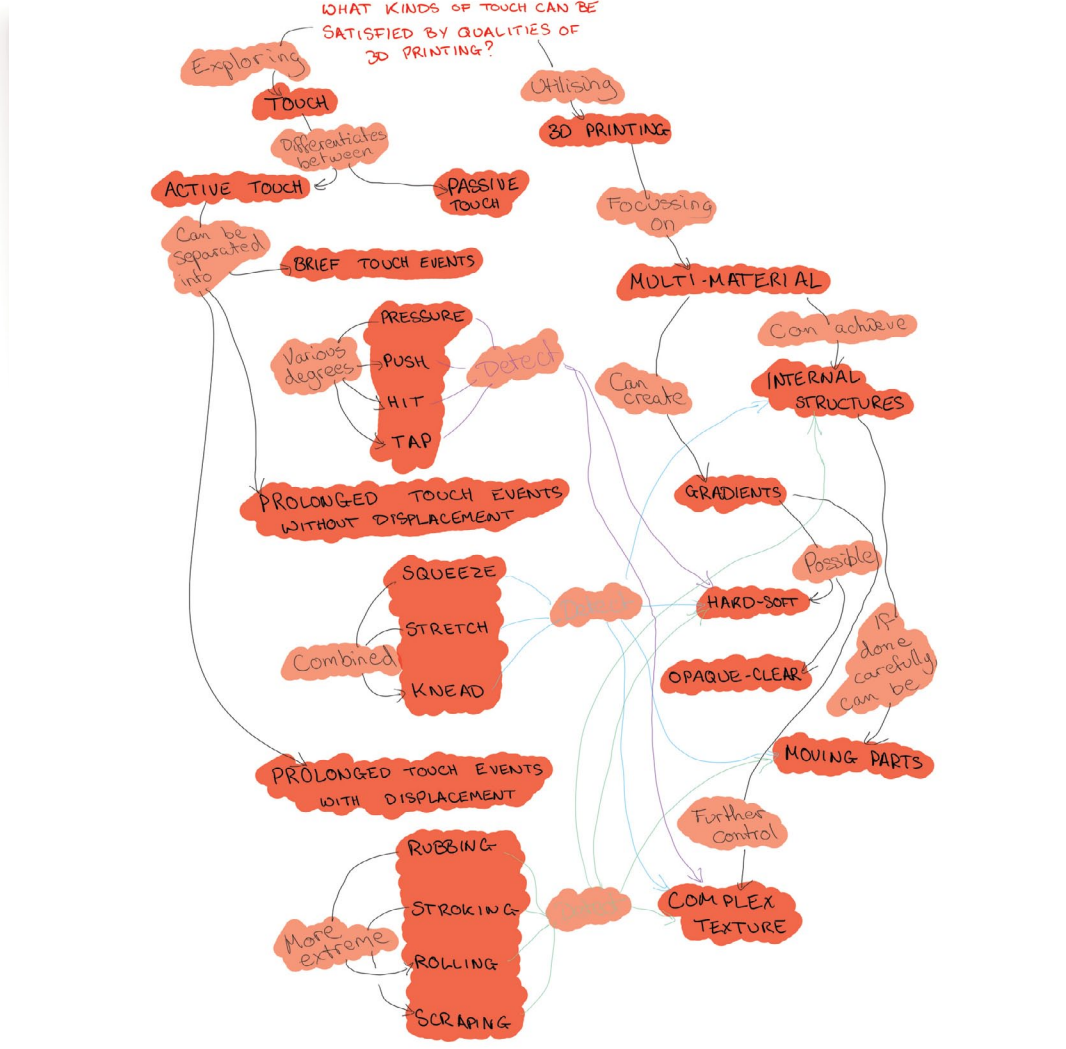
Figure 4.5 - How can 3D printing explore tactile control? (Map with connecting words)



3. What kinds of touch can be facilitated by qualities of 3D printing?

Exploring the nature of touch highlighted Gibson’s (1962) research into “active touch” (p. 477), where he suggested that there exist multiple kinds of physical events that stimulate the skin: “Brief events, ... Prolonged events without displacement, ... and Prolonged events with displacement” (p. 480). Heller & Schiff (2013) expanded on this description, suggesting that active touch was a key underwriter of the haptic perception of form. Unfortunately, this area of research quickly begins to fall outside the scope of this thesis. This concept map (figure 4.6 & 4.7) explores the potential of these kinds of touch in relation to 3D printing.

Figure 4.6 - What kinds of touch can be satisfied by qualities of 3D printing? (Mapping Setup)



Despite falling outside the scope, it was useful to mine this area for understanding of the kinds of touch that might be useful in lighting design. The concept map helped explore the types of motion and touch that 3D printing might be able to facilitate. One area of the research into touch connected well with the potential of the soft and flexible materials in PPP printing; where Katz (2013) suggested that “visually perceived elasticity is subject to verification by our sense of touch, but not vice versa” (p. 82). This suggests that even if users visually perceive soft materials as soft, there is still a possibility for a VTI to be elicited.

Figure 4.7 - What kinds of touch can be satisfied by qualities of 3D printing? (Map with connecting words)

	Rubberised Geode ▽	Collapsing Construct ▽	Tentacle Grasses ▽	Spiral Collapse ▽
What made it successful?	The way the form referenced comprehensible structures and understood materiality.	The expectation of severe rigidity being thwarted by the most softest forms.	The sense of play. The way the forms pushed against one another creating a compound movement. + Fun	The expectation of a solid form being revealed as a dynamic structure. + It proved to be one of the most positively responded to.
What can we learn?	Referencing understood forms is okay, but the interaction itself has to be fun, otherwise the surprise wearing off will likely kill it.	Sometimes it's what you don't see that's more important. Texture on clear SDP can make it seem opaque.	Multiple forms that have a certain degree of variance better than perfect uniformity. Again plays with multitude of smaller forms. "cute".	Careful separation between printed section can enable movement. Flexible capabilities of printed structure enables serious dynamism.
PHASE 2: What can the design focus on?	- Reference understood forms. - Explore fun, unique interactions - Explore lack of immediate clarity + encourage exploration - Mess with expectations	- Obstruction of view - Mess with expectations - Looks hard feels soft. - Texturing surfaces affects perception of them.	- Presence of the "many" - Displacement locally due to physical presence. - Variance between forms. "herd".	- Dynamic structure that can warp and change - Intense "reveal". - Flexibility - Internal structure - Fun!
What kind of touch does it engage with?	Prolonged events w/out displacement - Pushing - Exploring touch - Finger-based	Prolonged events w/out displacement - Full-hand - Crushing - Destructive? - Rough	Prolonged events with displacement - Small movements - Exploratory - Intimate - Delicate	Prolonged events with displacement - Revelatory - Expressive - Big movements
What specific touch interactions were observed?	- Stroking - Pressure - Kneading - Scraping	- Squeezing - Pinching - Scratching	- Stroking - Pushing - Pinching - Rubbing	- Stretching - Twisting - Pulling - Stroking

Morphological Analysis

Using the connections that were made between the concept maps, the Morphological Analysis was used to generate ideas and figure out what elements could be drawn from the chosen cube prototypes from the final phase of Design Phase 1. The analysis faced the 4 prototypes off against a series of exploratory questions. These served to develop an in-depth understanding of the knowledge and how it can be used to develop new lighting designs.

The questions that the analysis (figure 4.8) asked were:

1. What made it (the prototype) successful?

Figure 4.8 - Morphological Analysis used to analyse stand-out past prototypes.

Rubberised Geode ▽	Collapsing Construct ▽	Tentacle Grasses ▽	Spiral Collapse ▽
Reach-inside? Encourages tactile exploration of soft crystal structure. 	Dynamic Dome. Pressure on various parts of the dome trigger different aspects of light. Reference hard forms. 	Toggle tentacles. Image Object covered in large tentacles, some of which hide toggle switches. 	Pressure plate. → Incorporates reveal of light as well as underlying texture. Encourages exploration + tactile curiosity. → Integrate quad-delay?
Flexible structure - Use flexibility to catch corner under switch. Flex triggers switch. 	Structureless tube - Faceted collapsing structure. Uses LED strips to maintain flex. - Compress in places to activate it. 	Flex + tension response - Reaction of the individual tentacles determines brightness of LEDs. 	Flexible column. Can be connected to multiple different points around the base, triggering a different reaction.
Peel-back? Various sections of hard-looking areas can be peeled back to reveal switches. 	Crush cube - Crush cube in order to activate various switches. 	Electric Grass - Wire in SDP - Connects to others around it. 	Stretch-into-place - Reliant on flex sensors - Multiple flex sensors enhance dynamism
Connective flex. Flex rigid looking structures to achieve light. 	Squeezey Fluorescent Shaped + made to look like a fluorescent tube Squeezing right points reveals activation. 	Raised Dot board. Caves where correct activation point is found. 	Flex + hook - Separate parts are hooked together - Guiding structure. - Creates connection.
Exploratory Edges - Flick switches under the edge of a hard looking soft corner 	Butterfly lamp - Press various points in and see visual movement and illumination reflect outcome. 	Toggle switch conversion Large-scale rather out of SDP and a toggle switch 	Stretching supported connector - Connects to another part of the structure - Self-supports when not in use.

2. What can we learn from the design?
3. What could a new design focus on?
4. What kinds of touch does it engage with?
5. What specific touch interactions were observed?

Armed with the knowledge drawn from the analysis, I brainstormed several ideas for lights and interactions based off each of the prior prototypes from Design Phase 1. This series of mini sketches and ideas (figure 4.9) were built up and developed further in the next section.

Figure 4.9 - Miniature sketches and concepts developed out of the Morphological Analysis.



Development: Interaction & Form

Using the understanding developed from the Concept Mapping and Morphological Analysis, this section tracked the development of the four light designs from the inception of the ideas through to the final forms and interactions. Sketching was carried out across a variety of media for the various stages of the lights (figure 4.10). The approaches from the end of Design Phase 1 were brought into the fold once the ideas were being further developed; in order to focus those ideas more specifically.

- » Approach One: Visually referencing recognisable forms, objects and structures, but making them tactually different. (**Rubberised Geode**)

Figure 4.10 - A collection of the most important preliminary sketches.

- Crystalline Geode: Tactile exploration of a complex, yet familiar form.
- Flexible Crystal: Utilise unexpected flexibility as a control mechanism.
- Peel-Back: Use hidden flexibility as a revealing device, exposing switches.
- Connective Flex: Connect hard-looking components to each other for light.
- Exploratory Edges: Hide switches and light under a solid-, hard-looking edge.

- » Approach Two: Using material variances and unfamiliar forms to encourage interaction. (**Tentacle Grasses**)
 - Toggle Tentacles: Encourage exploration of a form by hiding switches beneath repeated forms.
 - Torsion Response: Flex of collective forms determines brightness.
 - Electric Grass: Exposed wiring creates flickering touch-reactive light.
 - Raised Dot Panel: Textured board that caves at certain points.
 - Toggle Conversion: Create a collapsing form that translates motion into a switch.

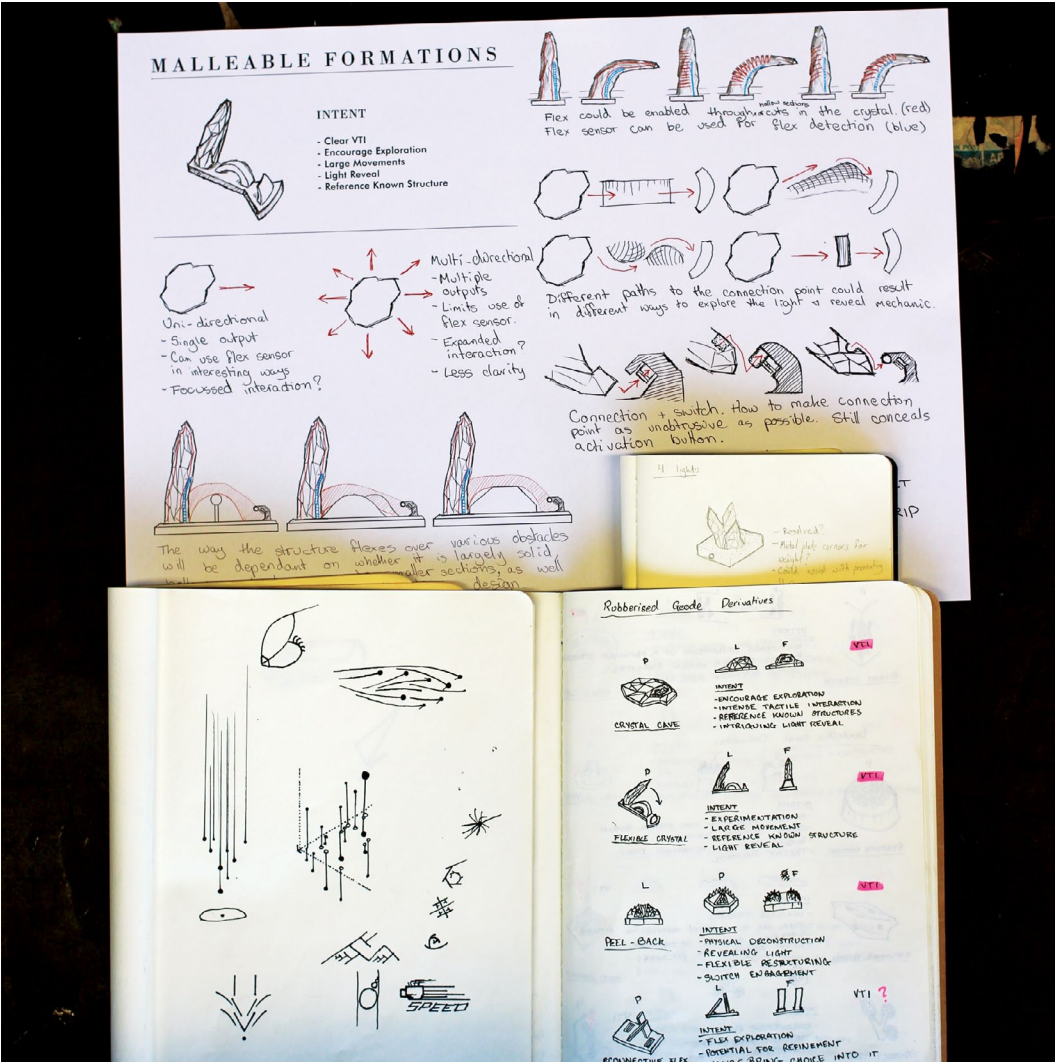
- » Approach Three: Suggesting surfaces have texture when they are actually smooth, through the use of an illusion. (**Spiral Collapse**)
 - Pressure Plate: Use textured-looking button to invite interaction: soft reveal.
 - Flexible Column: Connects textured-looking spring-like pillar to multiple points for different light.
 - Stretching Connector: Use flex sensor to measure bending and activate light.
 - Flex & Hook: Use separately textured forms to connect circuit and initiate light.
 - Fragmented Connector: Reveals segmented form when connecting circuit.

- » Approach Four: Using internal structures to challenge the initial visual perception of the material properties. (**Collapsing Construct**)
- Dynamic Dome: Pressure on various points elicit different illuminations.
 - Structureless Tube: Suggest rigid form that collapses and compresses in distinct sections.
 - Crush Cube: Crush sharp-edged structure to activate light.
 - Squeezy Fluorescent: Suggest structure through recognisable form, but make it soft.
 - Butterfly Construct: Use internal structures to create movement externally.

These designs were assessed for their ability to meet and respond to the criteria. This was done continuously during the sketching and ideation process, highlighting designs that would fit into the criteria as well as responding to the ideas and concepts brought forward in the morphological analysis and concept mapping. The following sections explored the development of the chosen designs. When developing the interactions for the lights, reflections back to the concept maps were used to develop ideas around how the interactions could be facilitated, as well as the electronics that could be used. Considering the fitting of the electronic components was a key factor in the design process, as a lot of the designs ended up fitting a variety of components into the body of the lights.

Design One: Malleable Structures

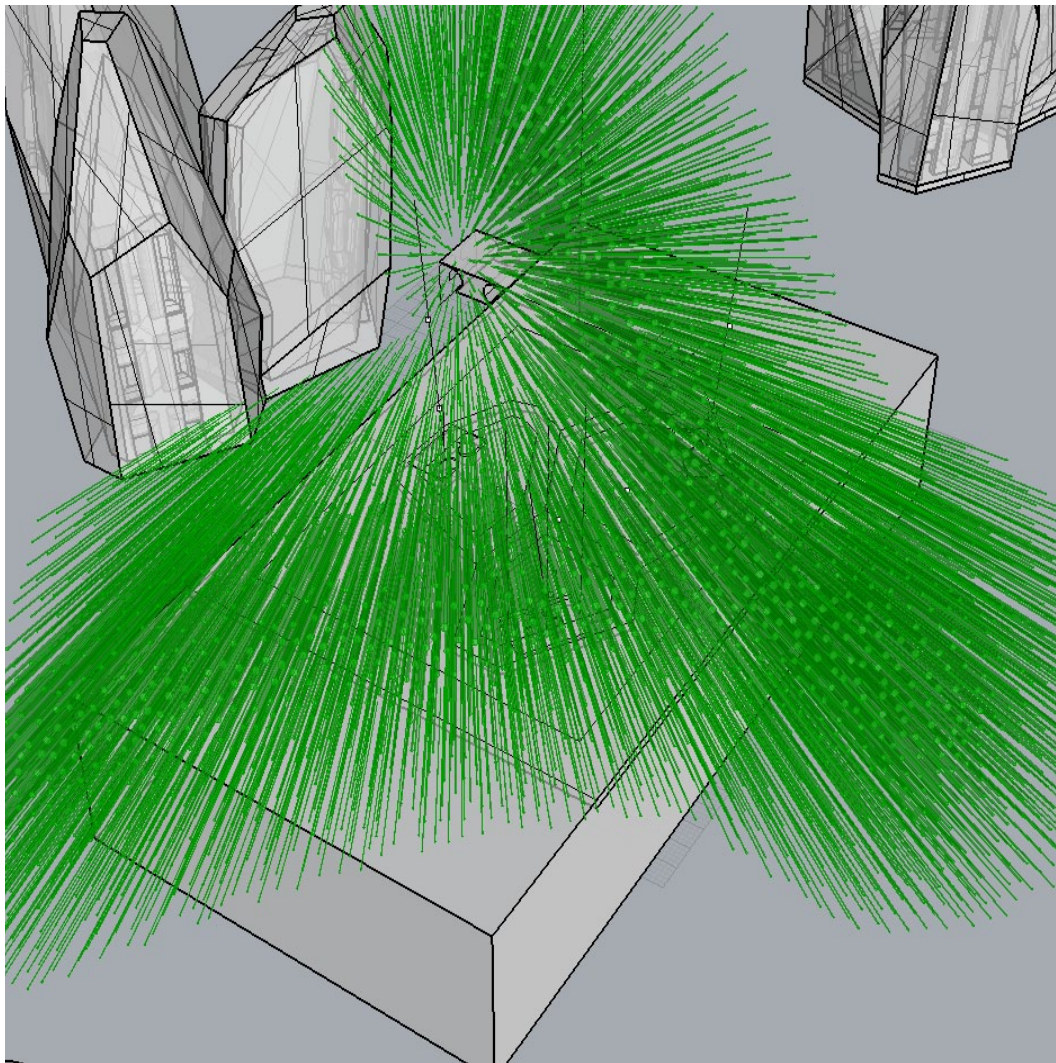
Design One expanded on the potential that Rubberised Geode brought in Design Phase 1. The use of crystalline structures as a reference to hard structures was well recognised and appeared to showcase a clear VTI. In a sense, this design seemed an obvious choice, especially after the reveal of the light qualities attainable with PPP printing. By thinning the walls of the structure and printing in the softest, clearest printing material, a very flexible and



malleable structure could be developed. This facilitated a variety of interaction scenarios, including compression, flex, touch-sensitivity, or the reveal of hidden texture. “No way. I was so sure it was hard. It looks like a crystal.” (Participant 5 on Rubberised Geode). This quote really captured the reaction that was sought in this design. Extrapolating this to the extreme could create a wonderful moment of “Oh wow”.

The direction that was ultimately chosen involved the use of a flex sensor that would register when the crystal structure was flexed in one direction. This concept was expanded in complexity to include two more crystal structures of differing sizes. Having three different crystals to control would allow the user to have choice and control over the amount of light. The choice of interaction was to separate the movement even further from what the form language of

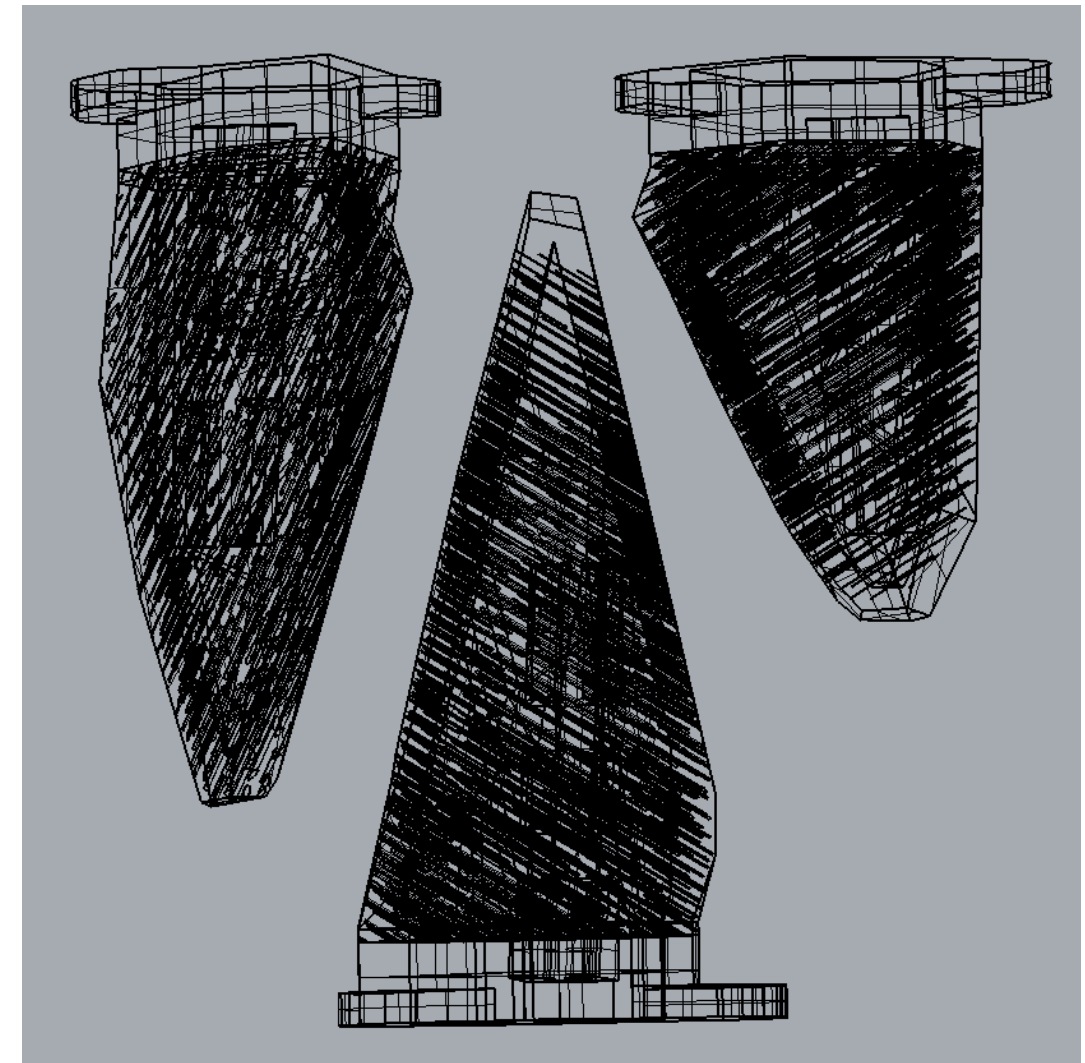
Figure 4.11 - Refining sketches for Design One.



the crystal suggested. This led into giving the user no obvious course of action: no clear switch would be in sight, encouraging exploration and curiosity. The interaction was designed to become clear as soon as the user knew the crystal structures were soft. Once they flexed the crystals away from the middle, the light in that crystal would fade up, casting an ethereal light from within.

Designing the light involved the use of extensive CAD modelling as well as the employment of Grasshopper for parametric design (figure 4.12). Modelling the crystalline structures involved building them in relation to each other from the start in order to ensure a smooth fit. A key enhancement was the choice to include textural/visual occlusions into the design. This was to imbue visible flaws and imperfections into the form (Using a blend that was translucent against the clear material), similar to real crystals and gemstones. The texture

Figure 4.12 - Employing Rhino & Grasshopper for Design One. By using an attraction field, a "realistic" series of occlusions could be developed in the gem-like forms.



was built using a linear projection of a field of polygons that had their size adjusted based off their proximity to a curve (figure 4.13). This allowed for the creation of a seam of varying density, as opposed to a uniform application across the crystals. This linear projection passing through at the same angle would ensure visual consistency and continuity across the crystals. The CAD modelling process here also considered the base of the model and the cavity where the 3D printed components would attach. By extending the prints into the base and having a wide foot for each crystal, this would allow the prints to be fixed into the structure. The crystals also had a spine arranged on the bending side of the crystals so that the flex sensors could be attached into the crystals easily. The three crystals were arranged on their sides and printed separately. This was done to improve flexing strength by having the layers of printing run along the length of the crystal structure.

Figure 4.13 - Occlusion and crystal development for Design One.

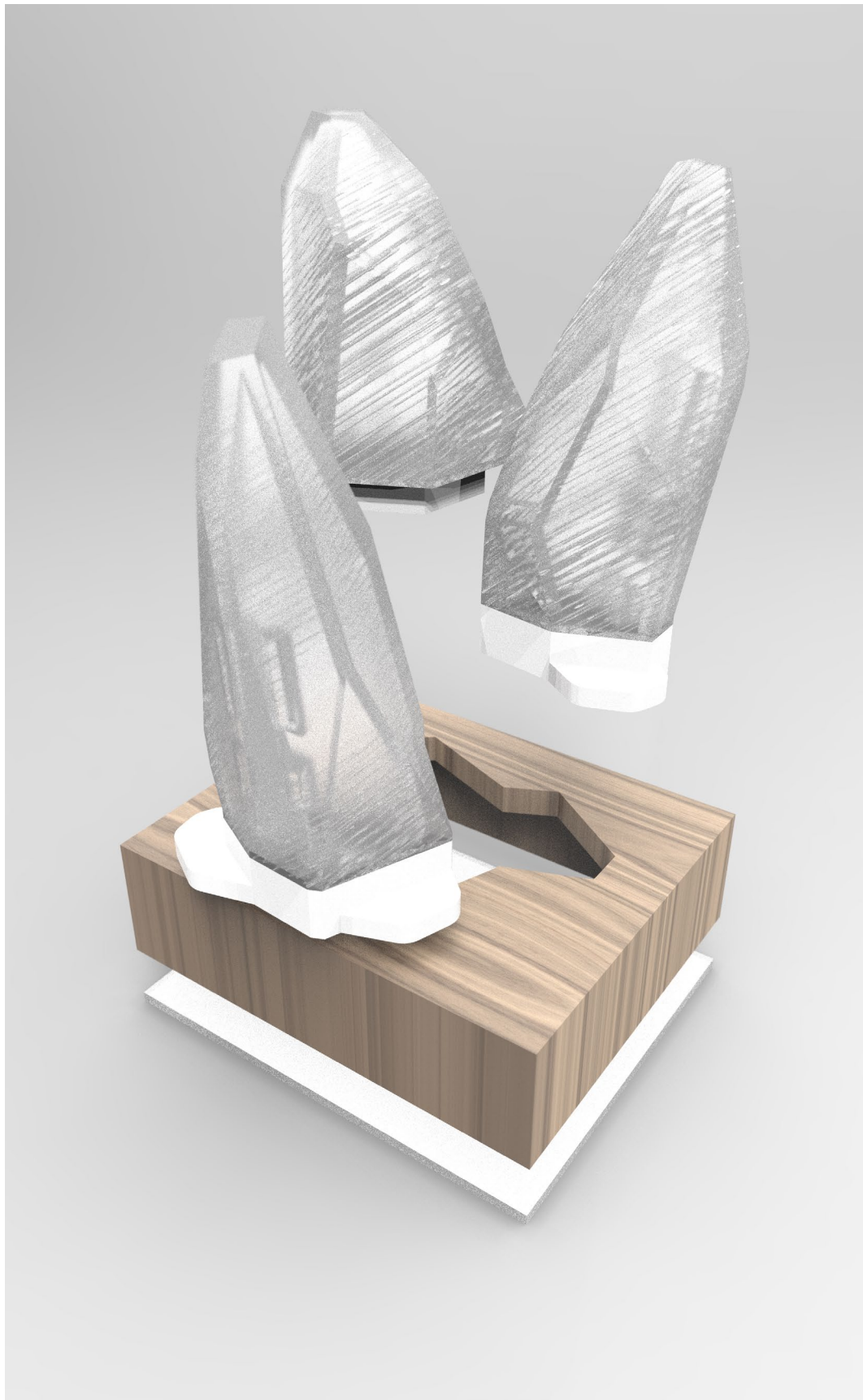


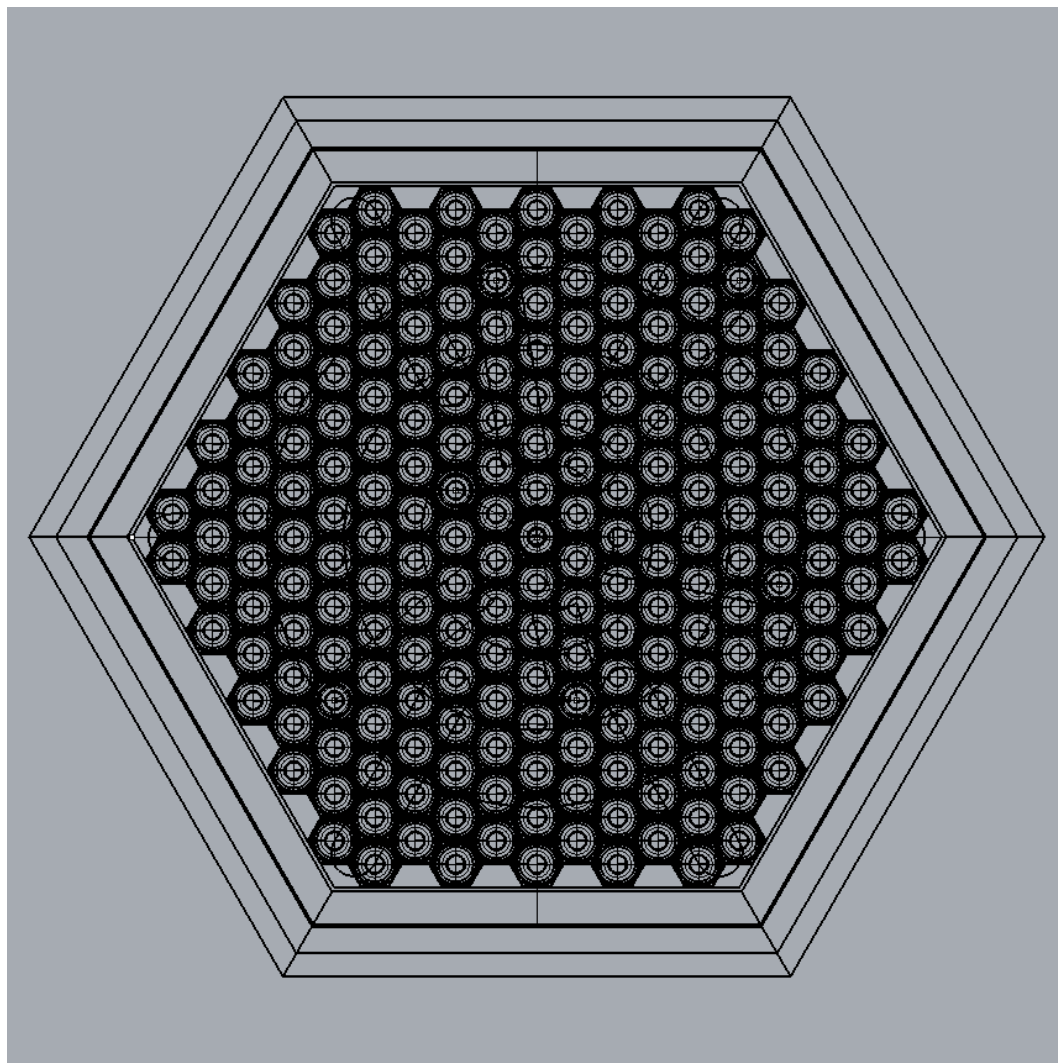
Figure 4.14 - Finalised render of Design One, exploded.



Design Two: Organic Formation

Design Two expanded on the interaction potential identified with *Tentacle Grasses*. One of the rapid-fire designs (*Toggle Tentacles*) highlighted the potential of embedding switches inside the individual tentacles. Originally conceived in a number of different forms, the design was ultimately orchestrated as a hexagonal prism that would incorporate a rotating top half. The purpose of the rotating top half was to potentially re-set the surprise between uses, forcing the user to re-find the embedded switches. “It moves in such a strange way!” (Participant 10 on *Tentacle Grasses*). This quote invited the design to take some outlandish steps, exploring the potential of extrapolating the ‘weird’ interaction to the next level.

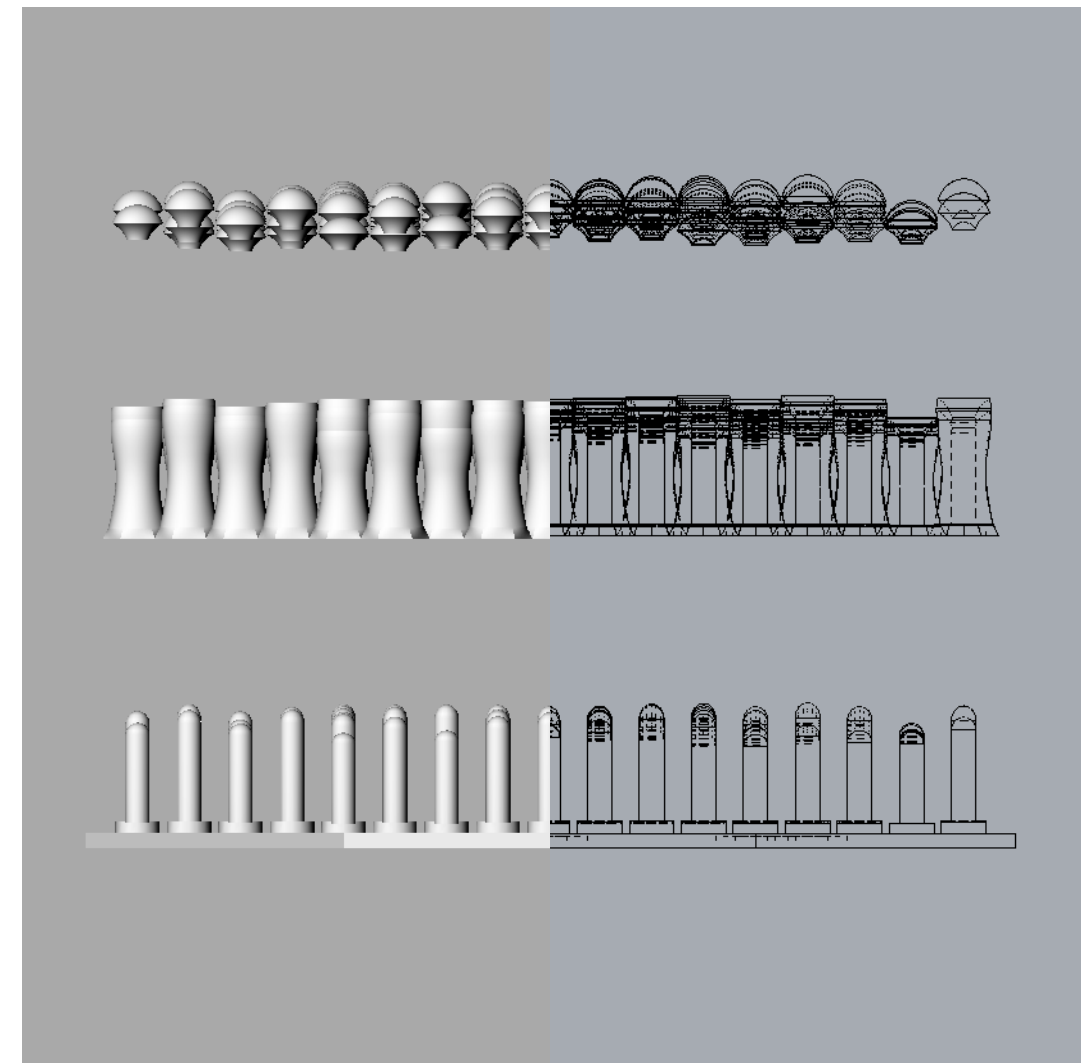
Figure 4.15 - Refining sketches for Design Two.



The 3D printed component would sit at the top of the prism, with 6 of the tentacles housing switches inside them. By making them more substantial than the tentacles from the *Tentacle Grasses* in Design Phase 1, they would be able to fully shroud the toggle switches. The lights for this design would be individually connected to the toggle switches, providing six different light panels to control. The interaction was so the user would have to stroke and prod the organic structures until they found the tentacles that provided resistance, and activate the lights.

This structure required extensive use of Rhino and Grasshopper (figure 4.16), as the structure included over 150 individual organic forms, of which six had hollow sections for the switches. The non-toggle organic forms were each made up of multiple PPP blends, in order to reinforce them when touched. The

Figure 4.16 - The structure was built from a hexagonal grid, with over 150 individual components.



tops of the organic forms were made of the hardest material, while the main body of each was designed with a much softer blend. The inside of each of the non-toggle components had a reinforcing spine made from a more rigid material. The structural breakdown of a filled component was meant to emulate one filled by a toggle switch (figure 4.17) in order to make the correct forms harder to find.

Grasshopper was used to alter the composition and the proportions of the various individual elements, in order to ensure a more organic look to the collection of forms. The structure of the rest of the light was designed to use laser-cut acrylic and hand-worked ash timber. The transmission of power from the base to the top half of the light was facilitated by a 3.5mm audio connector, so that it could spin endlessly without needing connecting cables.

Figure 4.17 - These images show how the organic forms were reinforced and how they facilitated the toggle switches.



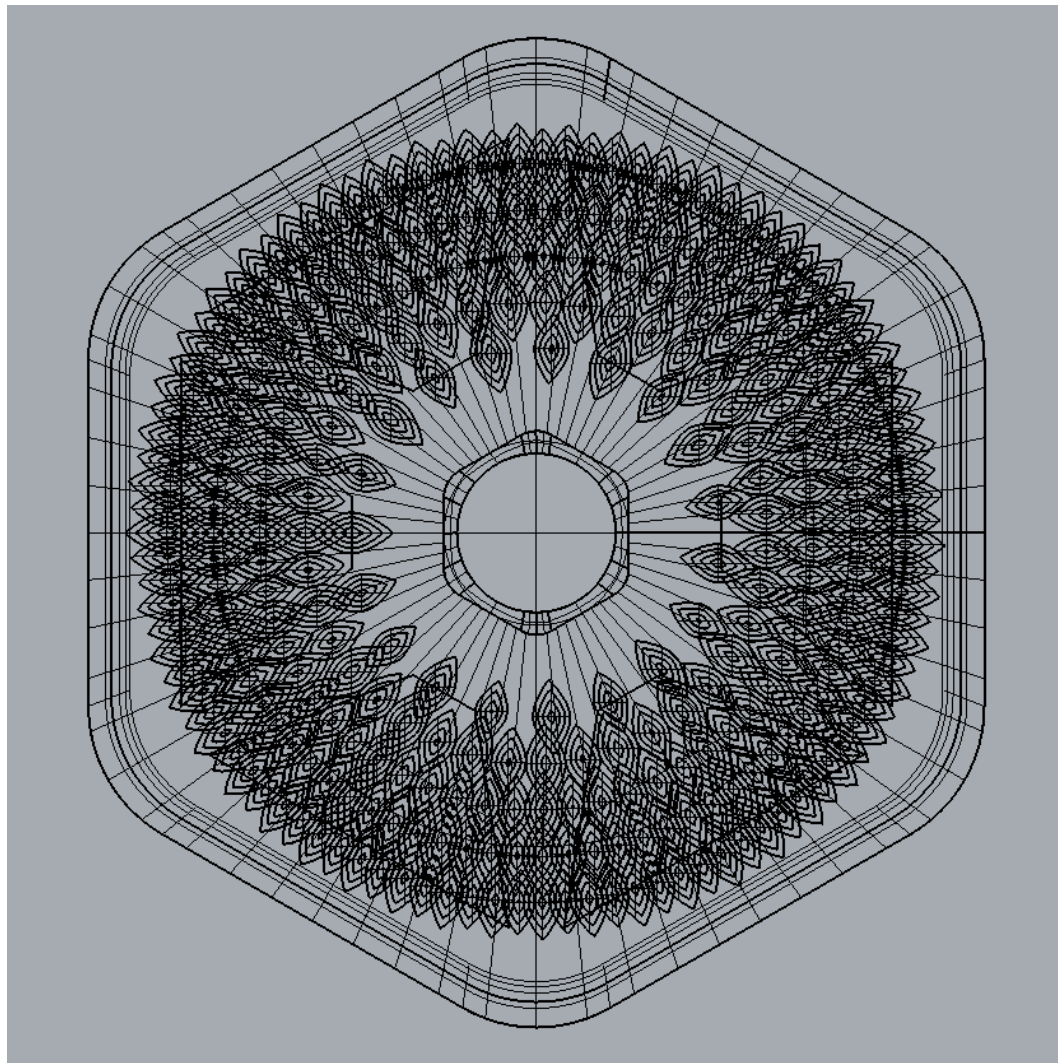
Figure 4.18 - Finalised render of Design Two, exploded.



Design Three: Spiral Connection

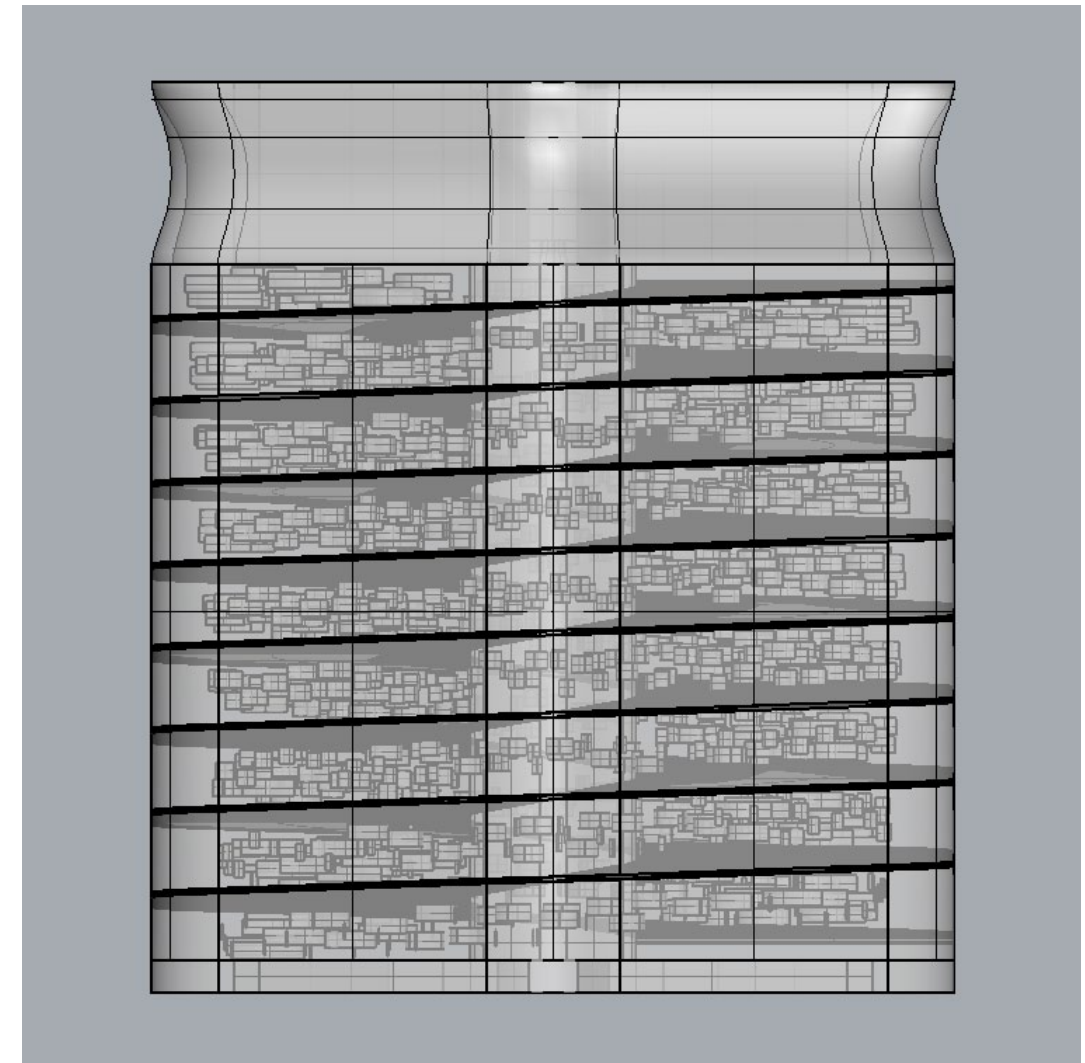
This design was built off the effectiveness of the VTI-inducing form *Spiral Collapse*. The design was further developed in the sketches at the beginning of this phase, exploring the potential of various connection/activation techniques. The challenge for this design proved to be devising a way to make the interaction feel natural. Other areas that were enhanced was the visual perception of texture, in line with the VTI and approach that was being targeted. “This one is like a super-cool slinky.” (Participant 1 on *Spiral Collapse*) “This is way smoother than I thought it was going to be.” (Participant 2 on *Spiral Collapse*). These two quotes exemplify the interaction and VTI that was the goal with this design.

Figure 4.19 - Refining sketches for Design Three.



This was done by suggesting a texture inside the structure and expanding the texture on the outside of the form, lengthening the structure and expanding on the number of coils. I continued the theme of the hexagons from the previous light, and utilised them here as well. These were softened by rounding the corners of the hexagon; further highlighting the layering and suggestion of texture. The interaction here was akin to a plugging motion, but rather than using a perceivable, obvious connection, the motion and electrical interaction were designed more poetically. This proved to be a situation that was perfect for a reed switch; a switch activated by the presence of a magnetic field. By embedding a small magnet into the head of the spiral connector, I facilitated an invisible connection. Transitioning this design into Rhino, Grasshopper was used to handle aspects of the CAD modelling, specifically the creation of the 3-dimensional texture on the inside of the spiral (figure 4.20). The way the

Figure 4.20 - The pattern inside the spiral section was built through the use of recursive Grasshopper code that changed the size of a shape over time.



texture was built was based off realisations made through experimenting with light in Design Phase 1. Even in materials that were not quite transparent, it was still possible to see small volumes of a more opaque material suspended in it. This would allow the texture to be highlighted by the light emanating from the base.

The ends of the forms were in contact with frosted acrylic plates in the wooden base that would serve as the primary points for light emission. LED strips would be fitted below the plates to shine light up into the 3D printed spiral when the circuit was closed. Not using the clearest PPP material was important to achieving the desired light quality, since if the material were too clear; the light would not volumetrically *fill up* the form quite as much, and more of the light would refract straight through it.

Figure 4.21 - Section split of the spiral structure, with texture visible.

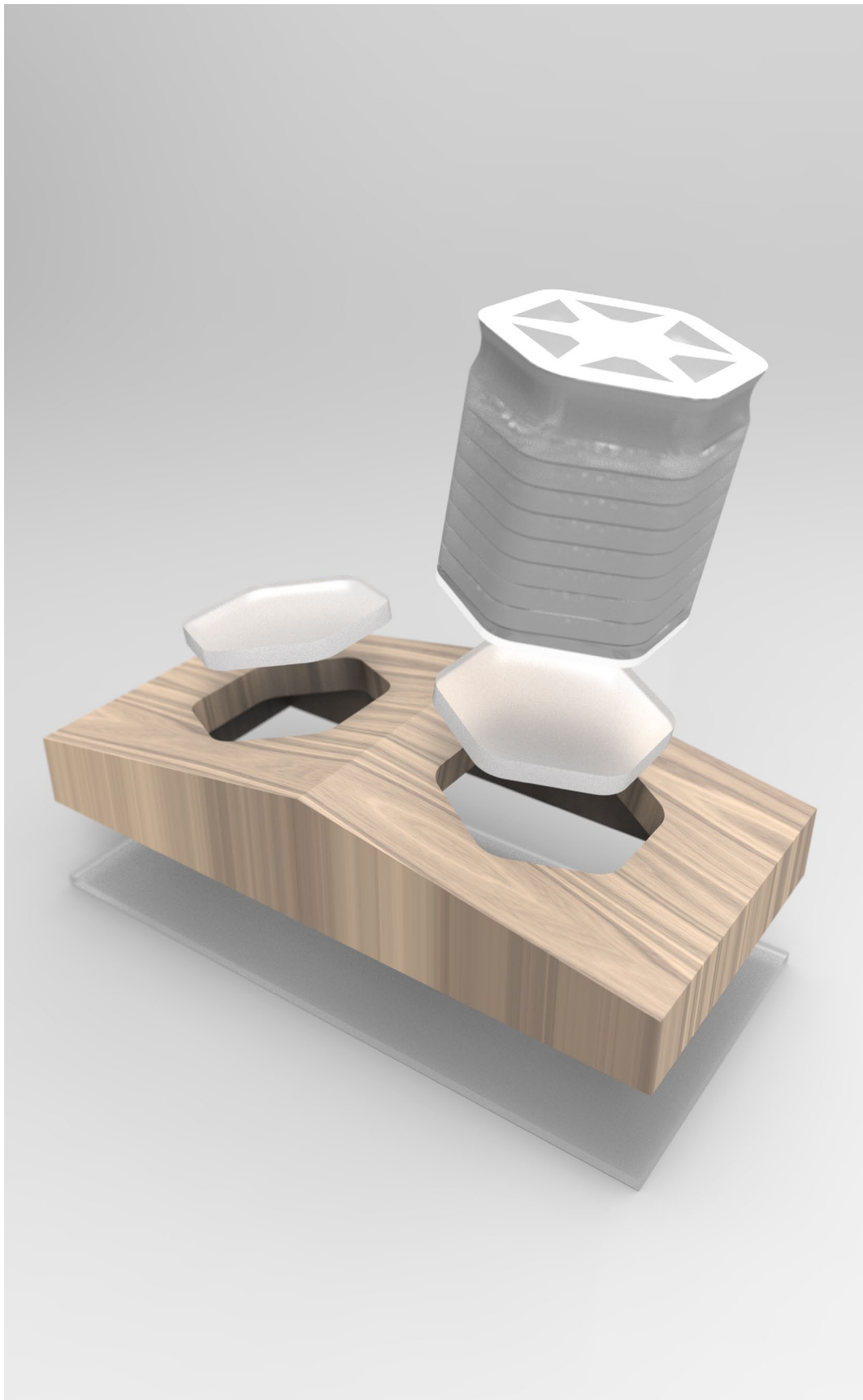
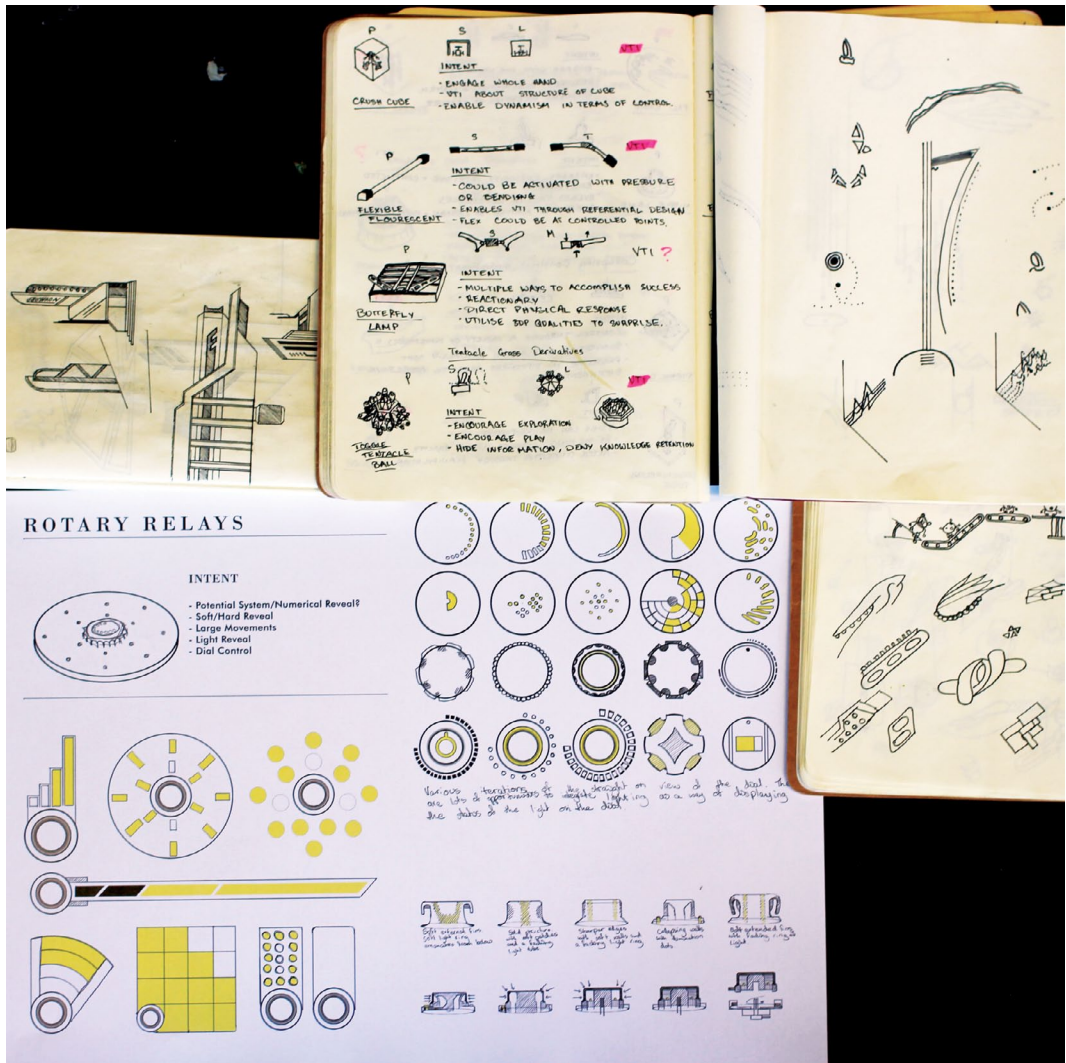


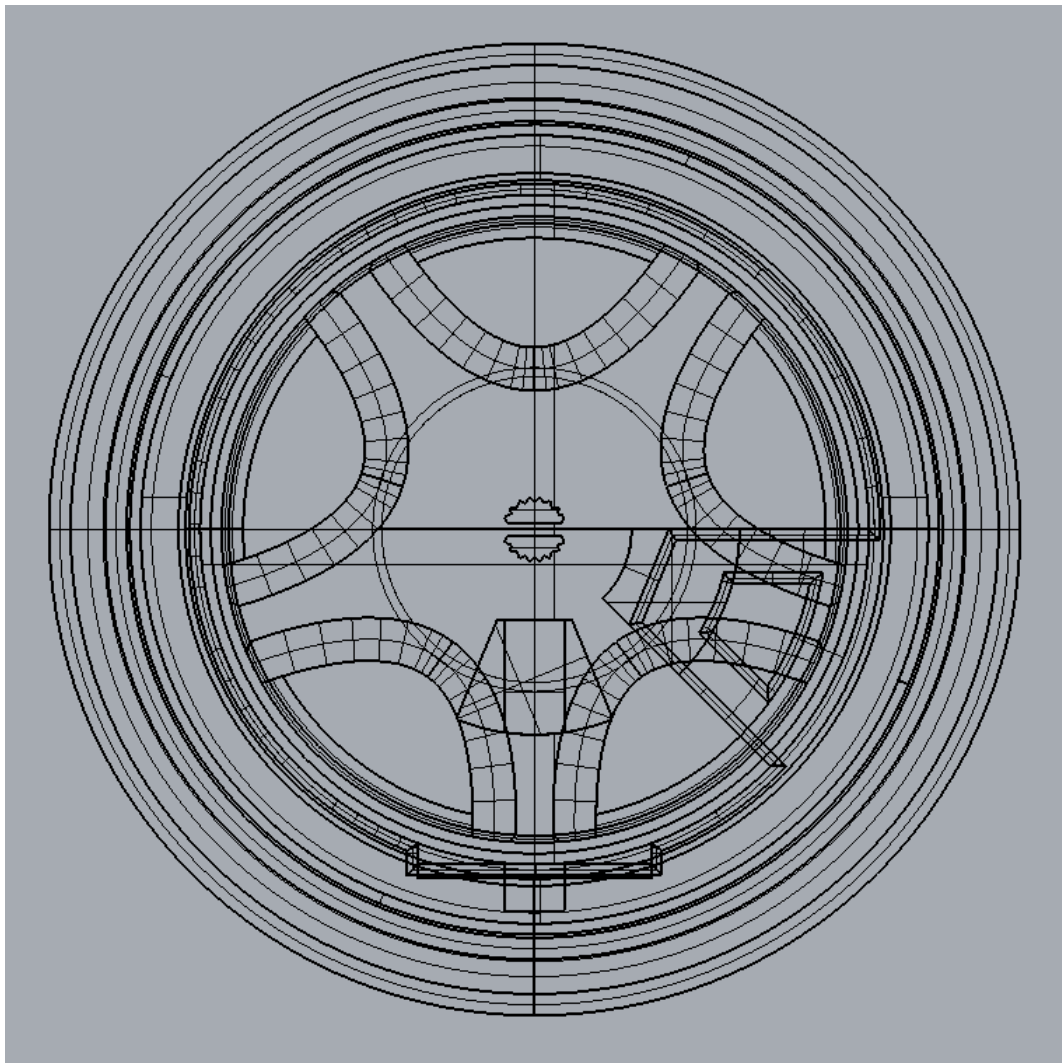
Figure 4.22 - Finalised render of Design Three, exploded.



Design Four: Rotary Relays

Design four employed elements from *Collapsing Construct*. Unlike prior designs in this phase, the design of the surrounding bezel was considered as significantly as the primary 3D printed component. One thing *Collapsing Construct* achieved was the illusion of pure rigidity. By having a smooth, round, sharp-edged form, there was little to suggest it was anything but what it appeared to be. By creating a void in the structure and texturing the inside of the void, the illusion seemed obvious to the viewer: there was something else inside the shape. This design capitalised on that same concept, but it was adapted to reference a more common shape in electronics design; the dial. “It looked sharp and hard-edged!” (Participant 6 on *Collapsing Construct*). This

Figure 4.23 - Refining sketches for Design Four.

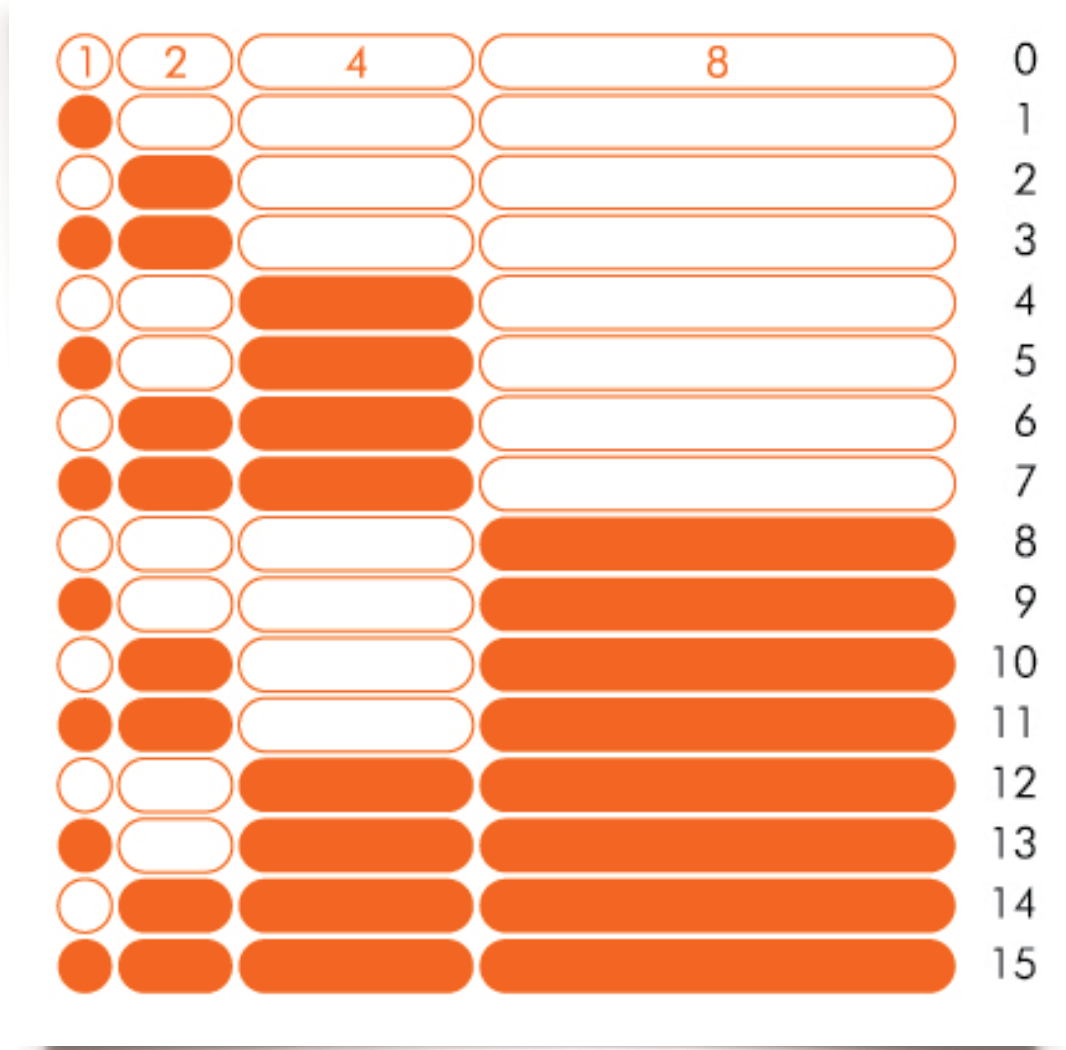


highlighting of the recognisable form featured heavily in this design process, and served to outline the plan for the structuring of this design.

The design of the interaction resulted from the choice to keep it recognisable as an existing dial (figure 4.23) for a stereo or a dimmer. This was to be expanded by toying with the creation of textured voids on the inside of the dial. This was broadened to become a functional element of the design, allowing the compression of the dial to lead to the user creating their own finger-holds by squeezing (figure 4.24).

Expanding the design of the dial for the use of the entire hand enabled more considerations for the overall form and illumination from the design. The concept for the activations of the light was born out of a concept for a 4-way

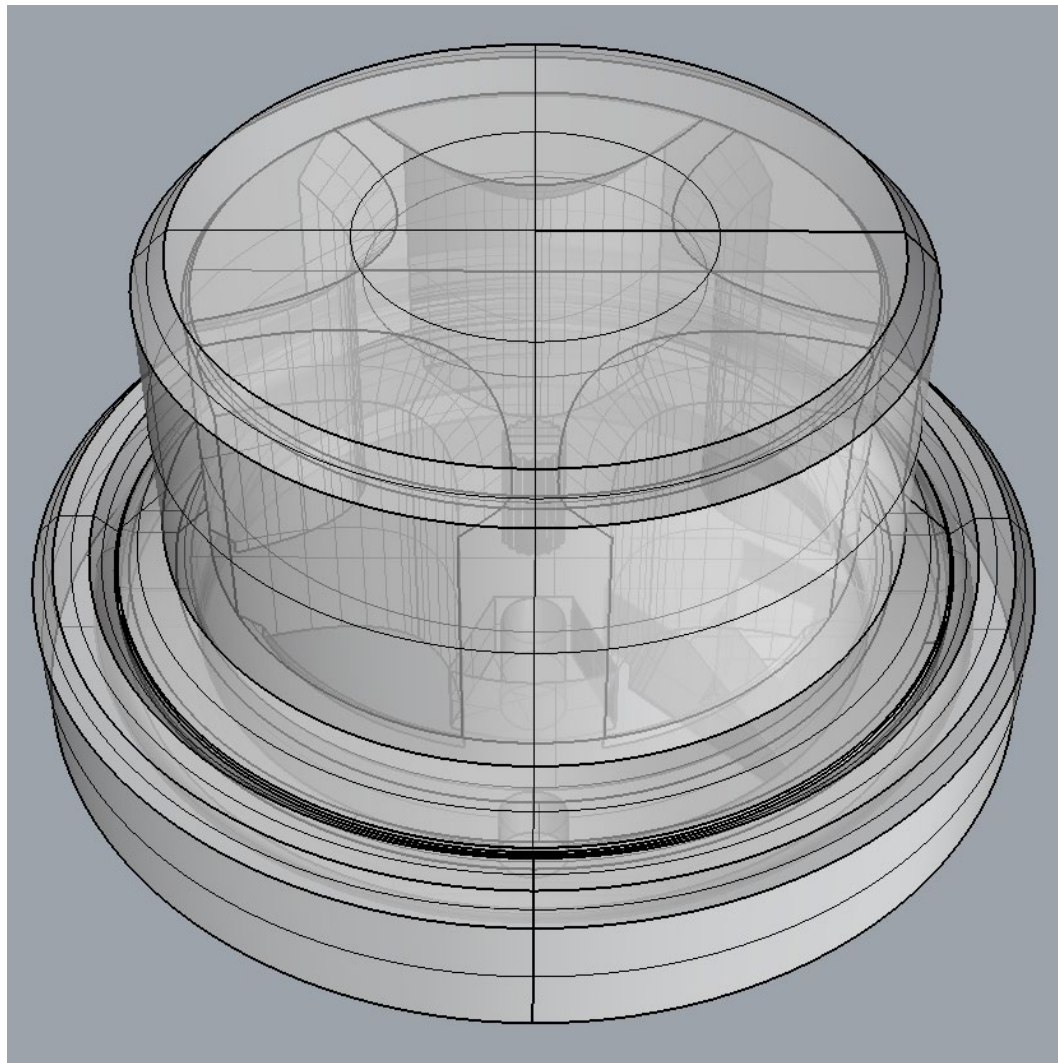
Figure 4.24 - The layered and spaced construction of the dial allowed it to be an all-in-one moving print.



binary lighting system. By having four different sets of lights, each with different total nett brightnesses (1 section of LEDs, 2 sections of LEDs, 4 sections of LEDs, and 8 sections of LEDs), each sitting on a different relay switch, it would be possible to create a mechanical dimming system. By turning the four sets of lights on and off in a sequence, a light system could be created whose nett brightness could transition in a very clear, systematic way from 0 'light' to 15 'light' (figure 4.25).

This physical cycling up of the lights was a major element in considering the design of the rest of the system. There were a myriad of designs proposed through the sketching process, ultimately leading to a design where the metric, quantified nature of the lighting was showcased. By splitting and grouping the lights into patterns that radiated from the central control node, the user was

Figure 4.25 - Illustration of mechanical dimming system for Design Four.



given a taste of the light sequence might be before actually activating the lights. The grouping and radiating pattern was iterated in CAD modelling, exploring the potential of a CNC routed base and laser cut acrylic disks for the lights.

One of the key decisions for this design was to make the dial a single print that had the rotation and bezel already built into the form, using PPP's ability to build working moving parts, the dial could be built as a single print (figure 4.26). This was designed to facilitate a smooth, gliding rotational action. The underside of the dial had notches prepared for the insertion of the electrical controls into the system as well, in order to cut down on post-processing.

Figure 4.26 - The bezel and the dial do not actually touch in the construction. There is a tolerance of 0.3mm between them in every axis.

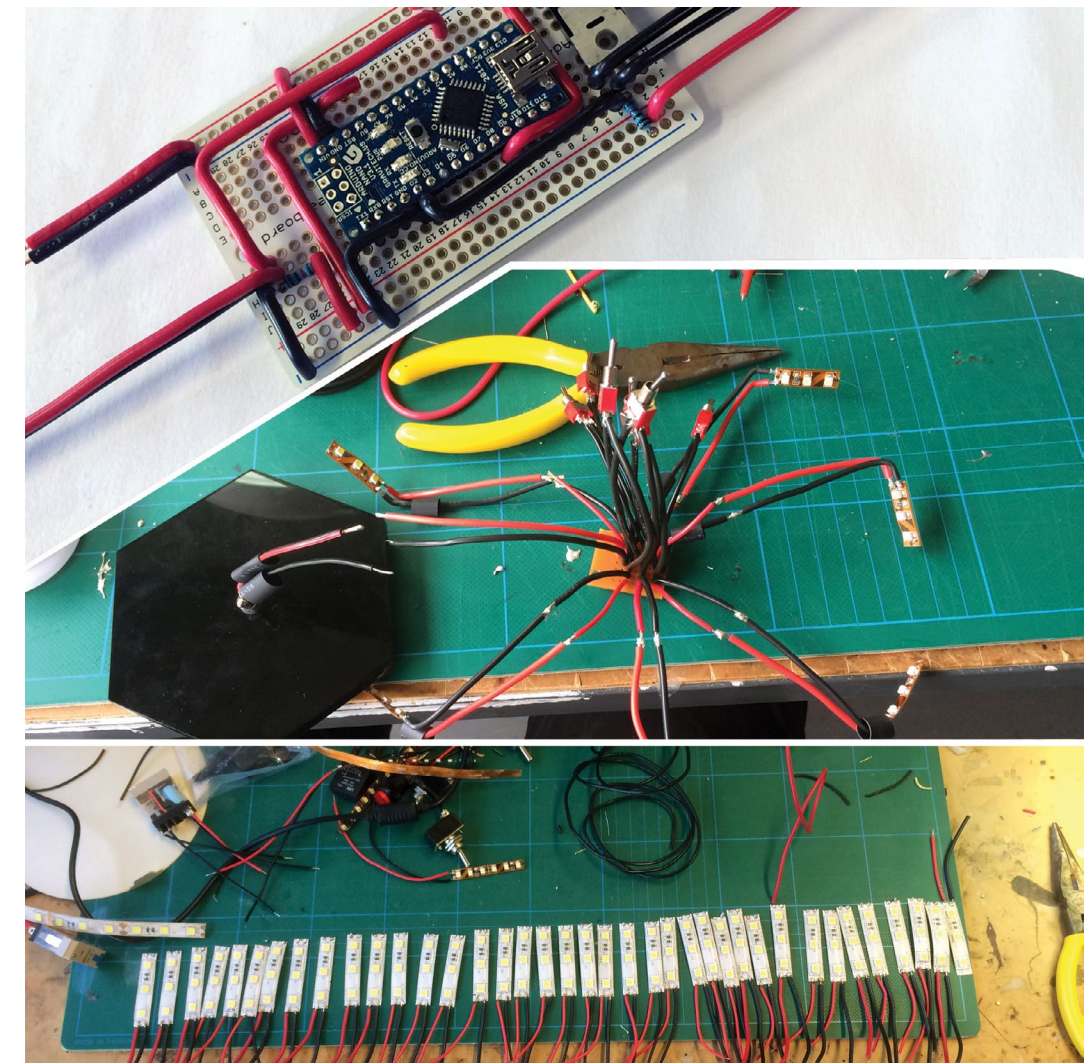


Figure 4.27 - Finalised render of Design Four, exploded.

Development: Electronics

The electronic requirements for each design varied significantly, and were developed after the design of the interaction and the physical components were finalised. Two of the designs, *Malleable Structures* and *Rotary Relays* relied on Arduino circuitry. A hobbyist-level programmable micro-controller, Arduino enabled rapid iteration through easy experimentation with a myriad of sensors and the ability to rapidly prototype circuits on breadboards. The requirements and components for each design were determined through a reflection to the concept maps, where different kinds of touch could be facilitated by different features of 3D printing. This was then expanded to look at different electrical components that could facilitate that kind of control. The following were the requirements identified for each light:

- » Design One: *Malleable Structures*
 - Arduino Nano (12V input, analogue and digital outputs, capable of running multiple sensors and LED pairings), Flex sensors (running up the crystal structures, testing for flexing), MOSFETS (altering the current supply to dim LED strips), LED strips (12V supply), Perfboard (provides soldered connections for components), Resistors, Wire.
- » Design Two: *Organic Formation*
 - Toggle switches (simple on/off switches), LED strips, Perfboard. Wire.
- » Design Three: *Spiral Connection*
 - Reed switch (switches based on presence of magnetic field), LED strips, Wire.
- » Design Four: *Rotary Relays*
 - Arduino Nano (for driving relay driver as well as reading analog inputs and transitioning between states), Relay Driver (connects to Arduino to activate physical switches and prevents the Arduino from having to



deal with high current and voltage), Potentiometer (rotary sensor that changes resistance based on rotational position), LED Strips (15 pieces in total), Rocker switch (for activating the entire system), Perfboard, Wire.

Malleable Structures capitalised on the ability to dim LED strips, and translated the flexing motion of the crystals into a dynamic adjustable lighting solution. *Rotary Relays* used the potentiometers analogue readout and translated it into instructions for the relay driver to switch on and off the different sets of LEDs.

Figure 4.28 - Prototyping and building the electronic circuits.

DESIGN / TEST RESULTS

Final Designs

The final designs sought to answer the question of “How can the design of lighting elicit surprise through the use of visual-tactually incongruous 3D printing?”. Each of the designs addressed the research question of this phase from a slightly different angle. Taking different starting points developed out of Design Phase 1, each of the lights followed one of the identified approaches. Following are a sequence of detailing images for each final light, accompanied by descriptions.

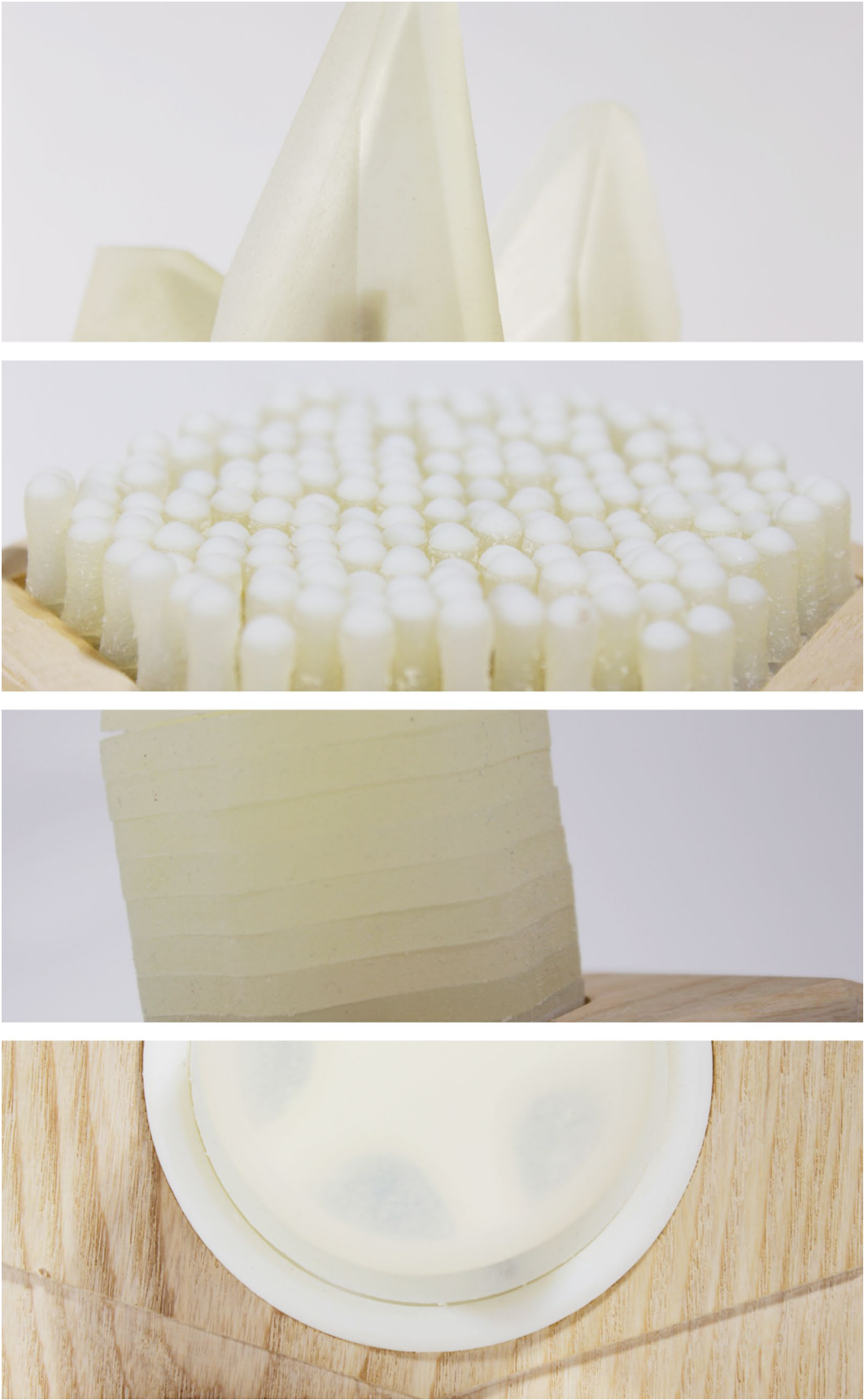


Figure 4.29 - Design One, Two, Three and Four.



Design One: Malleable Structures

Strategy / Approach: Visually referencing recognisable forms, objects and structures, but making them tactually different.

Design Inspiration: Rubberised Geode (HN2P4)

VTI: Reference familiar object and familiar material. (Hidden Novelty: New Material that looks like Familiar Material)

Interaction: The crystalline structures look hard but are actually flexible, and when bent outwards, the light fades up from within. Each crystal can be

Figure 4.30 - Malleable Structures.



individually controlled, and if the flexing is done carefully, the user can precisely determine how much light they want.

Final Design: A square-edged wooden bezel forms the base of the light, and from this base extend 3 crystalline structures: one small, one medium, one large. The structures have diffractive and visual qualities akin to real crystals; including broken edges and occlusions running through the crystal mass.

Figure 4.31 - Detail shots of Malleable Structures.



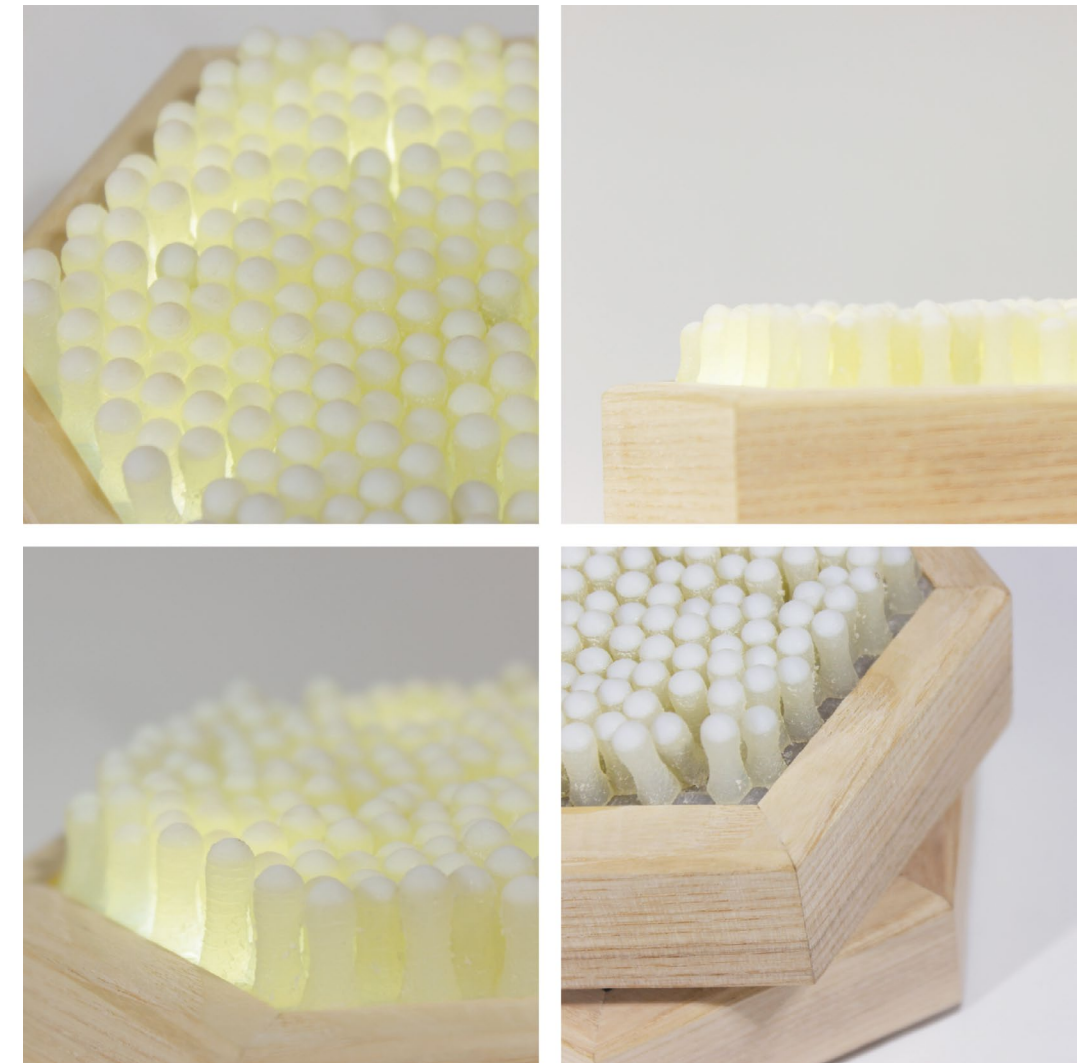
Design Two: Organic Formation

Strategy / Approach: Using material variances and unfamiliar forms to encourage interaction.

Design Inspiration: Tentacle Grasses (HN1P3)

VTI: Suggest multiple material properties that overlap, creating a sensory dissonance. (Hidden Novelty: Hidden Material Characteristics, Visible Novelty: New Material with Unknown Characteristics)

Figure 4.32 - Organic Formation.



Interaction: The individual organic forms are soft and flexible, and under six of them toggle switches can be found, which each activate a section of the light underneath the 3D printed structure.

Final Design: The 3D printed section emerges from the top of the hexagonal prism. The two hexagonal wooden halves are connected via an audio connector in order to spin freely. This is in order to refresh the surprise for the user by forcing them to have to find the switches again between uses.

Figure 4.33 - Detail shots of Organic Formation.



Design Three: Spiral Connection

Strategy / Approach: Suggesting surfaces have texture when they are actually smooth, through the use of an illusion.

Design Inspiration: Spiral Collapse (HN3P5)

VTI: Suggest texture that does not exist through a visual illusion. (Hidden Novelty: Visual Illusion)

Interaction: The 3D printed component can expand like a spring, and the top of the form can be connected to the matching shape on the other side of the light. This triggers a reed switch, turning the light on.

Figure 4.34 - Spiral Connection.



Final Design: The angled wooden base has two distinct sides, each with a hexagonal slot in it. One of the hexagonal slots has the 3D printed component emerging from it, while the other is simply exposed frosted acrylic. When active, the light passes through the 3D printed component, illuminating a hidden, untouchable texture on the inside.

Figure 4.35 - Detail shots of Spiral Connection.



Design Four: Rotary Relays

Strategy / Approach: Using internal structures to challenge the initial visual perception of the material properties.

Design Inspiration: Collapsing Construct (VN4P1)

VTI: Visually rigid structure collapses based off internal structure. (Hidden Novelty: Hidden Material Characteristics, Visible Novelty: Combination with Transparent Materials)

Figure 4.36 - Rotary Relays.



Interaction: The 3D printed dial has collapsible sections which cave inwards when gripped tightly. The dial can be turned to cycle up through all the light combinations.

Final Design: The lights radiate outwards from the dial, recessed under frosted acrylic disks into a routed wooden base. The design of the base groups the lights into distinct sections. These sections activate sequences based off where the dial is positioned. As the relays activate and deactivate, they make a series of delightful clicks.

Figure 4.37 - Detail shots of Rotary Relays.

User Testing & Data Collection

The user testing process was based off the process used for Design Phase 1. However, as discussed at the end of Phase 1, there were significant issues with elements of the process, and as a result a fair amount of that discussion was devoted to how to overhaul it for the next Phase. Refining the user testing process involved the following considerations:

- » The order of the four prototypes was randomised between participants. No participant had the same order as any other participant. This was done with a randomiser.
- » The material assessments were split across pages. This ensured that the participant could not use their previous assessment to prompt themselves.
 - The visual design of the responses was revised in order to improve clarity.
- » The Geneva Wheel of Emotions was moved to be the first thing the participant would fill out post-interaction. The GWoE had some modifications made to it to improve clarity:
 - GWoE modification: 'Positive' and 'Negative' in the surprise section were replaced with 'Pleasant' and 'Unpleasant', respectively.
 - The lowest value of each emotional response (in the previous version denoted by a square) was removed as the different shape seemed to potentially suggest a zero-value; when in fact not putting anything was considered a zero-value. Removing this section brought the scale to 1-5 (from 1-6), which added clarity.
- » Three extra questions were added to analyse participants' perception against their expectation.
 - One of these questions was added pre-interaction; to get the participant to explain what they expected the interaction to be.
 - This was supplemented by a question post-interaction asking them if it was as they expected.

- A question was also added, asking whether they found the light easy to turn on.
- The latter two questions used Likert scales for responding. The language in these questions was carefully evaluated to avoid bias.
- » There were 2 open-ended questions added at the end of each questionnaire; one regarding unexpected qualities, and one asking for additional comments. These were added to draw out more verbal responses.
- » The questionnaire was supplemented with specific questions based on their responses to the materiality asked of users verbally in the post-questionnaire interview. This gave them the chance to explain their thoughts in more depth.
- » A visual overhaul of the questionnaire, streamlining the experience and making the division between pre- and post- interaction clearer (figure 4.38 and 4.39).

LIGHT

Participant ____

1. What do you think the interaction will be to activate this light?

2. What do you think the plastic component will feel like?

pre-interaction

Soft Both Hard Smooth Both Textured
Neither Neither

post-interaction

3.a How would you emotionally define your experience with this prototype?

Anger Interest Amusement Pride Joy Pleasure Pleasant Surprise Contentment Love Admiration Relief Compassion Sadness Guilt Regret Shame Disappointment Unpleasant Surprise Fear Disgust Contempt Hate

None Other

3.b If you answered "Other" to question 3.a, what emotion(s) did you feel?

Figure 4.38 - Side 1 includes the pre-interaction questions as well as the modified GWoE.

LIGHT

4. What did the plastic component feel like?

Soft Both Hard

Smooth Both Textured

Neither

Neither

5. Was the interaction as you expected it?

Strongly Agree Agree Disagree Strongly Disagree

6. Was the light difficult to turn on?

Strongly Agree Agree Disagree Strongly Disagree

7. Were there any specific unexpected aspects of the design?

8. Is there anything else you want to point out?

Figure 4.39 - Side 2 looks at a matched question (for measuring the VTI) as well as Likert-scale responses.

The user testing process followed a comparable process to the last testing, and was as follows:

1. The participant sat across the table from the researcher. The researcher had each light under a separate shroud, so that the participant could not see them or their shape (numbered cardboard boxes were used).
2. The first prototype for that participant was exposed. At no point was the participant told the name of any of the prototypes. The participant was not allowed to touch it initially.
3. The participant was asked to report on their visual appraisal through filling out question 1 (*What do you think the interaction will be to activate this light?*) and 2 (*What do you think the plastic component will feel like?*) in the questionnaire.
4. The light was then plugged in, and the participant was invited to turn the light on.
5. If the participant was unable to figure out the interaction within the first 30 seconds, they were given the first clue, and another clue after a further 30 seconds.
6. The participant was asked to fill out the remainder of the questionnaire. They were allowed to engage with the model during this time if they needed to refresh their memories.
7. After completing the questionnaire for that light, the verbal questions (*What about the design gave you clues about its materiality?; What about the design gave you clues about its function?; and Do you want to add anything?*) were asked and responses noted.
8. Following the miniature interview, the light was turned off, unplugged, and the shroud was replaced.
9. This process was repeated for all of the 4 lights.
10. After the study was complete, there was an opportunity for the participant to ask any questions about the lights, see all of them again, and receive information on the thesis itself.

The data from the user testing was collected and aggregated by calculating the mean for each of the values. This follows the same process as used in Phase 1, with the sole difference being the inclusion of the new data points on ease of use and expectation.

Final Outputs & Data Representation

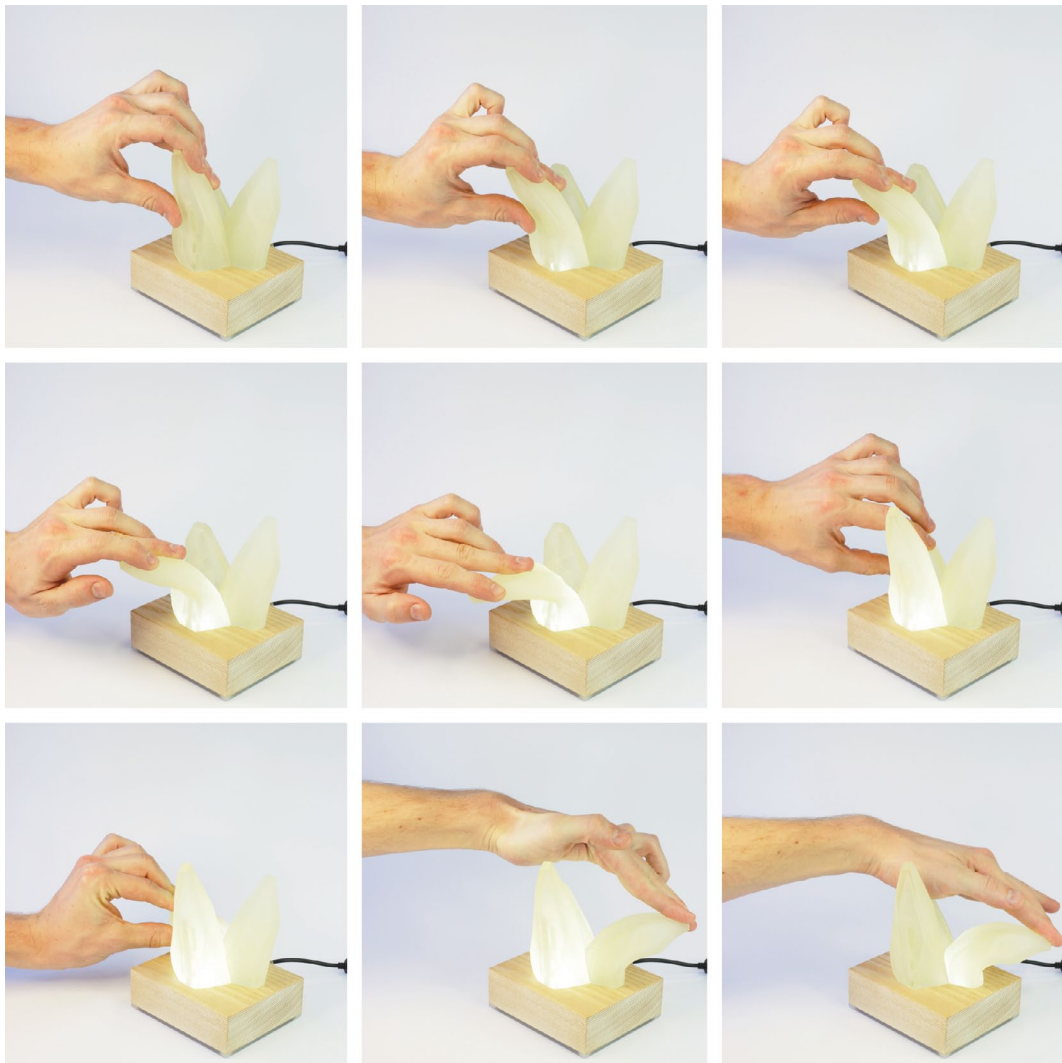
In order to provide a better overview of the final interactions with the physical outputs of Phase 2 as well as a comprehensible overview of the data derived from the user testing, these sections have been amalgamated. A sequence of images showing the interaction is presented alongside the data for that light.

The data that is presented is:

1. The Geneva Wheel of Emotions; showing the average emotional response for that prototype. (Represented in a polar diagram; a natural fit for the GWoE)
2. The average soft/hard perception shift of the participants for that prototype. (Represented in a small bar chart, showing the pre- and post-interaction perception)
3. The average textured/smooth perception shift of the participants for that prototype. (Represented in a small bar chart, showing the pre- and post-interaction perception)

Included with the data and interaction sequences are some of the comments made by the participants. A video of all of the lights in action is available online at:

<https://vimeo.com/sebastienvoerman/designedfordelight>



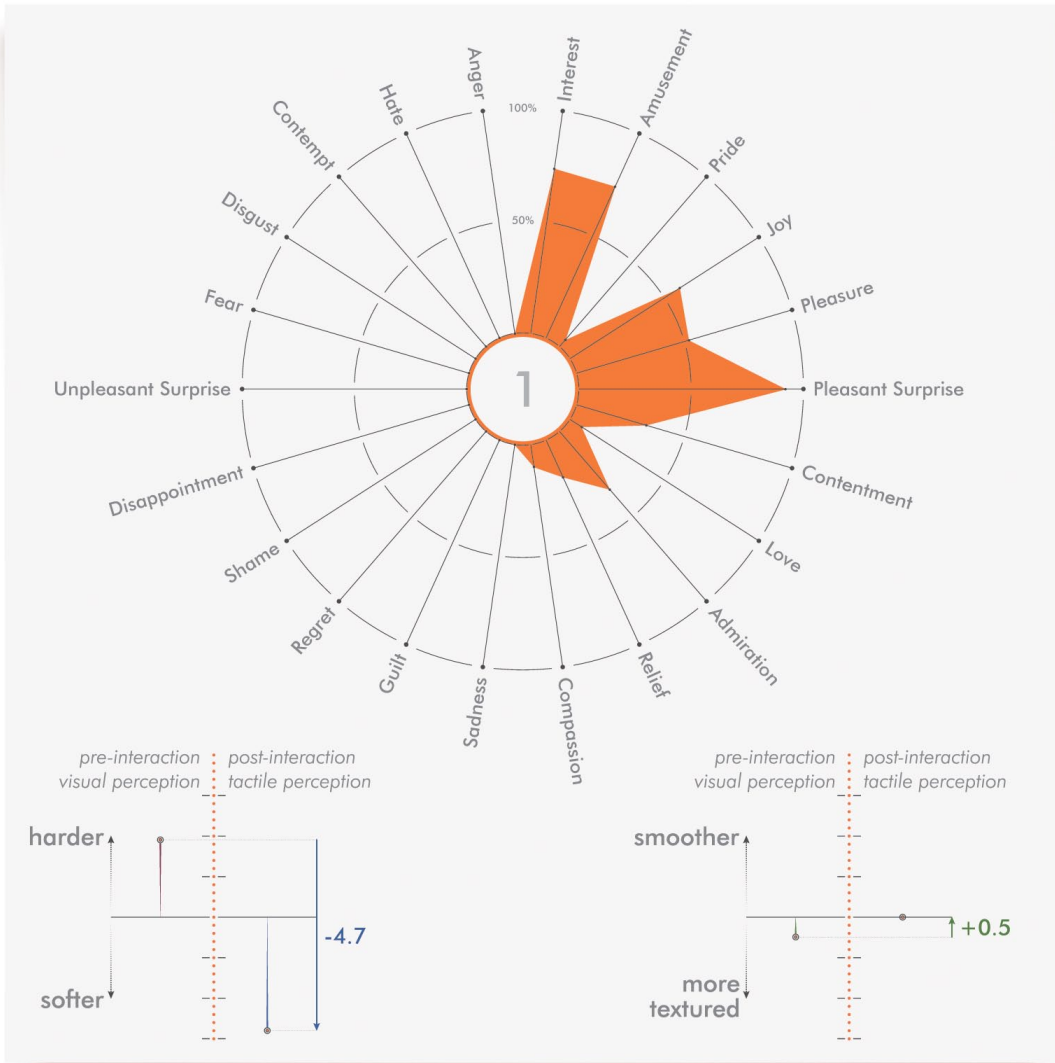
Design One: Malleable Structures

“This one was really cool. I got a sense that it was going to be hard from the sharp edges. That turned out to be totally wrong hahaha!”
(Participant 1)

“I totally got this one as soon as I figured out it was soft. It’s pretty intuitive.”
(Participant 4)

“I think I had the right idea of what to do from the beginning, but I still didn’t expect the light to be as soft as it is!”
(Participant 5)

Figure 4.40 - A usual interaction sequence for Malleable Structures.



“Oh man, once you figure out the interaction, I can totally see why you did what you did with the design. This is awesome.”
(Participant 7)

“I would never expected to have to bend it over!”
(Participant 8)

“I think I figured it out...but man they’re just so soft. How did you do this?”
(Participant 9)

“They just weren’t what I was expecting. I’m not sure. I still can’t work out how you did it.”
(Participant 10)

Figure 4.41 - 6/10 participants incorrectly believed that the interaction for Malleable Structures would be a touch-sensitive (capacitive) switch.



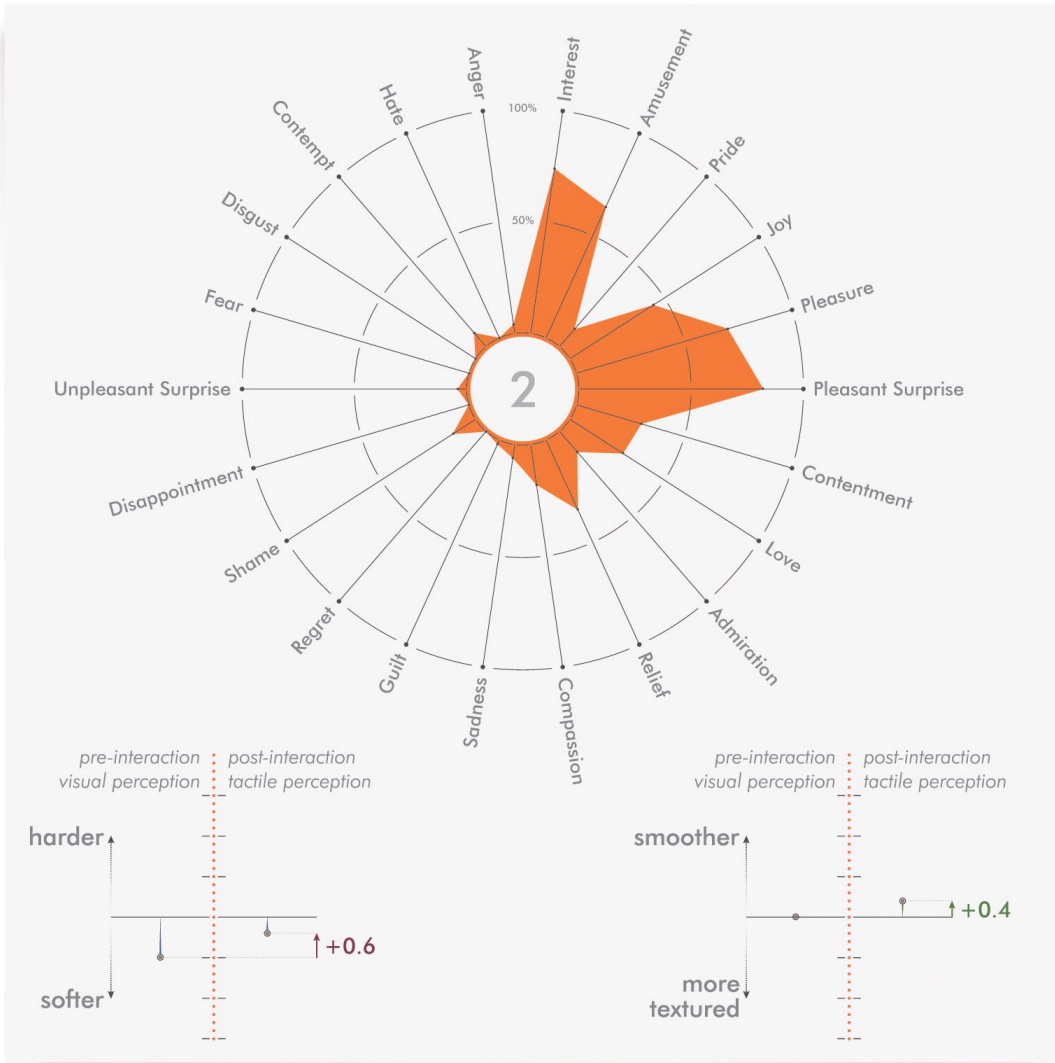
Design Two: Organic Formation

“Do I have to push it down? The gap in the middle makes me think I have to push it down.”
(Participant 1)

“Ooh it feels so strange! Can I buy this one? I want to have it.”
(Participant 2)

“I want the rotation to do something. Like I feel it should be affecting the light somehow.”
(Participant 3)

Figure 4.42 - A usual interaction sequence for Organic Formation.



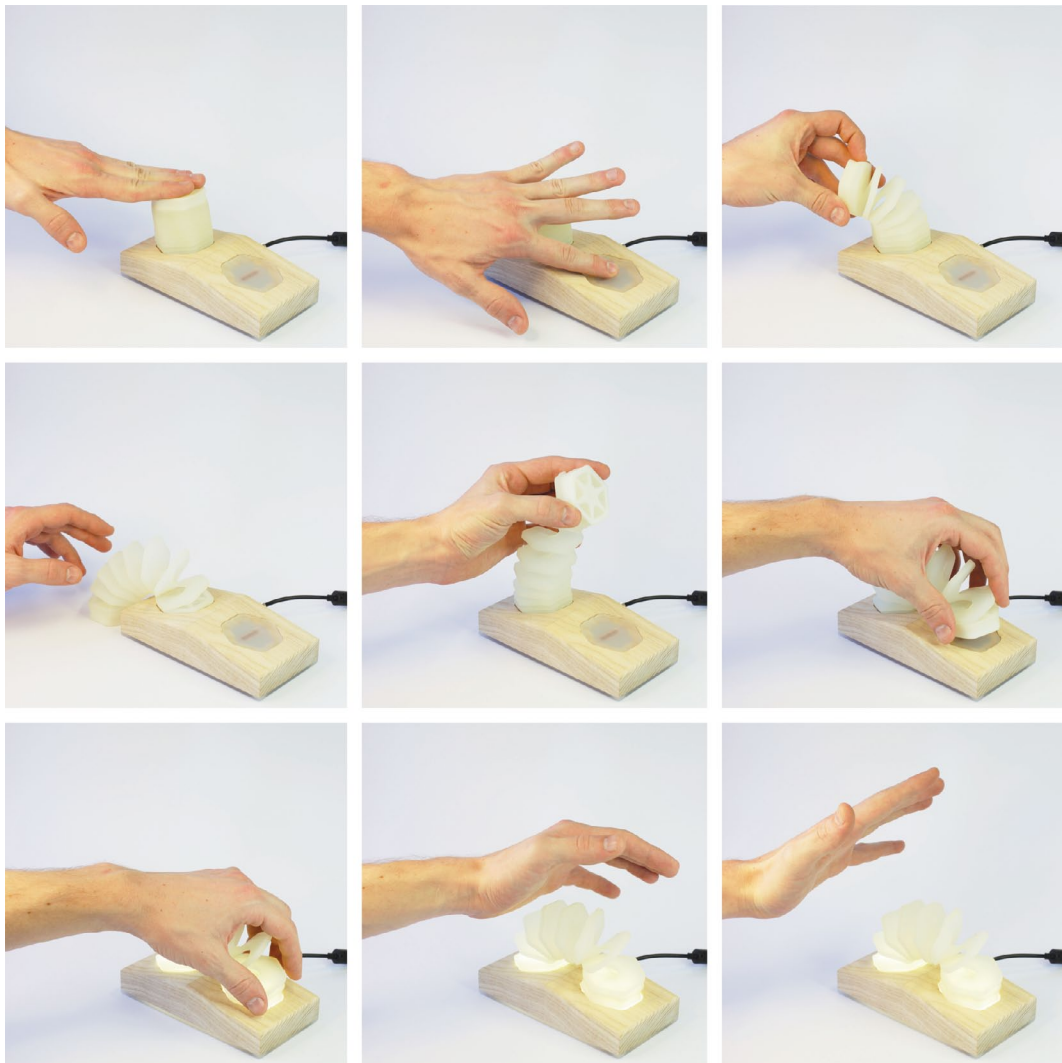
“This one is kind of like a bioluminescent creature. So neat. I just wish it had been easier to turn on.”
(Participant 4)

“If this one changed colours that would be so awesome.”
(Participant 6)

“I don’t know, I found this one really frustrating to deal with. Maybe if the tentacle parts were bigger?”
(Participant 7)

“I really don’t like this one. It’s way to tough to work it out.”
(Participant 8)

Figure 4.43 - 7/10 participants incorrectly believed that the interaction for Organic Formation would be to push the halves of the light together.



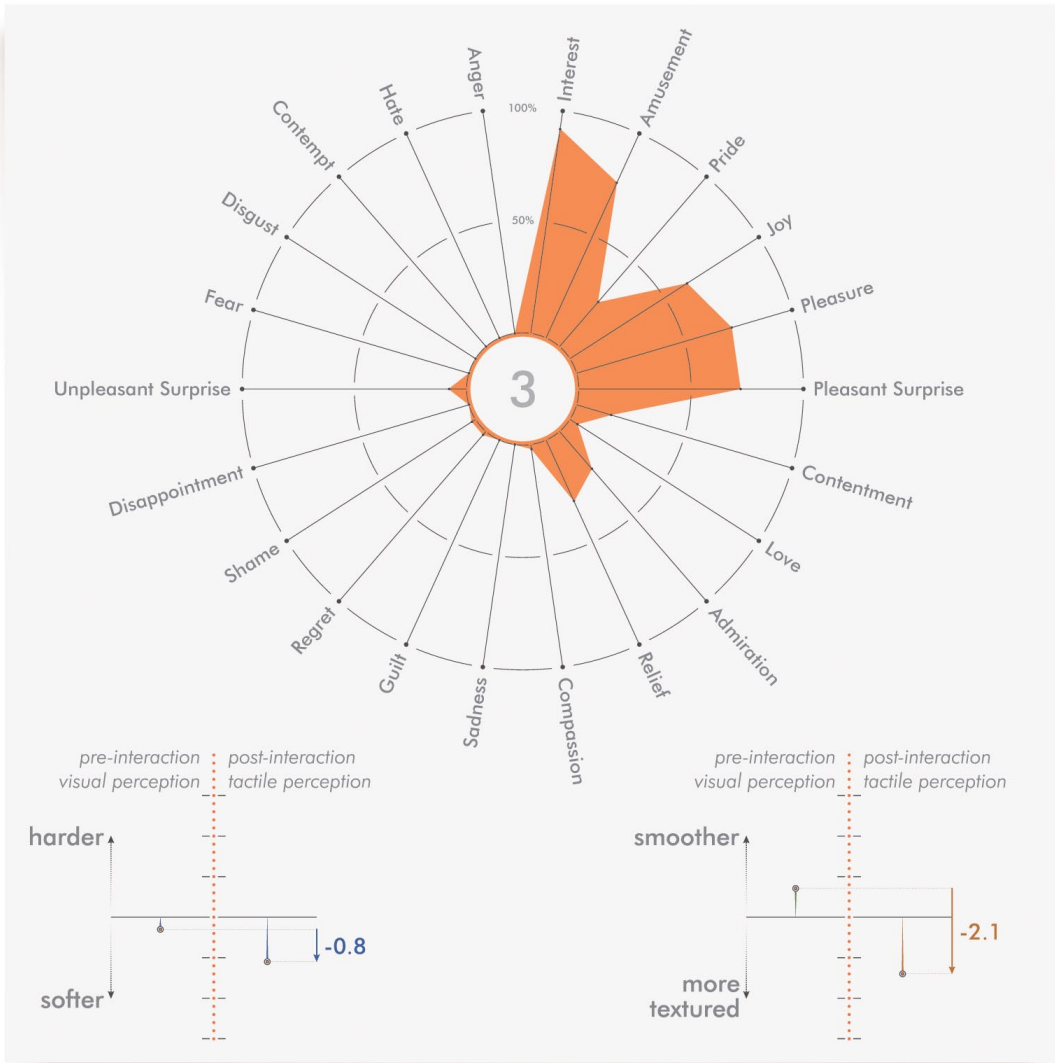
Design Three: Spiral Connection

“This one is amazing. I figured it out because my finger twitched and knocked it apart. Totally got me on that one.”
(Participant 1)

“Oh my...it looks like kiwifruit. That was such a cool way to do it. Can I have this one too?”
(Participant 2)

“It kind of reminds me of those old phone cords? You know, like the spiral ones. I like what you did with the form relationship here as well.”
(Participant 4)

Figure 4.44 - A usual interaction sequence for Spiral Connection.



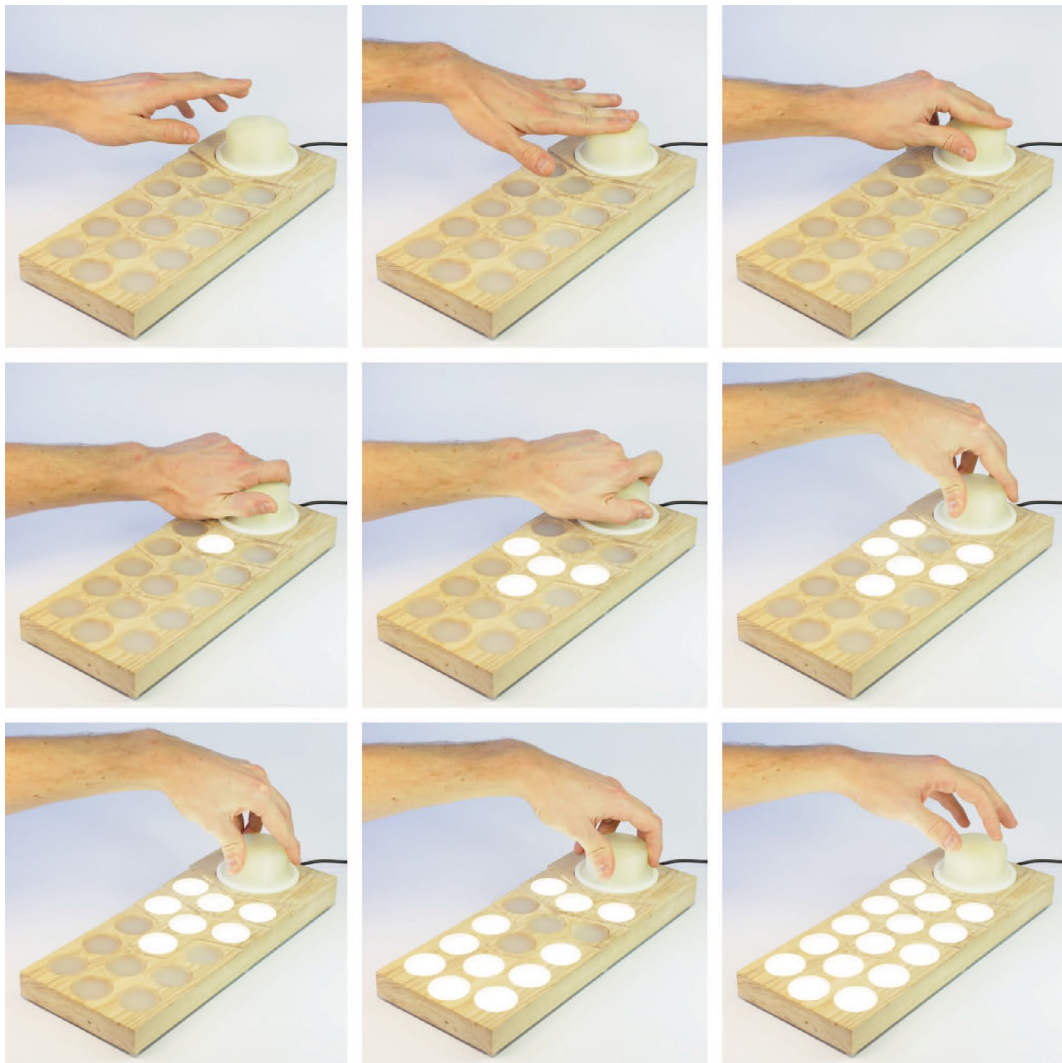
“This one is so playful! It’s like a squishy fun slinky.”
(Participant 7)

“The motion on this one is what really set me off. Once I saw how it moved I understood what I had to do.”
(Participant 8)

“Is it magnetic? Is that how it stays?”
(Participant 9)

“Oh wow! I didn’t expect it to stretch like that.”
(Participant 10)

Figure 4.45 - None of the participants anticipated the interaction; all believing the interaction would be to press the 3D printed component, rotate it, or that it would be touch sensitive.



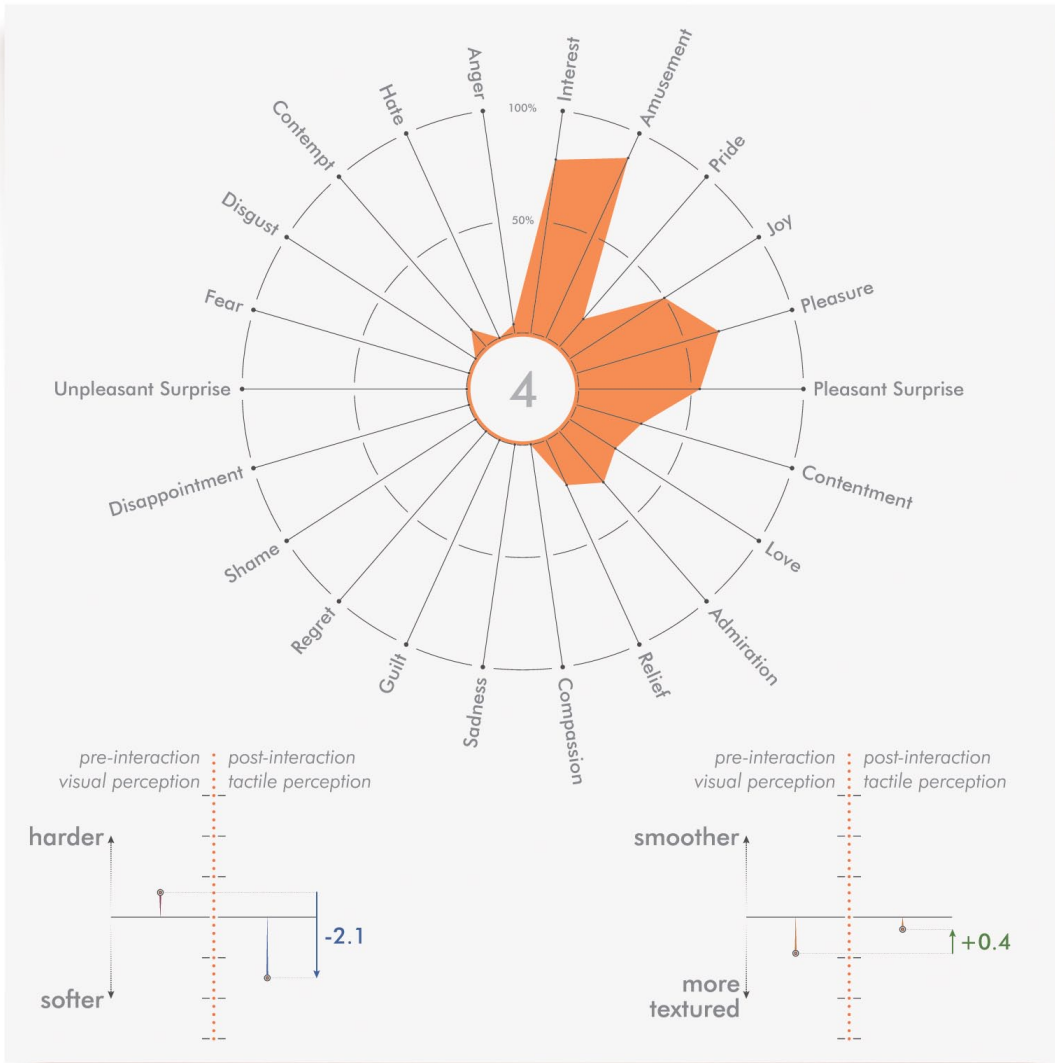
Design Four: Rotary Relays

"Ha! I totally knew this one was going to turn. The sequence of the lights was really neat though."
(Participant 1)

"This one makes me feel peaceful, I don't know why. Kind of expected it to be a big button though, not a dial."
(Participant 2)

"Oh man this one is so satisfying. And that clicking it makes? I love that."
(Participant 3)

Figure 4.46 - A usual interaction sequence for Rotary Relays.



"Has this one got an Arduino inside it? That clicking is amazing."
(Participant 4)

"I like that I can squeeze the dial. That's really neat."
(Participant 7)

"It's like the light is kind of echoing out of the dial. So awesome."
(Participant 8)

"This one is so satisfying to use."
(Participant 10)

Figure 4.47 - 5/10 of the participants anticipated the rotation interaction, with the other half incorrectly believing they would have to press it.

Data Aggregation, Translation & Analysis

In order to gain a better overview over the data from the responses. I collated all 40 questionnaires, 10 for each light. The way this data was aggregated into a spreadsheet is detailed in the user testing sequence of Design Phase 1.

Name of Design: Name assigned to light, served to make them more recognisable.

VTI Achieved: Was one or both of the perception shifts substantial, and if so which ones? (This was noted at 2+ points of change in either direction, and was for indication only)

Averaged perception shift for soft/hard: Difference between average initial visual perception and subsequent tactile perception for soft/hard. Shown in points of change. Positive numbers indicated participants found the prototype to be harder than visually perceived, and vice versa.

Averaged perception shift for textured/smooth: Difference between average initial visual perception and subsequent tactile perception for textured/smooth. Shown in points of change. Positive numbers indicated participants found the prototype to be smoother than visually perceived, and vice versa.

Cumulative Positive Valence Emotions: All averaged positive emotion values on the GWoE added together, with a maximum possible value of 55.

Cumulative Negative Valence Emotions: All averaged negative emotion values on the GWoE added together, with a maximum possible value of 5.

Was the interaction as you expected it?: This response was calculated by counting the number of responses that “agreed” and “disagreed” and determined which half held the majority.

Was the light difficult to turn on?: This response was calculated by counting the number of responses that “agreed” and “disagreed” and determined which half held the majority.

Name of Design	Notable VTI achieved:	Mean perception shift for soft/hard (in points of change)	Mean perception shift for textured/smooth (points of change)
Malleable Structures	Tactually found to be softer than visually perceived.	-4.7	0.5
Organic Formation		0.6	0.4
Spiral Connection	Tactually found to be smoother than visually perceived.	-0.8	-2.1
Rotary Relays	Tactually found to be softer than visually perceived.	-2.1	0.6

Collating the questionnaires into the chart (figure 4.46) made it significantly easier to perceive the effective outcome of the user testing. Notable discoveries from looking at the data included:

- » Design One had the strongest VTI (4.7 out of a maximum of 6) recorded, with most participants believing it would be very hard and discovering it was actually very soft.
- » Design Two was the only light that did not register a notable VTI in any category.
- » The GWOE results were interesting, as all the lights sit within the same 2% (41% - 43% of the maximum of 55) of the cumulative positive valence emotion section.

Figure 4.48 - Collected and averaged responses, as well as notation of VTIs that eclipsed a certain level, and responses to the final two questions.

Cumulative Positive Valence Emotions (Max: 55)	Cumulative Negative Valence Emotions (Max: 55)	Was the interaction as you expected it?	Was the light difficult to turn on?
22.7	0	Majority Disagree	Majority Disagree
23.3	1.8	Majority Disagree	Majority Agree
23.7	0.6	Majority Disagree	Majority Disagree
22.9	0.7	Even Split	Majority Disagree

- » All the lights sit very low on the cumulative negative valence emotional response (all sit below 3.5% of the maximum of 55).
- » Design Four had an almost 50/50 split in terms of the interaction being expected/unexpected (5/10 users correctly anticipated the interaction).
- » Design Three was a clear stand-out in terms of how difficult the light was to turn on (All participants “Strongly Agreed” or “Agreed” that the light was difficult to turn on).

Figure 4.48 contd. - The larger the number, the stronger the colour.

DISCUSSION & CONCLUSION

Data Interpretation

Comparing the cumulative GWoE values between the lights for this discussion did not prove particularly useful, as there was decidedly small variation between them. The individual emotional values for the different lights show more intriguing results, as well as the responses around visual perception against tactile verification.

Design One - *Malleable Structures* having the highest “Pleasant Surprise” value was re-affirmed by a large variation between visually and tactually perceived rigidity. This massive shift demonstrated the success of the VTI. Most participants visually gauged the design as hard, but discovered it was actually very soft. This average shift of 4.7 points towards soft was the strongest response in this thesis, even compared to some of the results from Phase 1. All the participants verbally reported surprise with this light as well, most stating variations on “I had no idea it was going to be soft!” (Participants 1, 4, 8 & 10). “Can I control all three of the lights? I can! That’s really neat.” (Participant 6).

- » Design Two - *Organic Formation* was a challenging prototype for a lot of the participants. Every single participant except for Participant 6 required one or two hints to get the light to work, which was reflected by the response to the question “Was the light difficult to turn on?”, with every participant putting either “Agree” or “Strongly Agree”. This was coupled with the strongest negative valence response, which while still exceedingly low, highlighted emotions such as “Shame” and “Guilt”. A few of the participants expressed frustration verbally: “I don’t know what I’m meant to do” (Participant 4), “I can’t see any way that I can get this” (Participant 9).
- » Design Three - *Spiral Connection* caught a lot of the participants off-guard. None of the participants anticipated what the interaction would be. The

surprise and attention, based off the verbal comments and responses, appeared to be elicited and drawn more by the interaction, as opposed to the VTI. Most participants anticipated a solid object that had texture, and what they got was a pliant, smooth structure. While the perception of the VTI was good it was not nearly as strong as for Design One. To support my belief that the surprise resided more in the interaction, all participants checked “Disagree” or “Strongly Disagree” in response to “Was the interaction as you expected it?”. Most comments made by participants included comments “Ooh it’s like a slinky” (Participant 5) and “Oh wow it stretches...how far can I stretch it?” (Participant 7), with no notable comments on the VTI itself other than minor observations on the visible but untouchable texture.

- » Design Four - *Rotary Relays* had the least unexpected interactions of the lot, with half the participants anticipating having to rotate the dial. It also registered a VTI, with most participants anticipating the dial to be harder than it actually was. Similarly to Design Two; based off the comments made by the participants, I do not believe the surprise entirely stemmed from the VTI, but more likely originated from the way the lights turned on. “I didn’t expect the lights to sequence like that, I thought they would dim up” (Participant 3), “Oh, I expected the lights to turn up differently” (Participant 1). This light was reported by most to be the easiest light to turn on, with most participants checking “Disagree” or “Strongly Disagree” to “Was the light difficult to turn on?”, likely due to its reference to comprehensible control systems.

Significance & Implications

The designs that showcased the strongest ability to surprise through VTIs were One, Three, and Four. An interesting realisation about *Malleable Structures* was the way the perception of the approach “*Visually referencing*

recognisable forms, objects and structures, but making them tactually different” was intertwined with the interaction with the light. This, I believe, is why this particular light was so successful at eliciting surprised reactions. Because the interaction and the VTI were directly tied to each other; you could not trigger the light without experiencing the VTI, this made the experience more evocative. This appears to be a reason why the other lights had fewer verbal mentions of surprise in addition to lower values on their perception shift.

If we look at the other three lights, the interaction for *Spiral Connection* is not explicitly combined with the VTI it employs. The approach that *Spiral Connection* was designed to achieve aimed to *“Suggest surfaces have texture when they are actually smooth, through the use of an illusion”*. While it succeeded on this front, I believe the issue was that this approach was not truly woven into the fabric of the interaction. Most remarks and comments were directed at the interaction and the way the 3D printed component moved, not the VTI that was embedded in the design.

The interaction for *Rotary Relays* worked extremely well; there was a solid input to output translation, with the light progressing from off to fully on in an enjoyable, clear way. The issue was that you did not need to squeeze the dial to be able turn it, and as a result, not all the participants picked up on the softness as well as was hoped. This likely also stemmed from the fact that the structure was a fair bit stronger than had been planned. *“Using internal structures to challenge the initial visual perception of the material properties”* still functioned and drew the attention of the participants; but could have been more intense, as well as directly linked to the function of the light.

Organic Formation presented a frustrating challenge, as when presented in the form of an abstract object, in the case of *Tentacle Grasses*, it was a firm favourite of many participants. Yet, in the form of a designed light, most participants found the surprise of the light illuminating from below underwhelming and the design frustrating to interact with. *“Using material variances and unfamiliar forms to encourage interaction”* in this instance

appeared to fall a little short as a surprise-generating VTI; as there was no direct, clear payoff. The design followed the approach precisely, yet it appears the issue lay with the approach being the only one that did not have a ‘this is not what you thought it would be’ payoff.

Limitations

The issues that emerged through the user-testing in Design Phase 1 provided useful insight for improving the user testing process this time around. As such, the problems of material familiarity, lack of direction and issues with the questionnaires were not visible this time. The limitations identified here are more broad-stroke and either much harder to solve or are high-level shortcomings with the research approach and fall outside the scope of this research. These were:

- » The research was inherently qualitative and limited by a sample size of 10.
- » Inherent bias from the researcher; I had a vested interest in seeing the participants be positively surprised and have a positive emotional experience.
- » The only data sources I had were:
 - My subjective interpretation of their experiences, watching their reactions and cataloguing their interactions.
 - Their self-reporting on the questionnaires, which could have been exaggerated due to prompting by the questions. This could have pushed the results negatively and positively.
 - Their verbal responses to my questions, given my bias I may have paid more attention to positive responses than negative ones. I was aware of this though and sought to actively be equally attentive to all verbal feedback.

5

DISCUSSION

EXISTING STRATEGIES

Ludden (2008) developed strategies through looking at existing products that evoked surprise; yet there was only one example of a product employing 3D printing, namely the “Konko Lamp”, designed by Willeke Evenhuis & Alex Gabriel. Exploring the possibility of using PPP 3D printing to elicit surprise through the use of VTIs, particularly using its capabilities to print in soft and hard material combinations, yielded interesting findings that suggested 3D printing appears to show a greater usefulness for the ‘Visible Novelty’ (VN) subset of Ludden’s (2008) strategies.

After conducting research into the applicability of these strategies, it would appear that some of her strategies do offer viable angles for exploring surprise through the use of 3D printing. However, given the visual qualities of PPP printing at present, achieving effective expressions of Ludden’s (2008) ‘Hidden Novelty’ (HN) strategies is still out of reach. Ludden et al. (2008) highlighted that the “HN surprise type includes products that seem familiar to the perceiver, but have unexpected tactual properties” (p. 30). While this appears to sound like the effect seen in the prototype *Malleable Structures*, participants still mentioned that “It looks odd” (Participant 8) and “It looks like a crystal, but I’m not sure” (Participant 2). A number of participants made comments suggesting that they were not convinced about their visual perceptions, suggesting a more predominant presence of VN in the designs. Achieving true HN designs could be addressed by finding materials that PPP can specifically emulate, and designing familiar forms and structures around those.

I believe this primarily due to the ‘look’ of PPP 3D printing. Many participants picked up on the visual strangeness of the materials (most of the prototypes ended up looking somewhat like complex arrangements of various kinds of candle wax). Based on their responses, it simply does not appear to have been possible to fully deceive the viewer’s perception enough to make them believe the materials they see are not ‘odd’. However, having a fundamental understanding of the qualities and possibilities of PPP can still offer designers specific ways to elicit surprise. Ludden et al. (2008) note that “people tended to exhibit more exploratory behaviours when interacting with VN products

...people often viewed VN products as more interesting than HN products” (p. 37). For the designs developed in Phase 2; which all incorporated aspects of VN, almost all participants spent well over a minute exploring most of the lights. The reverse of this was seen in several of the purely HN strategy cuboid prototypes from Phase 1; most notably *Fabric Falsifications*, which had some of the briefest interactions and comments such as “Oh, it’s just hard. That’s disappointing.” (Participant 4).

Ludden’s strategies in the HN category were still essential to the development of the final designs, but the final light designs themselves actually end up fitting predominantly into the VN category, due to the inherent inability for PPP to accurately simulate the visual qualities of other recognisable materials. The four designs developed in Phase 2 explored combining specific PPP capabilities with Ludden’s (2008) strategies. The approaches put forward are based on a systematic exploration through the Research through Design approach, as well as the questionnaires and interviews employed during the user testing. These approaches are not exhaustive and there is potential for research to develop further approaches related more specifically to other 3D printing technologies beyond PPP.

3D printing is an incredibly important growth area presently, with the latest Wohlers Report highlighting that “the 3D printing industry has grown by US\$1 billion” (Wohlers, 2016). Understanding the state of the art, what can be done with the technologies, as well as how it can be pushed to the limits is vital in ensuring designs utilising it can remain surprising. Surprise has, as discussed in previous sections of this thesis, a lot to offer to designers. Exploring the potential of 3D printing, how it can surprise and challenge our sensory perception through the use of VTIs is a topical, relevant exposition. Its application to the comprehensible field of lighting design is one particular angle that this thesis pursued. There are a myriad of other areas dependant on interesting, engaging interactions that this research could potentially inform.

CORRESPONDING DESIGNS

The four final designs were developed out of the systematic analysis of the applicability of multi-material PPP 3D printing to Ludden's strategies for generating surprise. The final physical outputs of this thesis were the lights developed throughout Design Phase 2, that also incorporated Fox-Derwin's (2011) multi-layered approach to designing for surprise.

Design One: **Malleable Structures** - *Visually referencing recognisable forms, objects and structures, but making them tactually different.*

This design explored the potential for referencing familiar forms, connecting archetypal forms and material perceptions to the design. By employing this, it allowed the designer to supply a false premise for the viewer's visual perception in order to elicit a VTI. This approach was adapted from Ludden's 'Hidden Novelty: New Material that looks like Familiar Material' and 'Visible Novelty: New Appearance for Known Product or Material'. Where Ludden suggests appropriating the appearance of a material, this approach utilises the form (in this case, the crystalline structure). This is because accurately referencing the visual qualities of materials is challenging with PPP 3D printing in its present state. The reason for why *Malleable Structures* appeared so successful, I believe was because the approach used for it was woven directly into the interaction. This removal of an obvious switch challenged the viewer to curiously explore, leading to the simultaneous discovery of the VTI and the interaction, compounding the layered surprise. Expanding this interaction here to include squeezing would be a natural extension and improvement of this design, enabling more versatility in the system.

Design Two: **Organic Formations** - *Using material variances and unfamiliar forms to encourage interaction.*

This approach explores the possibility for inciting curiosity and showcasing a clear Visible Novelty. Baiting the viewer into exploring something unfamiliar was an effective means of encouraging interaction, but the generation of surprise fell short. There appeared to be a distinct lack of 'this is not what you

think it is' that all the other designs capitalised on. This approach was adapted from Ludden's 'Hidden Novelty: Hidden Material Characteristics' and 'Visible Novelty: New Material with Unknown Characteristics'. *Organic Formations*, when tested, appeared to confuse the viewers, most appearing uncertain of what the qualities they were looking at might be, suggesting a clear visible novelty. The frustration emerged from the activation of the light being overly difficult to discover. I would argue however, that like the first design, the interaction is intrinsically linked to the approach, but usability considerations were lacklustre. Improving this design would involve making the interaction more natural and easier to complete, while still entertaining curiosity and inciting intrigue.

Design Three: **Spiral Connection** - *Suggesting surfaces have texture when they are actually smooth, through the use of an illusion.*

While this approach largely focussed on deceiving the viewer; the designed light, unlike the previous two lights, did not capitalise on combining the interaction with the revealing of smoothness. Exploring this strategy, adapted from Ludden's 'Hidden Novelty: Visual Illusion', the qualities of 3D printing allow complex or tactile texture to be visually suggested. These were shrouded with the clear material, nullifying the visually appraised tactile qualities. This approach highlights the capabilities of multi-material 3D printing well, as other automated manufacturing techniques are unable to create comparably visible yet untouchable textures. One important element explored was light's potential as a revealing tool; exposing hidden, almost invisible aspects of the design. Activating the light revealed the hidden texture on the inside of the 3D printed component, building on the layering of surprise.

Design Four: **Rotary Relays** - *Using internal structures to challenge the initial visual perception of the material properties.*

This approach took full advantage of the unique qualities that only 3D printing can achieve, through the use of carefully proportioned collapsible sections and

the employment of an all-in-one moving print. Similar to Design Three though, this design did not effectively amalgamate the approach into the interaction. The result was that not all the participants even registered that the dial was soft, since it was not key to unlocking or furthering the interaction. Adapted from Ludden’s *‘Hidden Novelty: Hidden Material Characteristics’* and *‘Visible Novelty: Combination with Transparent Materials’*, the approach still appeared to have the potential to elicit a VTI and surprise. To enhance the design, the interaction could have been expanded to utilise the VTI reveal as a control element. The surprise here was again layered through the employment of the dynamic light reveal, which extended the experience of surprise for this design.

LIMITATIONS

This research is distinctly qualitative, as the user testing both times was limited to 10 participants and the testing processes relied largely on subjective self-reporting, which means that the findings can only be applied to and explain the data collected and observations made in this research. The process of Research through Design significantly implicates the researcher in the process, as I was the only designer to work on any of these designs. The data and research from the user testing was instrumental to the development of the lights in Design Phase 2, but ultimately the progression of the design phases were intrinsically linked to my approach to design and who I am as a designer.

This specific link to me and my design sensibilities along with the subjective results reported by a small number of participants mean that another researcher may achieve a different series of results. However, the methodology to gather responses from the participants is reported here as objectively as possible and it suggests the four approaches put forward in this research can elicit surprise through qualities only presently possible through 3D printing.

FURTHER RESEARCH

Some of the areas this research could specifically branch into in future studies could be:

- » A longitudinal study, looking at the impact of 3D printing aiming to elicit surprise over a longer period of time. This could involve sending the designs home with participants and having them report on their experiences with the design multiple times over a period of time. This might allow the research to more specifically look at the process of decay as well as longer-term emotional sentiments. Ludden (2008) suggests that surprise does not disappear fully on the second or even the third exposure, but only the intensity diminishes. The presence of surprise has, in the long-term, positive effects on evaluations by users (p. 125).
- » Experimenting with the potential of colour 3D printing. Colour 3D printing is possible with the new generation of Objet Connex 3D printers, and would be an interesting area to explore next, based on the findings of this thesis. The potential of colour was outside the scope of this research, but could extend the ability of 3D printing to visually deceive, especially when paired with the capabilities and approaches achieved in this thesis.
- » An empirical, analytical study expanding on the number of participants in order to be able to generalise the findings. This would involve objective, visual measurement of participants' facial expressions as well as analysis of their movements and verbal responses in order to gain a multimodal understanding of the impact of 3D printing designed to surprise.

3D PRINTING APPLICATIONS

3D printing offers a variety of possibilities that other manufacturing techniques are incapable of achieving. These possibilities, combined with surprising interactivity, have the potential to expand our current offerings of interaction design, exploring more meaningful connections and usage scenarios and developing new person-product-relations. Understanding the situations that the user encounters and thinking of how 3D printing could be used to enhance or surprise is the kind of design process that this thesis is trying to encourage.

Certain applications and uses of 3D printing explored in some of the prototypes offer some interesting opportunities that have not been extensively explored in other literature:

- » Suspension of opaque objects in transparent sections: This was used in a number of the cuboid experiments (Hidden Red Peak, Frozen Reflection, Illusion Die) as well as Design Three: Spiral Connection. This allowed the creation of 3-dimensional, visible yet untouchable textures, as well as holographic-like structures.
- » Light pipes: This involved creating pipes of clear material through solid blocks of opaque material, using the same principle as fibre optics. Any light shone into the pipe transmits through to the other opening, even if they are bent through sharp angles. This was used in Hidden Light Tubes and Disconnected Light Tubes.
- » Manipulation of depth perception through layered material changes: By layering materials of incrementally less transparency, the designer can give the object a translucent appearance, but make it very difficult to gauge the depth of the volume of that material. This was used in Intangible Depth and Stress Stone to great effect.

Emulation of specifically similar materials: An opportunity for future designs could look at specifically targeting objects and products whose material qualities match those of PPP. This could enable designs that specifically address 'true' Hidden Novelty. I mentioned that the materials have similar qualities to candle wax, so a worthwhile design experiment could look at emulating candle-like structures and adapting them for a designed object.

These explorations could prove useful in more than just lighting control. We encounter interactive products everywhere. Expanding the palette of interactions possible in the systems around us can lead to more meaningful and delightful connections with our world. Delighting the senses and exploiting our perception can encourage a more exploratory, wondrous approach to our surroundings. Using surprise in a design commands the attention and invites the curiosity of the viewer, elevating the product beyond the mundane and encouraging us to think: “Maybe there’s more to this than I thought.”

6

CONCLUSION

Designed for Delight sought to expand on existing strategies for the elicitation of surprise to include the new, advanced manufacturing technique of 3D printing. The strategies, suggested by Ludden (2008), were based around visual-tactile incongruities. This thesis systematically explored and critiqued the possibility of applying these strategies to the 3D printing technology Polyjet Photopolymerisation (PPP), using this to then generate new and specific approaches. This was achieved through designed objects exploring all of Ludden's (2008) strategies, and these approaches then inform the design of lights that incorporated interactive controls imbued with VTIs. The exploration of lighting design was chosen due to the expectation of illumination from the interaction. This offered the opportunity to counter expectations of the interaction as well as the reveal of light.

Initiating with an analysis of the opportunities afforded by the relevant distinct research areas of *surprise*, *3D printing* and *lighting design*, this thesis employed a two-phase research through design process that explored the process of multi-material 3D printing. An analysis of Ludden's (2008) strategies for eliciting surprise through VTIs revealed an opportunity to explore the applicability of these strategies to 3D printing. Researching surprise revealed its potential as a means of encouraging exploratory interaction (Desmet, 2002; Fox-Derwin, 2011, p. 2; Rodríguez Ramírez, 2011, p. 263; Ludden et al., 2008) as well as drawing attention and persuading purchase (Grimaldi, 2006; Urquiola & Hudson, 2007, p.136).

Ludden's (2008) strategies were the first systematic analysis of surprise in product design. The first phase of research through design responded to the identified opportunity of exploring Ludden's (2008) strategies applicability to the emergent technology of 3D printing. In identifying the qualities of PPP, the potential for manipulating the perception of hardness to softness and smoothness to texture was identified. In order to explore Ludden's (2008) strategies, 3D printed experimental objects were developed for all seven of the strategies. These were then tested with participants in order to gauge responses and test for the elicitation of surprise. Unfortunately, given the current state of

PPP, Ludden's (2008) HN strategies are largely incompatible. This is due to the consistently unfamiliar look of PPP prints, which are hard to make convincingly look like other materials. PPP does however show excellent potential to surprise through VN strategies, where unfamiliarity is a key component of the eliciting of surprise. The data from the user testing was used to develop four approaches, each adapted from Ludden's (2008) strategies specifically in combination with certain capabilities and qualities of PPP 3D printing. Each of the developed approaches was used as the foundation for a light design in the second phase of the research. The first approach involves referencing familiar forms, but then making them tactually different from how they are visually suggested to be. This approach is demonstrated through the design of *Malleable Structures*, which references crystalline structures and breaks the hard expectation by making them soft. The second approach explores encouraging action through material variances and unfamiliarity. *Organic Formation* highlights this approach with an interactive, tactually intense surface that invites curiosity. The third approach is about showing texture where there is none, creating an illusion which is demonstrated through the untouchable textures and expanding form of *Spiral Connection*. The fourth approach suggests the potential for undermining visually-assessed material properties with internal structures, which is showcased through the compressible hollow dial of *Rotary Relays*.

Upon reflection over the data from user testing and the resultant developed lights, it was realised that a key determinant for the success of these approaches in these contexts was how well the approach for eliciting a VTI was combined with the interaction designed for the lights. The importance of this marriage between the approach, the interaction and the possibilities of the 3D printing technology cannot be overstated in this context. In order to generate surprise through a VTI, the designer needs to clearly comprehend their chosen 3D printing technology. This requires a display of sensitivity towards the qualities achievable, and carefully employing the desired approach. This will allow designers to craft products that can surprise and delight, conveying more meaning and allowing the end-users to build better person-product-relations.

WORKS CITED

Baumeister, R. F., Vohs, K. D., DeWall, C. N., & Zhang, L. (2007). How emotion shapes behaviour: Feedback, anticipation, and reflection, rather than direct causation. *Personality and Social Psychology Review*, 11(2), 167-203.

Burdick, A. (2003). Design (As) Research. In B. Laurel (Ed.), *Design research: Methods and perspectives* (82). Cambridge, MA: MIT Press.

Chua, C. K., & Leong, K. F. (2015). *3D printing and additive manufacturing: principles and applications*. Singapore: World Scientific.

Creswell, J. W. (2013). *Research design: Qualitative, quantitative, and mixed methods approaches*. Thousand Oaks, CA: Sage Publications.

Demir, E., Desmet, P. M. A., & Hekkert, P. (2009). Appraisal patterns of emotions in human-product interaction. *International Journal of Design*, 3(2), 41-51.

Desmet, P. M. A. (2002). *Designing emotions* (Doctoral dissertation). Delft, the Netherlands: Technical University of Delft, Industrial Design Engineering.

Desmet, P. (2003). A multilayered model of product emotions. *The Design Journal*, 6(2), 4–13. <http://doi.org/10.2752/146069203789355480>

Dugar, A. M., Donn, M. R., & Osterhaus, W. (2011). Tangible lighting controls—Reporting end-users’ interactions with lighting control interfaces. *Leukos*, 8(2), 123-136.

Fox-Derwin, E. (2011). *Honest deception: Skin, incongruity and surprise* (Master’s thesis). Wellington, New Zealand: Victoria University of Wellington, School of Design.

Gibson, J. J. (1962). Observations on active touch. *Psychological review*, 69(6), 477.

Green, W. S., & Jordan, B. (2002). *Pleasure with products: Beyond usability*. London, England: Taylor & Francis.

Godin, D. & Zahedi, M. (2014). Aspects of Research through Design: A Literature Review. In Proceedings of DRS 2014: Design’s Big Debates. Umeå, Sweden. Retrieved from <http://www.drs2014.org/media/648109/0205-file1.pdf>

Grimaldi, S. (2008). The ta-da series - A technique for generating surprising designs based on opposites and gut reactions. In P. Desmet, J. Van Erp & M. Karlsson (Eds.), *Design & Emotion Moves* (pp. 165-189). Newcastle, England: Cambridge Scholars Publishing.

- Hekkert, P. (2006). Design aesthetics: Principles of pleasure in design. *Psychology Science*, 48(2), 157-172.
- Hekkert, P., Snelders, D., & van Wieringen, P. C. (2003). 'Most advanced, yet acceptable': Typicality and novelty as joint predictors of aesthetic preference in industrial design. *British Journal of Psychology*, 94(1), 111-124.
- Heller, M. A., & Schiff, W. (2013). *The psychology of touch*. Psychology Press.
- Jordan, P. (2000). *Designing pleasurable products: An introduction to the new human factors*. London, England: Taylor & Francis.
- Katz, D. (2013). *The world of touch*. Psychology Press.
- Kim, J., & Robb, D. (2014). 3D printing: A revolution in the making. *University of Auckland Business Review*, 17(1), 16.
- Kittur, A., Chi, E. H., & Suh, B. (2008, April). Crowdsourcing user studies with Mechanical Turk. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 453-456). ACM.
- Kuniavsky, M. (2003). *Observing the user experience: A practitioner's guide to user research*. Burlington, MA: Morgan Kaufmann.
- Lazarus, R. S. (2006). *Stress and emotion: A new synthesis*. New York, NY: Springer Publishing Company.
- Lipson, H. & Kurman, M. (2013). *Fabricated*. New York, NY: Wiley.
- Ludden, G. (2008). *Sensory incongruity and surprise in product design* (Doctoral dissertation). Delft: Technical University of Delft, Faculty of Industrial Design Engineering.
- Ludden, G., Schifferstein, H., & Hekkert, P. (2008). Surprise as a design strategy. *Design Issues*, 24(2), 28-38.
- Martin, B., & Hanington, B. M. (2012). *Universal methods of design: 100 ways to research complex problems, develop innovative ideas, and design effective solutions*. Beverly, MA: Rockport Publishers.
- Matell, M. S., & Jacoby, J. (1971). Is there an optimal number of alternatives for Likert scale items? Study. *Educational and psychological measurement*, 31, 657-674.

- Merriam-Webster's. (2016). *Surprise*. Retrieved May 15, 2015, from <http://www.merriam-webster.com/dictionary/surprise>
- Michalski, M., & Ross, J. (2014). The shape of things to come: 3D printing in medicine. *JAMA*, 312(21), 2213-4.
- Milton, A., & Rodgers, P. (2013). *Research methods for product design*. London, England: Laurence King Pub.
- Mogey, N. (1999). *Likert scale information page*. LEARNING TECHNOLOGY DISSEMINATION INITIATIVE. Retrieved 2 July 2016, from http://www.icbl.hw.ac.uk/ltdi/cookbook/info_likert_scale/index.html#endhead
- Norman, D. (1990). *The design of everyday things*. New York, NY: Double Day.
- Popovic, V. (2002). Activity and designing pleasurable interaction with everyday artifacts. In W. S. Green & P. W. Jordan (Eds.), *Pleasure with Products: Beyond Usability* (pp. 367-376). London, England: Taylor & Francis.
- Prince, J. D. (2014). 3D printing: an industrial revolution. *Journal of Electronic Resources in Medical Libraries*, 11(1), 39-45.
- Rodríguez Ramírez, E. R. (2011). *Elements of surprise : Industrial designers' strategies for eliciting surprise through interaction* (Doctoral Dissertation). Wellington, New Zealand: Victoria University of Wellington.
- Rodríguez Ramírez, E. R. (2012). The role of surprise on persuasion in industrial design. *International Journal of Product Development*, 16(3-4), 263-283. <http://doi.org/10.1504/IJPD.2012.049837>
- Robson, C., & McCartan, K. (2016). *Real world research*. New York, NY: Wiley.
- Ross, P. (2008). *Ethics and aesthetics in intelligent product and system design* (Doctoral dissertation). Eindhoven, Netherlands: Eindhoven University of Technology.
- Ross, P. R., & Wensveen, S. A. G. (2010). Designing behaviour in interaction: Using aesthetic experience as a mechanism for design. *International Journal of Design*, 4(2), 3-13.
- Sachs, F. (1988). The intimate sense. *The Sciences*, 28(1), 28-34. <http://doi.org/10.1002/j.2326-1951.1988.tb02993.x>
- Scherer, K. R. (2005). What are emotions? And how can they be measured? *Social Science*

FIGURE LIST

Information, 44 (4), 695–729. doi:10.1177/0539018405058216

Schifferstein, H. N. (2006). The perceived importance of sensory modalities in product usage: A study of self-reports. *Acta psychologica*, 121(1), 41-64.

Scott, M. (2001). Tactual perception. *Australasian Journal of Philosophy*, 79(2), 149–160. <http://doi.org/10.1080/713931200>

Smith, C. A., & Lazarus, R. S. (1990). Emotion and adaptation. In L. A. Pervin (Ed.), *Handbook of personality: Theory and research*. New York, NY: Guilford Press.

Smith, C. A., & Lazarus, R. S. (2001). Appraisal components, core relational themes, and the emotions. In G. Parrott (Ed.), *Emotions in social psychology: Essential readings* (pp. 94-114). Sussex, England: Psychology Press.

Sonneveld, M. H., & Schifferstein, H. N. J. (2008). The tactual experience of objects. In H. N. J. Schifferstein & P. Hekkert (Eds.), *Product Experience*. San Diego, CA: Elsevier, <http://dx.doi.org/10.1016/B978-008045089-6.50005-8>.

Stratasys. (2016). Rubber-Like Materials for 3D Printing [Text]. Retrieved from <http://www.stratasys.com/materials/polyjet/rubber-like>

Urquiola, P., & Hudson, J. (2007). *The international design yearbook 2007*. London, England: Laurence King.

Wohlers, T. (2016). *Wohlers report 2016*. Wohlers Associates, Inc.

Yassine, A. A. (2012). Parametric design adaptation for competitive products. *Journal of Intelligent Manufacturing*, 23(3), 541-559.

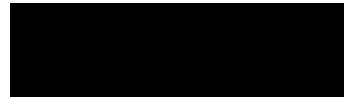
Zwicky, F. (1967). The morphological approach to discovery, invention, research and construction. In *New methods of thought and procedure* (pp. 273-297). Heidelberg, Germany: Springer Berlin Heidelberg.

Figure	Title	Source
1.1	<i>Konko</i>	Evenhuis, W., & Gabriel, A. (2008). <i>Konko</i> . Retrieved from http://www.pinterest.com/
1.2	<i>Flexlamp</i>	Hecht, S. (2003). <i>Flexlamp</i> . Retrieved from http://shop.gessato.com/
1.3	<i>3D Printed Hairbrush</i>	3D Hubs. (2016). <i>3D Printed Hairbrush</i> . Retrieved from https://www.3dhubs.com/
1.4	<i>Colony Series</i>	Buckman, A. (2016). <i>Colony Series</i> . Retrieved from http://www.alex buckman.com/
1.5	<i>Huddle</i>	Graas, D. (2012). <i>Huddle</i> . Retrieved from http://www.davidgraas.com/
1.6	<i>Bloom</i>	Jouin, P. (2012). <i>Bloom Table Lamp</i> . Retrieved from http://inhabitat.com/
1.7	<i>two.parts/atom & two.parts/ heatsink</i>	Logan, C. (2016). <i>two.parts/atom & two.parts/ heatsink</i> . Retrieved from http://two.parts/
1.8	<i>The On-Edge Lamp</i>	Grimaldi, S. (2008). <i>The On-Edge Lamp</i> . Retrieved from http://www.pinterest.com/
1.9	<i>Fonckel One</i>	Ross, P. (2008). <i>Fonckel One</i> . Retrieved from http://www.materialise.com/
2.1 - 2.2	All images, tables and figures made by author.	
3.1 - 3.64	All images, tables and figures made by author.	
4.1 - 4.48	All images, tables and figures made by author.	


APPENDIX ITEM 1

This item includes the Human Ethics approval form, extension and amendment. It also includes the consent forms and information sheets handed out to participants. It does not include the questionnaires, as those are included in the main body of the thesis.

Phone
Email



MEMORANDUM

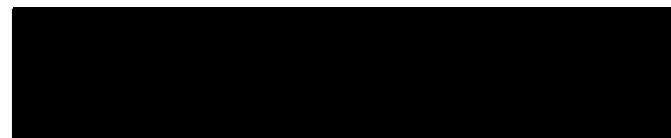
TO	Sebastien Voerman
COPY TO	Edgar Rodriguez
FROM	AProf Susan Corbett, Convener, Human Ethics Committee
DATE	15 November 2015
PAGES	1
SUBJECT	Ethics Approval:  Surprise in lighting design: Tactile interactions for encouraging engagement and use

Thank you for your application for ethical approval, which has now been considered by the Standing Committee of the Human Ethics Committee.

Your application has been approved from the above date and this approval continues until 12 June 2016. If your data collection is not completed by this date you should apply to the Human Ethics Committee for an extension to this approval.

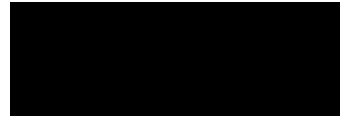
Best wishes with the research.

Kind regards




Susan Corbett
Convener, Victoria University Human Ethics Committee

Phone
Email



MEMORANDUM

TO	Sebastien Voerman
COPY TO	
FROM	AProf Susan Corbett, Convener, Human Ethics Committee
DATE	5 May 2016
PAGES	1
SUBJECT	Ethics Approval:  Surprise in lighting design: Tactile interactions for encouraging engagement and use.

Thank you for your request to extend your ethics approval. This has now been considered and the request granted. Your application has approval until 13 July 2016.

If your data collection is not completed by this date you should apply to the Human Ethics Committee for an extension to this approval.

Best wishes with the research.

Kind regards




Susan Corbett
Convener, Victoria University Human Ethics Committee

MEMORANDUM

Phone

Email

TO	Sebastien Voerman
COPY TO	
FROM	AProf Susan Corbett, Convener, Human Ethics Committee
DATE	5 May 2016
PAGES	1
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Best wishes with the research.

Kind regards

Susan Corbett
Convener, Victoria University Human Ethics Committee

Interactivity in lighting: Designs for encouraging use and attention.

CONSENT TO INTERVIEW AND QUESTIONNAIRE

This consent form will be held for 1 year.

Researcher: Sebastien Voerman, School of Architecture & Design, Victoria University of Wellington

- I have read the Information Sheet and the project has been explained to me. My questions have been answered to my satisfaction. I understand that I can ask further questions at any time.
- I agree to take part in a semi-structured interview and questionnaires.

I understand that:

- I may withdraw from this study up by **13/7/2016**, and any information that I have provided will be returned to me or destroyed.
- The information I have provided will be destroyed **1 year** after the research is finished.
- Any information I provide will be kept confidential to the researcher and the supervisor. I understand that the results will be used for a Masters thesis and a summary of the results may be used in academic reports and/or presented at conferences.
- My name will not be used in reports, nor will any information that would identify me.
- (Note for Victoria University students)* I understand that my participation or non-participation in this research will not affect my grades at VUW in any way.
- I would like a copy of the transcript of my interview: Yes ☐ No ☐
- I would like a summary of my interview: Yes ☐ No ☐
- I would like to receive a copy of the final report and have added my email address below. Yes ☐ No ☐

Signature of participant: _____

Name of participant: _____

Date: _____

Contact details: _____



Interactivity in lighting: Designs for encouraging use and attention.

INFORMATION SHEET FOR PARTICIPANTS

Thank you for your interest in this project. Please read this information before deciding whether or not to take part. If you decide to participate, thank you. If you decide not to take part, thank you for considering my request.

Who am I?

My name is Sebastien Voerman and I am a Masters student in the Masters of Design Innovation at Victoria University of Wellington. This research project is work towards my thesis.

What is the aim of the project?

This project explores new interaction designs for lighting and aims to explore a diverse range of prototypes based around 3D printing.

This research has been approved by the Victoria University of Wellington Human Ethics Committee. Application Number: [REDACTED]

How can you help?

If you agree to take part, I will be showing you a number of prototype lights. You will be invited to interact with each one and asked to fill out a questionnaire about each prototype. After interacting with all the prototypes, I will interview you, asking questions about the prototypes you just interacted with. The interview will take 20 minutes. I will take notes in the interview and write up a summary later. After the interview, there will be an opportunity to review the exercise and review more information.

You can stop the interview at any time, without giving a reason. You can withdraw from the study by the **13/7/2016**. If you withdraw, the information provided will be destroyed or returned to you.

What will happen to the information you give?

This research is confidential. I will not name you in any reports, and I will not include any information that would identify you. Only my supervisors and I will read the notes or transcript of the interview. The interview transcripts, summaries and any recordings will be kept securely and destroyed **1 year** after the research ends.

What will the project produce?

The information from my research will be used in my Masters thesis. You will not be identified in my report. I may also use the results of my research for conference presentations, and academic reports. I will take care not to identify you in any presentation or report.

If you accept this invitation, what are your rights as a research participant?

You do not have to accept this invitation if you don't want to. If you do decide to participate, you have the right to:

- choose not to answer any question;
- withdraw from the study up until four weeks after your interview;
- ask any questions about the study at any time;
- receive a summary of your interview;
- read over and comment on a written summary of your interview;
- agree on another name for me to use rather than your real name;
- be able to read any reports of this research by emailing the researcher to request a copy.

If you have any questions or problems, who can you contact?

If you have any questions, either now or in the future, please feel free to contact either:

Student:

Sebastien Voerman

[REDACTED]

Supervisor:

Dr. Edgar Rodriguez

Programme Director - Industrial Design

School of Architecture & Design

[REDACTED]

[REDACTED]

Human Ethics Committee information

If you have any concerns about the ethical conduct of the research you may contact the Victoria University HEC Convener: Associate Professor Susan Corbett. [REDACTED]

[REDACTED]