Emotive Materials: Towards a shared language of the meaning of materials

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Bachelor of Science in Engineering, Master of Science in Engineering, University of Pennsylvania (2014)

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of

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Abstract

Due to advances in design generation and digital fabrication, novice designers are able to access more and more tools to bring their visions to life. As materials begin to evolve and change shape, having a set of rules with which to evaluate, interpret, and design them will become increasingly important. In moving towards tools that allow us to design and create our own materials these the two worlds of creation and curation must be (re)connected: in this work I strive to quantify and understand the emotive aspects of materials, such as haptic responses to, cognitive evaluation of, and emotive perception of materials; in order to understand how materials communicate meaning. My aim is to produce a set of guidelines that enable designers and scientists to communicate and help creators understand the implications of emerging material combinations. For those without the resources to conduct time intensive user studies for every project and without the intuitive knowledge of a professional, it can be very difficult to predict the implications of materials and their impact on the interaction. In this thesis, a repeatable methodology for exploring these impacts was implemented and evaluated. As a result, it will be possible to create a holistic material selection process. By combining materials to maximize properties, I plan to go beyond existing databases and fabricate objects designed to evoke specific reactions. Developing an effective methodology would enable fabrication of more engaging objects.

Through this research, I plan to establish guidelines and provide a common language that enables designers to influence materials development and connect designers and researchers in a more effective way than is currently possible. This will promote unique research of materials and expand their range of use. Such a tool will enable new design practices by adding emotive factors that are not rigorously understood to the material selection and fabrication process. At its core, materials science is the study of how the structure and processing of materials impact the properties of compounds. I plan to help designers and scientists go one step further, and use material combinations to connect directly with the end user.

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Contents

List of Figures

List of Tables

1

Introduction

A Brief History of Materials Design

"To some extent, then, what allows us to behave as humans are our clothes, our homes, our cities, our stuff, which we animate through customs and language. The material world is not just a display of our technology and culture, it is a part of us. We invented it, we made it, and in turn it makes us who we are."

– Mark Miodownik, *Stuff Matters* [54]

1.1 Engineering Matter

As I began my exploration of what gives materials meaning, I asked some friends to describe their favorite material. My favorite response, from Colleen, captured the wonder we experience when we encounter a new material for the first time:

> I think I was in third grade. It was Dr Suess's [sic] birthday and we were reading the book Bartholomew and the Oobleck. In this book there is a mysterious new weather phenomenon called Oobleck which is falling from the skies reeking havoc on the kingdom. Oobleck is a green goopy substance that seems to stick to everything and trap people in their tracks. I'm sure there's more to the story, probably a moral, and I think Bartholomew saves the day but this isn't about that story. Once we finished the book we made some of our very own Oobleck–it was a real

> thing! It was green, slimy, and was harder to stir the faster you tried to stir it. I think I liked it mostly because it behaved so differently from anything I had encountered before. It seemed to break all the rules I knew about the physical world. And I couldn't figure out if it was a solid or liquid since it seemed to behave like both. So this Oobleck may have just been cornstarch water and green food coloring, but to 8-year-old me it was something exciting and otherworldly. Also it kind of made a mess, which was always a sign of a good time. Years later when Oobleck was only a vague but pleasant memory, I learned about non-Newtonian and shear thickening fluids. It turns out what was once an alien substance was in fact a well understood physical phenomenon. So now I have a new apprecitation for Oobleck. It's a material that, to me, represent the application of physics and known science in a different way to obtain surprising and exciting properties[1]

One can easily imagine the visceral reaction Colleen describes so well: as the slimy green-colored cornstarch water is poured from one cup to another, it begins to separate in a gloopy way, creating a thin shiny layer on the surface of the material that looks alien in comparison to the materials found in nature.

But we do not need to look somewhere as outlandish as slime to understand the power of material substances. Colleen's description of her first interaction with non-Newtonian fluid compels us to better understand the nature of the human experience when interacting with materials. There are many lenses through which we can examine human expression in the physical world. Our ability to engineer matter has played out in health, art, architecture, education, and communication, and this ability is a fundamental aspect of what makes us human. "Making, using and sharing things played a key role in developing human behaviour. The ability to make tools allowed humans to adapt to new environments and out-compete other animals. Gradually [these abilities] would lead to humans becoming the most successful animal in the world" [48]. These early developments were the basis for all modern technology.

Altering our surrounding physical environments has required constant development of new technologies. Engineering materials by manipulating the properties exhibited by matter has allowed us to develop advanced weaponry to protect ourselves, insulating walls to house ourselves, and breathable, flexible textiles to clothe ourselves (in addition to the slimy, green, non-Newtonian fluid that turns eight-year-olds into material scientists). At the core of these developments have been material advances. The combination of copper and tin ushered in the Bronze Age, during which material possibilities altered the nature of trade relations. Iron enabled and

[1] Colleen Reynolds, Personal Communication, February 24, 2016

age of advanced weaponry and decorative design and redefined warfare. We currently find ourselves in an age defined by semiconductors, where silicon's versatility and use in integrated circuits revolutionized how we process information and communicate with each other.

Materials science and engineering as it is currently known is the study of how the structure and processing of materials impact their properties and functionality. The earliest work with manipulating materials was based upon taking readily existent elements (such as copper, silver, and gold) and capitalizing on their observed ductility, strength, and hardness. The first knowledge about processing was developed through physically beating metals into shape, melting, and casting them to achieve hard objects. One of the earliest and most iconic examples of the harnessing of the immense power of nanomaterials to produce intriguing and almost magical results is the Lycurgus cup. It exhibited a fascinating transition between colors that was achieved through the incorporation of gold particles in a glass matrix.

Figure 1-1: The Lycurgus Cup
[3]

As new material combinations were discovered, new processing methods had to be created to implement them. Mixing elements allowed for the creation of alloys that possessed even more desirable elements than the initial components. High temperature ovens were developed to cast elements like iron. Over time, this developed into the symbiotic process of empirical observation and theory formation that serves as the basis for engineering today. As the tools to analyze and synthesize materials have improved, the degree of control has expanded and the scale has reached imperceptibly small levels.

Our ability to engineer matter to exhibit the properties we seek enables us in every aspect of life, allowing us to venture as far as outer space, but also supporting us in on a level as personal as the clothing we wear on our bodies or the medical devices we implant in our organs. "[The] desire for stronger, more comfortable, waterproof, breathable fabrics creates a need for the understanding of the internal material architectures that are required to create them. This drives our scientific understanding, and so drives materials science. In a very real way, then, materials are a reflection of who we are, a multi-scale expression of our human needs and desire." [54]. It is here that we begin our exploration.

1.2 Communicating Through Design

Communication through the physical world is at the core of societal progression. Objects have been used to represent cultural, societal, and functional values by every group of humans. Indeed, it is often through the study of objects and spaces that we gain insight into the nature of the lives of our ancestors. Designers often use metaphors and stories to embody experiences through physical vessels. Through experience, they develop an intuitive understanding of the means of communicating using physical design.

While we are familiar with the idea that objects can be representations, we are perhaps less accustomed to the notion that they can actually influence our understanding of the world around us. After all, vital connections have been established between our physical senses and our mental states. Temperature, texture, weight, sound, taste, smell, and color, among a symphony of other physical sensations, affect us everyday. Our actions are greatly influenced and sometimes created by the sensory world around us. In some cases and stages of life, our physical interactions even go as far as to shape our learning: physical sensations constitute the scaffolding for representing and understanding abstract higher concepts such as friendliness, emotional distances, and social status. Our emotions, thoughts, and behaviors are grounded in physical sensations [47]. In this manner, our environment can serve not only as reflections of our preferences and personalities, but also as elements that shape our mentality and perception.

But what gives objects their depth? There are numerous factors that impact our understanding of the meaning of these items: the form, the color, and the material and some of the strongest. In many ways, it is the material composition that conveys the personality of the object and adds emotional weight. Consider, for instance, the distinction between credit cards made of plastic and those made of metal. Not only are the thick, heavy, metal ones distinguished due to their rarity, but they carry a literal weight with them that indicates their prestige. Even if a plastic cards boasts the exact same design as its metal counterpart, it cannot achieve such gravity. The role of materials in our lives spans from technical to aesthetic: the ability to engineer smaller and more efficient batteries and electronic components has allowed us to carry extremely powerful computers in our pockets in the form of stylish, slim phones, and the prevalence of machinery able to process the metal casings allows for their beautiful exteriors. The role of materials is central to everyday life; we engage with them everywhere, often intimately- consider the sheets you selected for your bed and the casing you selected for your pillows, or the soft cloth that new parents place over a newborn baby. Despite the intimacy we experience with such objects, we often consider these final products to be extremely distant from the chemicals, processing, and fabrication that are involved in their creation, and we often could not specify what properties or compounds contribute to the attributes that make these objects so dear to us.

Materials are extremely rich in information, not only through the properties that they possess, but also through the stories and personality that they convey. How much, for instance, are we willing to pay for an apartment with hardwood floors over one with linoleum tiles? When I walked into my first apartment, I was immediately struck by the manner in which the hardwood floors created a drastically different feel for the environment than the tiles that I had come to strongly associate with dorm living and spaces intended for temporary living and ease of cleaning. How can we account for the visceral differences we experience when reading a paper book versus an electronic one? As the editors posit in *Materials Experience*, "there is a character hidden in material even before it has been made into a recognizable form- a sort of embedded personality, a shy one, not always visible, easily concealed or disguised, but one that, when appropriately manipulated, can contribute to good design" [99]. An analogy can be drawn between materials and actors - some materials are chosen for lead roles in certain applications, while others go unnoticed as essential background actors [99], and ultimately, "designers paint with materials" [99]. In every day life, "materials allow for the realization of sensory experiences" [62].

Yet, despite the acknowledgement of the importance of material factors, the development of materials often remains a mystery. The process of going from concept to finished consumer product can take decades. In order to truly delve into the manner through which we perceive the meaning of materials requires considering many different fields of knowledge-from cognitive psychology to product design to material science - all of which use many different languages, approaches and tools.

"Material attributes can very broadly be thought of in terms of their *technical properties* that stem from the intrinsic characteristics of the material itself (its density and its mechanical, thermal, optical, and chemical properties for instance); their perceptual qualities that stem from our senses (sight, touch, hearing, taste, smell); and those *culturally dependent qualities* that fundamentally stem from the way our society or culture views materials" [75]. In this thesis I hope to shine some light on the interplay between these attributes to explore the full potential of materials.

1.3 My Perspective

There are so many languages used for the making, handling and experiencing of materials–as mentioned earlier, the vocabulary for technical development and categorization is a far cry from the delight Colleen expresses with the viscous, gloopy Oobleck. Materials mediate our understanding of the world. Its why we see wood as comforting and steel as cold and professional. However, we do not necessarily know why this is or how to apply to this thinking across all materials. When I first began building things, I was intrigued by the challenge of selecting which materials to use. The process can be extremely tricky for designers and I often ended up forfeiting by using common materials for my designs, such as wood and plastic. The process of selection becomes even more challenging with novel materials, which is undoubtedly one of the largest barriers for technology to go from lab to market.

My undergraduate research and studies focused on the technical development and understanding of materials- I experienced the joy of producing things that had never existed before and learning how to tailor properties. I quickly became frustrated, however, by the fact that the particles I synthesized (with the intention of producing more efficient solar devices) would take decades to reach the market, by which point the supposedly new technology would have been surpassed by more efficient, more novel systems. It was this frustration, coupled with a desire to build for individuals and societies, that led me to consider design.

My thesis stems from explorations that began with the creation of Dusk, a personal resting space for the Media Lab community. Dusk exposed underlying questions about using materials to evoke reactions and create ambiances. This connected me to broader group interest that has established unconventional avenues of communication through the physical embodiment of information, manipulation of material properties, and physical interaction and context of objects. Within my exploration of these methodologies, I have narrowed my personal contributions and interest towards the development of an integrated system for material selection and development.

This thesis is a product of my own varied interests but also of the environment within which it was conceived. Through the process of scoping out my research, I had the chance to visit material libraries in the area and became acutely aware of the fact that traditional engineers almost never interact with materials in such a manner. Most technical material scientists are not given that opportunity to develop an intuition about the "feel" of materials. I have interviewed many individuals in relevant fields spanning designers, material librarians, engineers, and users (some of whom are quoted in this thesis). I have visited material libraries to learn about existing systems, form lasting relationships, and find ways in which to contribute to the expansion of their efforts. Through repeatedly reaching out to practicing individuals I am working to ground my work and prepare it for deployment and to explore the viability of this field. It is important to note that there is so much more that can be learned from the ideas proposed in this thesis. I present this work not as a set of concrete answers, but as an exploration of the potential of this type of thinking and process of material design. I hope that this body of work will spark conversations and streamline this process for future material designers.

1.4 Thesis Overview

In the following pages I delve into a literature review of the diverse array of fields from which this work is drawn (chapter two), through which I identified existing gaps in the process of working with materials for human-centered design (chapter three). As a means for inspiration, I explore the personality embedded in material and the storytelling potential that lies in this space, discussed in the fourth chapter. In the fifth chapter I describe the first experiment I conducted as a step towards forging a methodology. In this study, I took a familiar form with a specific, but nuanced purpose (the die) and constructed it through a variety of materials to delve into the means through which we derive meaning from material differences. I began to identify the salient properties and considered the manner through which different individuals approached the questions. Based on the findings from this broader study (and existing literature), I conducted a longer term study focused on three specific properties, as explained in chapter six. In Chapters seven and eight, I wrap this thesis up by considering the implications of this work and suggesting future work to build upon the potential of using materials to communicate emotive meaning.

In this thesis, I started with broad study as a foundation from which to determine what types of questions could help reveal connections between the quantitative and the qualitative. This led to relations that indicate that specific attributes are related to specific properties. I have determined that this method should be considered as part of a broader discussion due to the viability of results of the study. Ideally, this work will open up a discussion for others to use this methodology and collectively understand the language of materials.

2

Background and Relevant Work

"We live in a world of materials; it is materials that give substance to everything we see and touch. Our species homo sapiens differs from others most significantly, perhaps, through the ability to design to make things out of materials and in the ability to see more in an object than merely its external form. Objects can have meaning, carry associations, or be symbols of more abstract ideas. Designed objects, symbolic as well as utilitarian, predate any recorded language they provide the earliest evidence of a cultural society and of symbolic reasoning. Some of these objects had a predominantly functional purpose: the water wheel, the steam engine, the gas turbine. Others were (and are) purely symbolic or decorative: the cave paintings of Lascaux, the wooden masks of Peru, the marble sculptures of Attica. But most significantly, there are objects that combine the functional with the symbolic and decorative."

– Mike Ashby and Kara Johnson, *Materials and Design* [9]

2.1 The Existing Workflow of Design and Materials

2.1.1 Material Development Process

In order to examine the differences in perspective and vocabulary surrounding materials, it is important to understand the process through which materials are developed. Scientists and engineers are primarily concerned with achieving new functionalities; materials are fabricated to exhibit specific technical properties. Often, engineers will begin the process of creating materials by reproducing existing work. The majority of new knowledge about materials stems from hands-on experimentation and incremental advances in technical methodology. Scientists who work on lab experimentation complement the work done by theorists who strive to build models to describe and predict physical phenomena. In recent decades, advances in technology have allowed for more and more powerful computational material science, as simulations and modelling are now a crucial part of the process of planning experiments and understanding results. Through the combination of empirical testing, theoretical calculations, and predictive and analytical simulations, scientists and engineers can now tailor unique structures with specific intended functionalities. Instrumentation provides a level of control that allows us to manipulate individual atoms. Tools such as the Materials Project aim to illuminate and predict material combinations and the resulting properties. This project uses web-based computing to allow scientists to access powerful analysis tools and information on predicted material behavior to "inspire and design novel materials" [33]. Typically, a complete development process would begin with the reproduction of previous work, use of theory to predict results, synthesize the materials in lab (through wet chemistry, deposition, etching, lithography, printing, mechanical drawing, crystallization, or other techniques), characterization of the resulting compound, and analysis of these results. The process becomes more complicated, though more interesting, when scientists produce hierarchical structures such as binary superlattices, where particles of different materials are combined to maximize and tune the properties of the system. For research conducted in academic settings, the primary output (other than the compound itself), usually takes the form of conference talks, publications, or patents, as opposed to the explicitly consumer-facing nature of many design outputs. As a result, "function is inscribed in materials before they leave the lab or producer" [90].

Due to the rigorous, analytical methods that power material development, the process can be very long, tedious, and time-consuming. Materials are designed and explored based around specific requirements, and "it can take years, decades, for an exciting new discovery to lead to a useful application if it ever gets there at all" [10]. In order for these materials to be selected for use, not only do they need to be recognized by potential industries and individuals willing to use them, but they must meet stringent cost, safety, manufacturing, and durability requirements.

There is a "mismatch between designers and entrepreneurs' understanding of market needs exacerbated by the many layers of separation between material and end consumer" that contributes the slow uptake of new materials [49]. Materials can take as long as 20 years to reach the marketplace due to factors such as "an initially high cost invention, cost barriers to materials substitution from entrenched materials, and insufficient knowledge of market applications by inventors" [90]. As such, "history is replete with examples of seemingly fabulous scientific discoveries that surely seemed to the discoverers to have huge potential applications in many areas, only to have them lie idle for many years or not be developed at all" [75].

2.1.2 Materials Selection

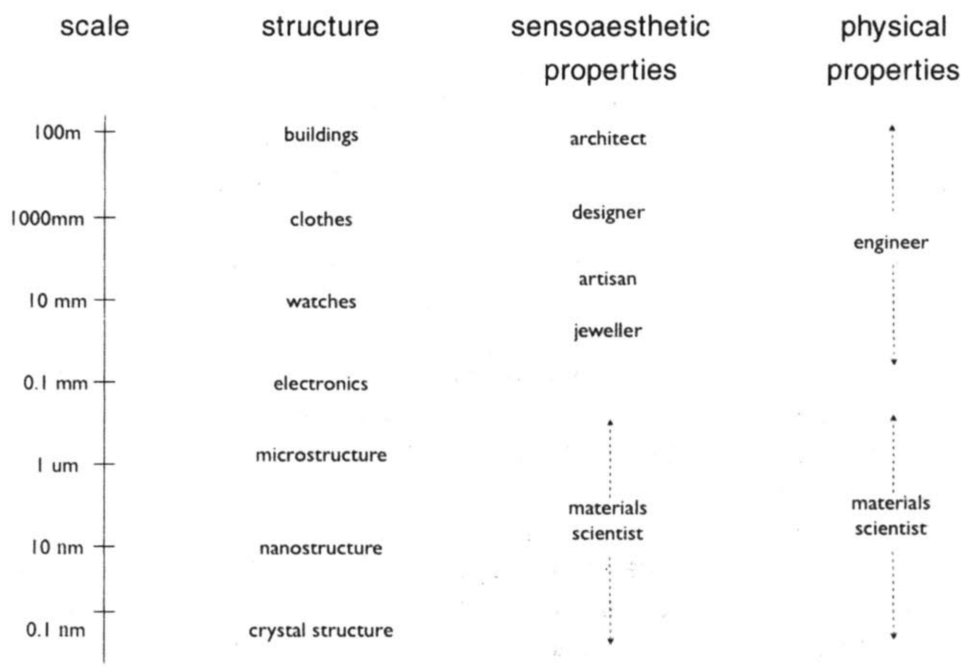


Figure 2-1: How different properties of materials and structures are applied to different professions at different scales [55]

The disconnect between the engineering perspective of materials and the design perspective is exemplified profoundly by the materials selection process. According to Phillip Ball, there are between 40,000 and 80,000 options to choose from when fabricating. "The pace of materials innovation is incredibly fast, and as a result of overwhelming competition, many new materials simply do not reach the marketplace" [90].

2.1.2.1 Technical

Understandably, the technical process of materials selection is primarily driven by functional requirements. Engineers focus primarily on the performance of the material. They consider aspects such as degradation, maintenance, and compatibility with other materials by focusing on properties spanning strength, weight, melting point, conductivity, ductility, moldability, etc. Material choices may be cut based on access to manufacturing processes and tools or cost and rarity of the material. It is often the responsibility of the engineer to consider the construction of the object at a systems level- considering the mechanical integration of pieces, the scaling of manufacturing, and the equipment needed to support fabrication. To collect information, engineers will often refer to technical manuals, textbooks, literature released by manufacturers, specifications released by companies such as MacMaster Carr, or official sources such as the National Institute of Standards and Technology (NIST) or American Society of the International Association for Testing and Materials (ASTM). Typically, cost and performance are the primary considerations.

Typically, cost and performance are the primary considerations. Technological terms serve to "predict service performance" and "gather engineering design data" [99]. Information on these properties is often collected in databases.

One of the most formal and rigorous procedures used by engineers and scientists was developed by Mike Ashby. By allowing users to plot properties (or ratios of properties) against each other, this method allows easy visualization of the relations between different classes of materials in "Ashby charts." This concept was packaged into a quantitative database called CES Edupack [5] that streamlines the process of sorting through and eliminating material options through easily parsible visualizations.

Many of the simulations and models mentioned earlier can also be used to select materials using techniques such as Finite Element Analysis. It is interesting to note that most material scientists rarely interact with types of material samples that designers and manufacturers might examine. Mark Miodownik also describes the contemporary climate of materials science as one that is missing out on the "tactile pleasures of materials" [90]. He describes materials science departments as "places of pure deductive reason" and states: "It's kind of weird that materials science departments are almost empty of the materials we study...What does that say about us as a community? We are becoming more and more theoretical; we are losing touch with the more physical side of what we do" [90].

2.1.2.2 Nontechnical

Design carries with it the heavy responsibility of inducing emotional attachment in people that results in the well-being of the consumer and the preservation of the environment- social efficacy, and potential of materials [90]. In this effort, designers utilize intuitive perception and nonverbal communication cues to convey

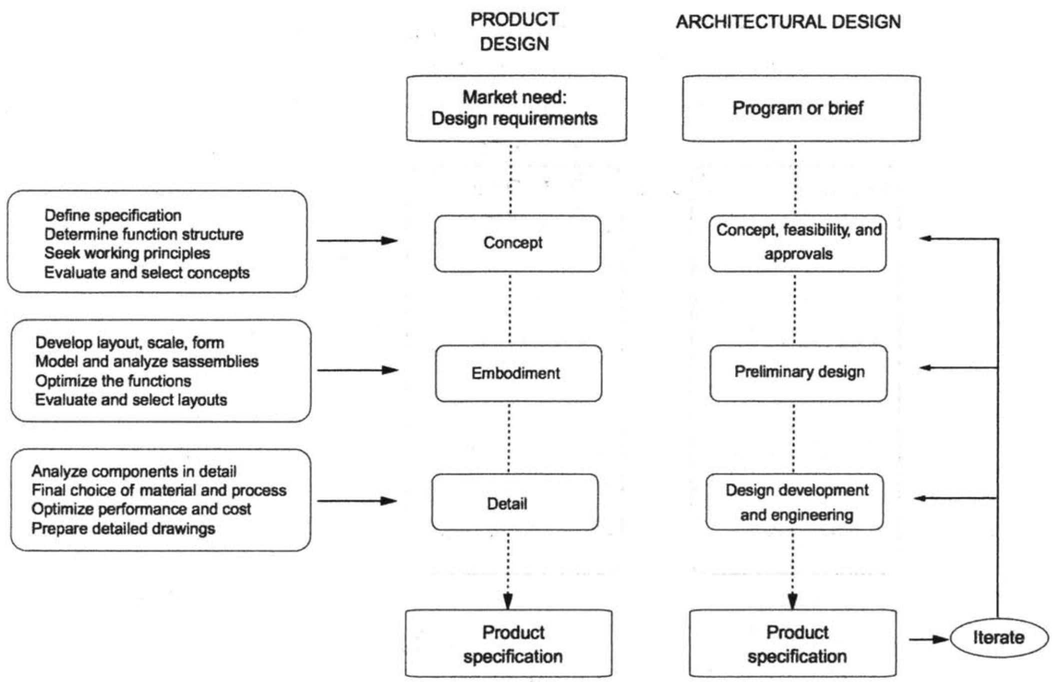


Figure 2-2: Design Flowchart, [75]

meaning through produced objects. "Designers endeavor to capture the emotionality of some information or experience, and to embody that emotionality in physical sensorial attributes so that our expectations of the object are extended past pure functionality" [56]. They "mostly rely on tacit and implicit knowledge to inform decisions" [64].

In contrast to the process generally followed in engineering disciplines, the design process is typically an iterative, potentially non-linear one. Rather than technical properties, designers need materials that "please users and touch them emotionally in some way" [85]. Many designers begin by observing their intended users and practicing ethnography to effectively identify the needs of the intended community. Further steps can include defining design goals and parameters, generating a large number of ideas and thinking broadly, prototyping and testing to narrow down options, broadening back out to ideas based on the results, prototyping refined solutions, evaluating the results, and working with production teams to evaluate the viability of manufacturing. In this process, materials are often considered as a last stage decision, "as a kind of afterthought" [90].

As opposed to the simulations, models, and technical manuals often used by engineers, designers will often refer to material libraries, where they are able to explore the intangible aspects of the material by physically interacting with it. Through

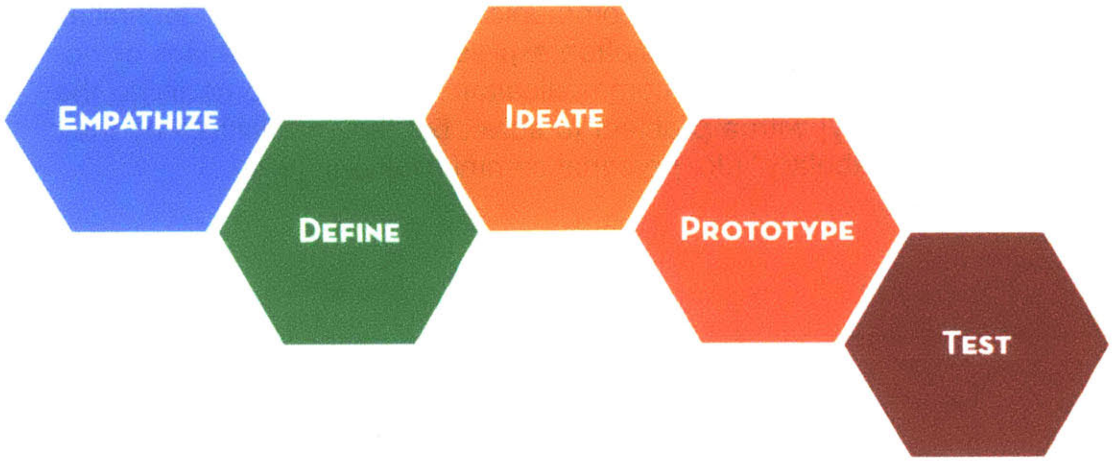


Figure 2-3: A typical path for design [59]

these interactions, they can evaluate the performative aspects of materials. One librarian mentioned that students come in with context wide open, so these venues can serve as an incredible source of inspiration. Many designers will also draw heavily from personal experience, especially as they become more well-versed in their craft.

In some ways, the increasing effectiveness of Computer-Aided Design tools may even be exacerbating the issue of material selection being an afterthought - for some designers, the model itself can be their final output, and the widespread accessibility of prototyping tools such as 3-D printers arguably make the material decisions less salient. An interesting divide arises here, where for some the CAD model and its creation involves very little consideration of the material, and on the other side, as Wilkes notes from her personal correspondences, some materials are so precisely engineered that they are, in and of themselves, the product. For some designers, it can be difficult to gain necessary information about materials:

> The legacy of the intellectualisation of the high arts can be seen in the paucity of materials education that many design, architecture and art students receive. A materials consultant at a globally renowned design and engineering firm commented that the lack of materials knowledge displayed by many practising architects was a "perennial problem" since many "just dont learn much about the practical uses of materials, their properties, how to form them, their limitations" (Duncan, personal communication). Jo, a materials librarian, commented"I have even had to explain in the past that stone is not manufactured but quarried from the

earth, and that metals are not quarried in sheet or lump form but extracted from ores" (personal communication). This lack of 'technical' knowledge about materials is often expressed in terms of a lack of 'vocabulary' or a 'problem of communication': "students come in [to the materials library] with a problem to solve, but they are limited by their materials vocabulary" (Jo, personal communication). [90]

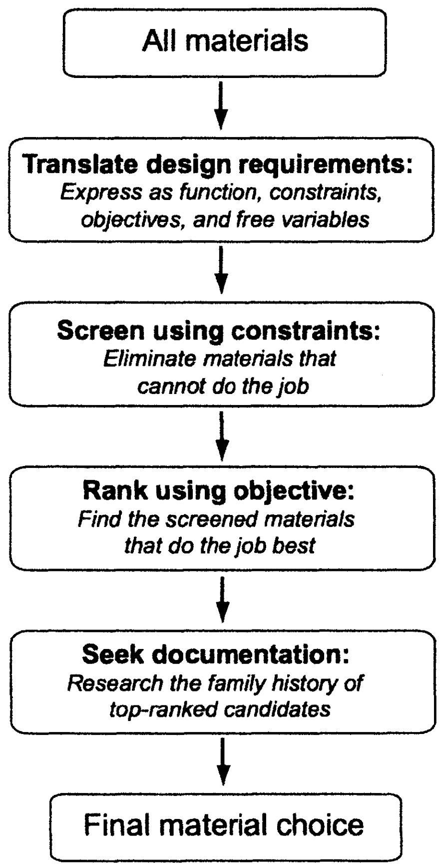


Figure 2-4: Material Selection [75]

Presently, definitive information on a materials "success" is frequently determined through extensive user testing. Interviewing focus groups or observing individuals using a product or material in their daily lives is an extremely rich form of learning, but it is also extremely time consuming. With some materials, such as newer ones, this is not feasible. The designer's decisions on where and how to include novel materials are central to their general interpretation of these compounds, especially in early stages. If designers are unable to effectively familiarize users with a compound, the material will remain mysterious, unfamiliar, and potentially even fear-inducing. New materials are often seen as risky as there are no guidelines or examples of performance. Designers and product builders are concerned about the lack of experience designing with and manufacturing these materials, and may feel unsure of how the limits can be pushed when they need to scale up production. Often, this can be too big of a risk.

2.2 Human Perception and Embodied Cognition

> *"The aesthetic experiences of a material originate from the perception and notice of material sensorial information, such as softness, warmth, smoothness, sound, weight, and stickiness. As a direct conduit from the human sensory system, the aesthetic component of experience is omnipresent and inevitable."*
>
> – Elvin Karana, et al, *Materials Experience* [42]

Our experience with materials is essentially a study in our response to different physical and cognitive signals. Many researchers have explored human perception and psychophysics (which deals with the connection between physical stimuli and our mental responses).

Examining the manner through which we approach physical stimuli also provides fruitful insights while digital co-design is an important part of the design process, experiential engagement, such as active and passive touch of a material, is crucial, especially as most digital channels are impoverished or unavailable [64]. As a means of enabling better human-computer interface interactions, Petreca and the team observed and interviewed designers about how they examine textiles. They noticed "different types of touch disposition and attention according to the type of engagement with the textile" [64]. Experts perform diverse touch behavior according to the property they investigate: holding the corner to observe how a piece falls, squeezing or dropping it to feel its weight, shaking or stroking it to feel the temperature, or pulling it to feel the resistance. As such, the body is used as a surface to test ideas [64].

Even for those of us who are not acutely aware of this fact, physical stimuli constantly shape our perception. "Perceiving, knowing, and and imagining are intrinsically related activities" [43]. Cognitive psychologists use spreading activation theory to describe this phenomenon, in which the "impact of a physical experience on mental concepts operates on a semantic mapping process" [86]. Accordingly, physical sensations increase awareness of related mental concepts that exemplify the experience. Based on the spreading activation model, these activated concepts may then spread over the enhance the salience of other semantically related concepts [86]. "These activated elements may further activate other associative concepts, such as important, which subsequently influence people's judgment of importance on an unrelated item" [6], a bit like a chain reaction. Subtle context cues can, thus, impact us immensely. We use metaphors as a central aspect of communication, and in many ways, these metaphors extend out our responses to physical sensations (i.e. heavy, etc). Our mental action is grounded in a physical substrate, and thus sensory and motor processing constitute necessary components of cognition [6]. Such concepts provide much of the foundation for the field of embodied cognition, or the idea that the mind is connected to the body and the body influences the mind [53]. Cognitive linguist George Lakoff and cognitive scientist Rafael Nez posited that "the mind arises from the nature of our brains, bodies, and bodily experiences" such that our cognition is based in our experiences with the physical world [53].

The field of embodied cognition gained true traction as Lakoff asserted that our semantics arose from the nature of the body [53]. We use metaphors to describe our states - Im feeling down in the dumps- based on the physiology of our emotions. We associate anger with heat because our skin literally heats up and our heart beat rises [53]. This can have powerful implications for decision making: marketing professor Lawrence Williams further refers to scaffolding by stating that "embodied cognition is an example of how scaffolding occurs in human development, such that priming people with fundamental sensory and perceptual experiences has downstream effects on higher-order judgements" [94]. Interactions with the physical world have a pervasive impact on our mentalities. Our responses to physical stimuli do not just end with cognition, however. Social psychologist Paula Niedenthal states that congruence between bodily expression of emotions and the emotional tone of the sender facilitates comprehension, whereas congruence does not [57]. In this manner, the physical world has deep emotional implications as well. While internally evaluating sensory stimuli such as materials, "through cognitive processes, like interpretation, memory retrieval, and associations, we are able to recognize metaphors, assign personality or other expressive characteristics, and assess the personal or symbolic significance of products" [21].

Our cognitive responses can be even more directly tied to physical stimuli, and thus to materials by looking at some existing research that addresses embodied cognition. Numerous researchers have examined the impact of sensations on social behavior and judgment. Williams and social psychologist John Bargh demonstrated that holding a warm cup of coffee incited subjects to view a target person as having a "warmer" personality, and holding a warm sample caused the to give to a friend rather than themselves [93]. Referring back to spreading activation theory, holding a cup of hot coffee makes relevant concepts (e.g., warm) salient, which further spread to activate metaphorically related concepts such as a warm personality [93]. Ijzerman and Semin corroborated this, and further added that holding a warm beverage caused them to feel closer to another individual [32]. Researchers from the University of Toronto had subjects play a game and purposefully excluded some: those who were excluded perceived the experimental room as being about five degrees colder than those who were not, and when given a choice between a hot or cold beverage, excluded individuals chose the warm one more often. One those who were excluded and had the cold beverage continued to feel bad afterwards. After being excluded, individuals physically became colder [47]. Williams and Bargh further tested temperature, demonstrating that individuals holding a hot pack were more willing to give money to a supposed "investor", whereas those with the cold pack experienced less trust and gave less money. The hot pack generated a sense of intimacy and trust [38].

Social psychologist Ackerman, Christopher Nocera, and Bargh found that, when presented with the same scenario script, individuals who were given a soft blanket found the participants to be softer negotiators, and individuals who were given a wood block saw the characters are more rigid. In a second experiment, participants were asked to sit in either a wooden or soft chair and imagine that they were at a car dealership. Those with softer chairs changed their initial offer more significantly than those in a hard chair [6]. Ackerman conducted a study in which he gave subjects either a smooth or rough puzzle and asked them to judge a social interaction. Those with the rough samples perceived the scene as more competitive and less friendly, while those with the smooth paper saw it as more cooperative [67].

Ackerman, Nocera, and Bargh demonstrated that resumes viewed on heavier clipboards were perceived as more important and those candidates were perceived to be more seriously interested [6]. When estimating the value of foreign currency, those who judged the money on a heavier clipboard thought it was worth more [36] indicating that weight embodies importance. Psychologist Michael Slepian showed that those keeping a secret behave in the same manner as those carrying physical weight [77]. In a fascinating exploration of secondary responses, Chen Wang and her team demonstrated that touching a rough surface enhances individuals' empathic responses and willingness to donate to charity [86]. Together, these studies all demonstrate the influence of embodiment on our actions and judgments. In many ways, these findings are intuitive- this same knowledge causes us to provide small children with safety blankets. Yet, these findings imply that material differences could have dramatic influences on mood, emotion, and behavior.

The concepts become even more interesting when our senses work together. The interaction of the senses allows us to manipulate our perception for instance, when paired with the sound of containing pepper, glass can be perceived as plastic [25]. Similarly, high frequency sounds can produce a feeling of dry skin [37].

Before attempting to bridge human perception and emotional meaning, it is important to understand the methods used to understand how we perceive the world.

Sensation involves the "first contact between an organism and its environment" [97]. Studying sensation involves the immediate, direct experience we have and our conscious awareness of qualities or attributes of our physical environment [97]. Sensations are produced by isolated physical stimuli and described with words like hard, rough, or cold. We interpret sensations through the transmission of energy from our environments to specialized receptor cells (eye cells capture light, tongue cells taste chemicals, etc.) which connect to our brains. Perception is slightly more complex, and involves our psychological response to these sensations. In this process, we draw upon meaning, relationships, context, judgment, past experience, and memory [97]. From a sensory perspective, we might ask how hard a surface seems, and from a perceptual one, we might ask if it is comfortable or if it is pleasant to touch. Thus, the study of perception is the study of how individuals form a conscious representation of the outside environment [97]. In practical settings, it can be very difficult to separate sensation and perception, so many experiments address them simultaneously.

Examining the sensory perception of materials, then, uses sensory properties, which are properties that are understood through sensory organs, but can evoke physiological and psychological responses, thus exhibiting subjective-objective dual attributes [98]. We can receive an objective distribution of energy across the range of visible wavelengths that we ultimately interpret as a color (or lack thereof), and subjectively interpret it based on our experiences. According to Hengfeng Zuo, presently, "in most cases industrial designers utilize sensory properties of materials by experience, without a systematic information resource" [98], a problem that this thesis aims to address.

Researchers employ a combination of direct and indirect methods to collect the information necessary to understand these properties. Direct methods include using actual material samples to interview users, observe their interactions, and analyze primary data. Indirect methods can either stem from secondary representations of the samples (such as visual images used by Ashby and Johnson in the creation of a taxonomy), where the data collected is how designers will perceive the materials, or theoretical modelling and deduction from related disciplines [97]. To create a bridge here, we need objective information about the materials, subjective data about individual affective feelings and associations, and a relationship between these two [98], which often involves a combination of quantitative and qualitative methods. There are straightforward methods of collecting the objective information, but subjective data can be difficult to quantify. Associative and emotional dimensions can be examined using quasi-quantitative methods such as Likert and semantic differential scales [98]. Often, videos are recorded to understand and observe the interactions that users have with materials. Since much of this data is so subjective, it is important to attempt to control external variables to the extent possible by setting up a reference sample (such as the standard dice in experiment

Table 2.1: Visual, Auditory, Tatile, and Affective Terms used in the experiment [25]

Visual	Auditory	Tactile, Thermal	Affective or Preferential
matte- gloss surface	damped-ringing sound	rough-smooth	fake-genuine
dark-bright surface	dull-sharp sound	cold-warm	cheap-expensive
dull-clear surface	mixed-pure sound	soft-hard	dirty-clean
		light-heavy	old-new
		dry-wet	unpleasant-pleasant
		sparse-dense	tense-relaxed
			fragile-sturdy
			common-rare
			plain-sophisticated
			boring-interesting

one, or the "normal" phone case in experiment two), and keeping environmental conditions constant.

Fujisaki and a team of researchers explored wood across the senses, comparing fake and real samples and generating bipolar adjective splits across perceptual and affective stimulus types [25]. Using Likert scales, interviews, factor analysis, multiple regression analysis, and interparticipant correlation, they were able to investigate the structure of the relations between these terms.

An interesting parallel to this thinking can be found in the field of robotics, and many of their techniques prove relevant for this work, especially with regards to quantifying subjective data. Roboticists have an extensive interest in understanding the nature of human perception. As robots become prevalent in more and more aspects of life, spanning from household chores to medical assistance and therapy to bomb deactivation, they increasingly need to be capable of interacting on a human level. As examined by Katherine Kuchenbecker's Haptics group at Penn, much of this work is founded in natural language communication and learning to achieve "generalizable physical knowledge" [15]. "Robots will need to be able to learn new words and concepts through their physical experience with the world, as human children do, by seeing, hearing, and manipulating real objects and environments. To deepen our understanding of perceptually grounded language acquisition and improve robotic interaction with the physical world, [we aim] to create a robot that can learn the meaning of haptic (touch-based) adjectives by physically interacting with labeled objects through sensitive fingertips" [15].

However, successful completion of such a task is dependent upon rigorous understanding of human perception. For many such experiments, the first step is to establish "ground-truth" ratings of samples using human subjects [15]. I drew from many of these techniques in my experiments. Presently, some of the most compelling work towards understanding and reproducing human sensing has fallen under the umbrella of vision, hearing, and feeling. Many relevant techniques have been used by roboticists in understanding and recreating human tactile perception. "Texture gives real objects an important perceptual dimension that is largely missing from virtual haptic interactions due to limitations of standard modeling and rendering approaches...Unfortunately, the richness of these interaction cues is missing from many virtual environments, leading to a less satisfying and immersive experience" [18].

As a foundation towards building such richness, Shogo Okamoto and his team completed an extensive review of the vast array of experiments and studies on the tactile dimensionality of physical properties of materials. Tactile perception was defined as "perception of the qualities and properties of material surfaces by touch" [60]. "The dimensional structure of the perceptual space has attracted the interests of researchers in haptics, and many studies have been conducted attempting to specify this structure" [60]. However, each individual experiment suffered from significant drawbacks due to limitation in the psychological experiment, the mathematical approach, the stimuli used to test hypotheses, an unbalanced set of materials, etc [60]. In their work, the team determined a common structure for dimensions by investigating a large number of related works and thus compensating for individual weaknesses. Tactile perception was described as hierarchical, starting with a psychophysical level, followed by an affective level. So far, most of the extensive and complete work has focused primarily on the psychophysical level of perception which determines physical properties, rather than the deeper layer that is mediated by thought and reflection. In chapter 5, when explaining the methodology for Experiment 1, I will further outline techniques that were used to establish discovered tactile dimensions. This research becomes even more intriguing when paired with research that examines the impact of haptics on social evaluative processes, much like Wang's work on roughness and empathy.

To further explain the nature of research on human perception of stimuli, a breadth of research on the tactile sense was collected to understand how research in this field is conducted (especially since the tactile sense is less well understood than vision and hearing). Important parameters are identified and broken down, probes and instrumentation are built to mimic human interactions, dimensions are established, and interaction modes for touching an object are teased apart. Bergmann Tiest demonstrated that roughness, coldness, compliance, and slipperiness are the most notable aspects of tactile perception by using multidimensional scaling to evaluate perceived dissimilarity [80]. In this technique, materials are positioned in a dimensional space, where their position is correlated with either subjective [29] or objective measures [81]. Initial examinations involved technical evaluation using precise instruments in tandem with qualitative inquiry from human subjects [80].

The team examined the difference between surface and bulk properties and active or passive touch, and established that "perceived roughness of one stimulus will depend strongly on other types of stimuli available" [80]. In a second experiment, the same team had subjects complete a free sorting task of 124 materials and used multidimensional scaling (MDS) to analyze the results [81]. Again, the haptic space was calibrated using technical measurements, and an exponential relation between objective and perceived properties was found. With these tests, the number of samples is crucial: "to fill a four-dimensional space, at least 16 stimuli are needed to have one in each corner of the space" [81]. Thus, much of the research in this arena involves a small number of samples of a very specific type, and results may be correlated with quantities that may not be well defined [81]. Bergmann Tiest then compared sensory modalities by having subjects perform rank ordering tasks, ultimately discovering that vision and tactility yield similar results, though neither is necessarily more accurate [82]. Wongsriruska built on the work of Tiest to connect physical and psychophysical properties and prove that simple psychophysical tests could provide an accurate correlation between measured properties and the tactile perception of a set of materials [95]. In that study, there was a strong positive correlation between measured physical properties and perceived properties across the three tested properties of roughness, coldness, and hardness.

Researchers such as George Torrens and D.E. Gyi have modeled hand-object interaction by incorporating the various interaction modes. Having such a set of standards helps designers, manufacturers, and ergonomists make decisions. In the process, they compared the gross interaction of the skeletal structure with the intermediate interaction of soft tissue of the glaborous hand with large surface features, and with micro-interacts between the skin and fine surface material of an object [84]. Liu (et al) characterized the surface friction generated by fingertip strokes to further understand how we sense and perceive. They examined four modes of perception: smooth-rough, slippery-grippy, warm-cold, and soft-hard. Kansei testing was used, where samples with different surface properties were described subjectively, and the words were post-facto related to actual physical properties [46]. The team developed a tribological probe microscope to examine the interface and imitate finger strokes. The team calculated the correlation between affective perception and measured values, and finally showed that when a surface is less rough than a fingertip, it will generate desirable feelings, but when it is rougher than a fingertip it will generate undesirable feelings [46].

These methods can be, and often are, repeated across senses, and can allow us to simulate and render robotics and human-computer interaction systems that mimic reality, as well as allowing makers to justify their decision-making using rigorous methods.

2.3 Classifying Materials: Taxonomies and Beyond

Taxonomies are frequently used as a way of categorizing, quantifying, and understanding key elements of the world around us. Much of the groundwork in terms of approach and thought processes was established by Philippa Mothersill in her Master's Thesis: The Form of Emotive Design. In this work, Mothersill built on the idea that "novice designers can express the 'character' of the objects they want to design using familiar vocabulary, but may not be able to draw on expert design skills to transform this meaning into the medium of form" [56]. Her thesis explored the physical design language encoded into objects and the underlying emotive design 'grammar' of the form of objects in the context of bottles. Based on existing research on the connection between shapes and emotive meaning, she identified and quantified key design elements. By mapping these elements onto existing emotional models (a combination of the Russell Circumplex and Plutchik's dyads), she developed a quantitative framework for emotive form design. Mothersill then went a step further, generating a CAD tool to help novice users more easily create inspirational and emotive forms through descriptive adjectives as an input. Using existing literature and validating her methods, hypotheses, and resulting forms with extensive user testing, Mothersill created a robust taxonomy for form and emotion in the context of bottles. In many ways, this work inspired the thinking that sparked this thesis-the idea of adding a material layer to a tool such as the Emotive Modeler could prove very exciting. Similarly, many researchers have also explored the rich field of human perception of material stimuli.

The taxonomies examined in the literature review of the field were developed using a variety of methods. Many followed a basic combination of selecting vocabulary from the literature on relevant media (such as magazines), testing the vocabulary on relevant parties (such as design students) to determine how words are related and eliminate redundancy, conducting in-depth interviews with relevant individuals, and using statistics to analyze the relevance of terms. Johnson and Ashby conducted a survey of design reviews, museum exhibitions and commentaries on products in their goal of uncovering a common language [9]. Other researchers, such as Wongsriruska, employ empirical testing to establish taxonomies [95].

In discussing materials, there are various levels of categorization that occur (see autorefTax). In my analysis of existing work, I placed these efforts on a scale of subject, ranging from primarily product side to primarily material side. Along this continuum, some researchers (such as Desmet), examined only the finished product, of which materials are a crucial, but subtle part, and others focused entirely on the materials. For this discussion, I am focusing only on those taxonomies that do relate in part to materials and design, as opposed to some of the more technical options mentioned at the beginning of this chapter. As such, this section only

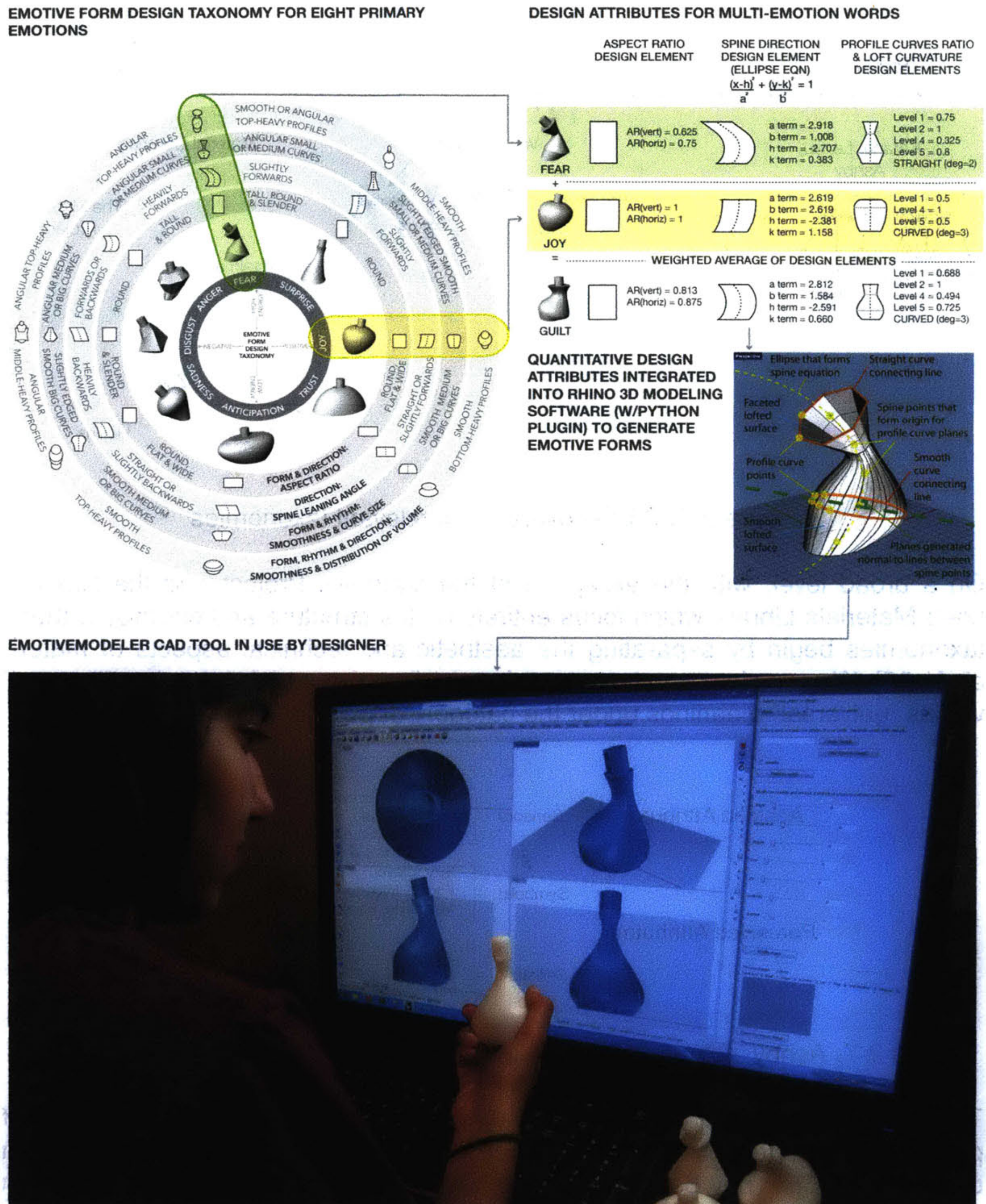


Figure 2-5: Pip Mothersill's Emotive Modeler tool and shape taxonomy [56]

addresses a small subset of existing taxonomies in this space.

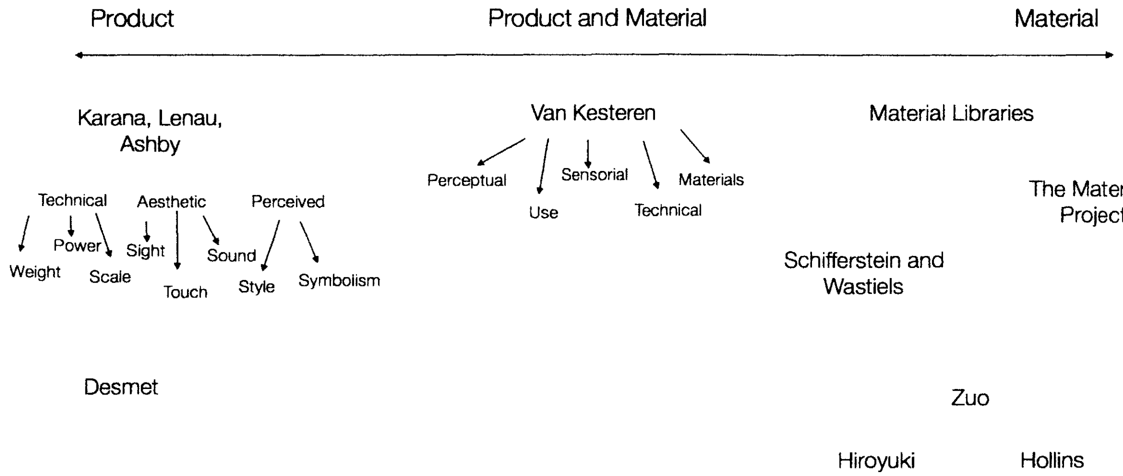


Figure 2-6: A brief overview of relevant taxonomies

On a broad level, with the exception of the Materials Project and the Harvard Loeb Materials Library which focus entirely on the structure and chemistry, these taxonomies begin by separating the aesthetic and technical aspects of materials [1,35]. We can also examine our understanding of materials based on "learned" versus "universal" meanings under the category of perceptual qualities [41].

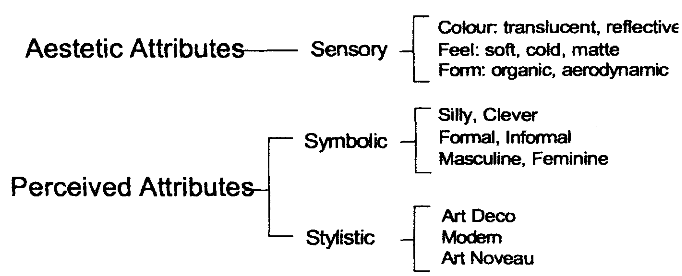


Figure 2-7: Ashby, Johnson, Lenau's initial categorization of material terms [35]

Towards the product side, Ashby, Karana, and Lenau propose a vocabulary of perception, an attempt to quantify visual, tactile, and acoustic attributes through description [35]. They begin by describing and categorizing materials based on their technical, aesthetic, and perceive attributes. These technical attributes can be measured in a standard method, while the aesthetic aspects are those that we actually respond to, and the perceived attributes pertain to the stylistic and symbolic associations we have. In the middle of the continuum, van Kesteren goes into

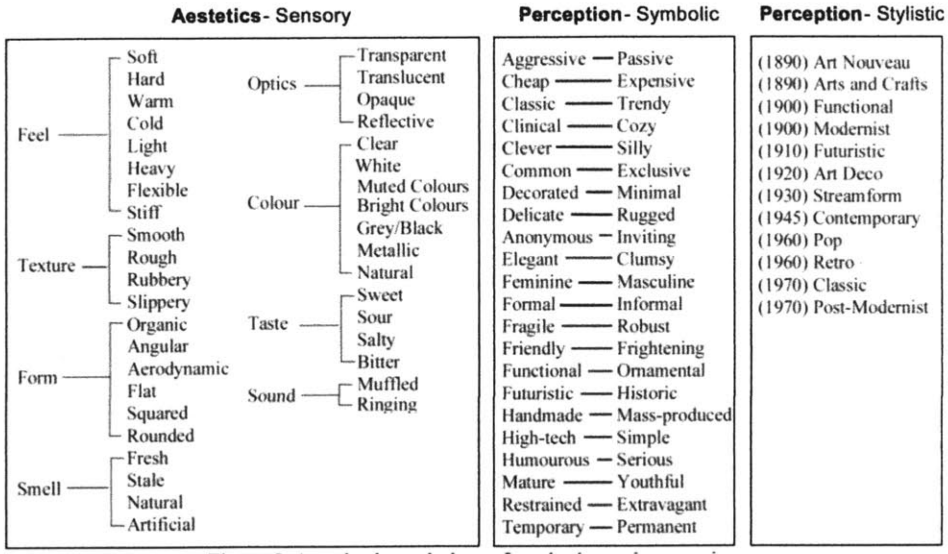


Figure 2-8: Ashby, Johnson, Lenau's revised vocabulary of aesthetics and perception [35]

further detail, describing the categories of properties that can be used to evaluate materials [85]. Descriptors for samples can be split into perceptual (pertaining to perceptions, emotions, and associations), use (pertaining to usage), sensorial (pertaining to aspects we can sense), technical (pertaining to material and manufacturing properties), and material names [85]. She lists the sensorial properties divisions of reflection, color, pressure, manipulation, friction, sound, smell, taste, temperature and light radiation.

In contrast, on the materials end of the spectrum, the users to explore materials in terms of chemistry, composition, or technical properties, [33] harnessing simulations to design new compounds using the structure editor. Material Connexion provides a digital complement to the on-site service, searchable by processing, usage properties, physical properties, and level of sustainability.

For physical samples, materials libraries can be arranged based on class of material, structure, color, feel, or typical use. Library categorization systems can be split into property-based or composition-based. The Harvard Loeb Materials library organized choices based on composition (with sub-details about form, properties, and processes), while the Rhode Island School of Design Library is inspiration-based, and materials are grouped by categories such as color, translucence, natural, etc.

Other researchers have categorized specific aspects of the material experience, as the narrower the scope, the more specific the descriptors. Hiroyuki, for in-

Reflection	***Pressure***	***Sound***
reflective – not reflective	denting – not denting	muffled – ringing
glossy – matte	soft – hard	low – high pitch
transparent – translucent – opaque	fast – slow dampening	soft – loud
not bright – bright	massive – porous	
rough – smooth		***Smell and taste***
regular – irregular texture	***Manipulation***	natural odour – no odour – fragrant
	stiff – flexible	fragrance
Colour	ductile – tough	flavour
hue of colour	brittle – tough	
one colour – many colours	light – heavy	***Temperature***
colourless –colourful		warm – cold
dark – light	***Friction***	
durable – faded colour	sticky – not sticky	***Light radiation***
pattern	dry – wet – oily	low – high light emission
	rough – smooth	

Figure 2-9: Van Kesteren's Categorization of Sensorial Properties [85]

stance, breaks tactile properties into thermal character (warm-cold), moist character (wet-dry), surface contour (rough-smooth), and denseness (densely-loosely packed) [8]. Hollins used 17 samples to develop a three-dimensional texture space of rough, hard, and springy [29]. Hiroyuki also developed 25 dimensions for visual tactile analysis of a leather texture [8]. Zuo created a matrix of material representation for studying human perception and response with the intention of producing a dimension-lexicon system to allow people to "subjectively describe the material texture in a common way" [97]. The work produced a four-dimensional framework for tactile perception on a macroscale level: geometrical dimension (pertaining to our response to the configuration of a surface), physical-chemical (subjective response to physical or chemical attributes based on the interaction between our skin and the surface), emotional dimension (affective and hedonic feelings evoked by touching a material), and associative (relating to subjects imagination related to the material). These dimensions often work hand-in-hand, where lively or cheerful associations tend to correspond to a perceived shiny surface on the physical/chemical dimension. Okamoto performed an extensive literature review of studies in the field of haptics, revealing five primary dimensions:macro and fine roughness, warmness, hardness, and friction (wetness and stickiness) [60]. Similar in-depth studies have been conducted for the other senses.

In our consideration of the interplay between technical attributes and sensorial perception, it is informative to consider the scales and means through which we can interact with and perceive stimuli. At the present, we interact with stimuli through visions, audition, olfaction, touch, and taste. Visual information often dominates: it is both what we are presented with first (with the exception of intense sounds or

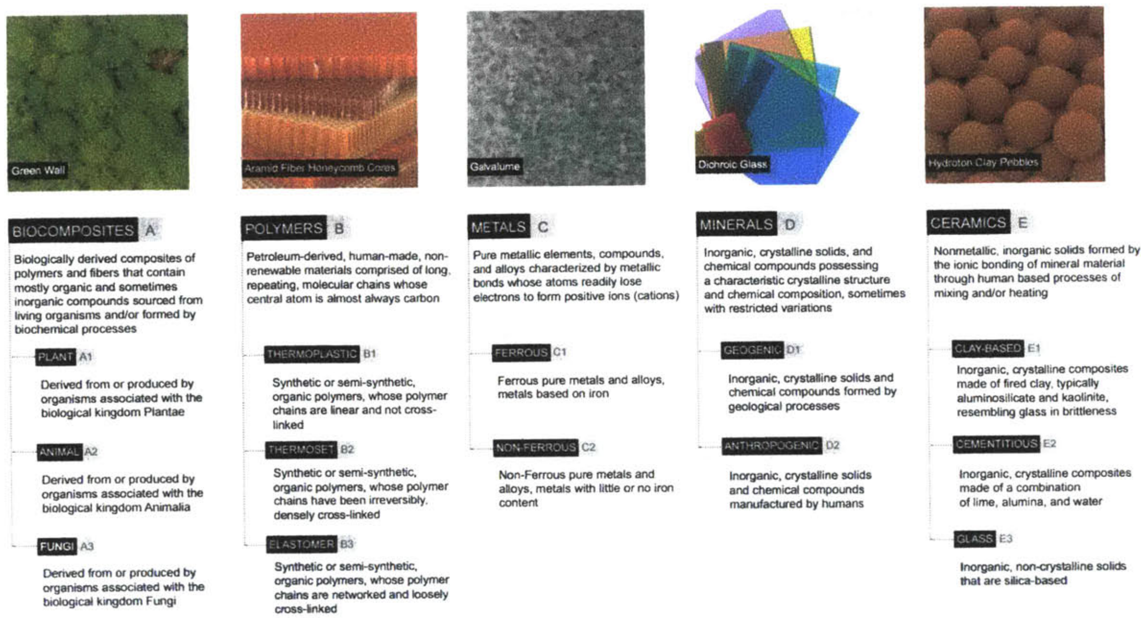


Figure 2-10: Categorization scheme explained in the Harvard Material Collection Primer [1]

smells that greet us when we enter an environment), and it is the only sense that we can use when selecting a product. Vision dominates in customer selection of products [72] as people cannot typically actively engage with a product before purchase. However, as customers use their products over time, they interact with more sensory modalities and vision is often surpassed. In this manner, time also plays a role in our sensory interactions. Schifferstein and Wastiels explain the phenomena that trigger our sensory perception: the electromagnetic radiation that causes vision, the vibration of air molecules that cause audition, the changes in mechanical pressure and temperature that we feel through touch, the volatile substances that move through the air to allow us to smell, and the water-soluble substances that trigger taste. Thus, visual stimuli work on the macro scale, tactile information works on both the micro and macro scale, and smell and taste work on the molecular scale. However, experiences that engage multiple sensory modalities are more powerful: in these cross-modal correspondences, we are able to perceive interactions between stimulation in many sensing modes. After perceiving some properties, people are often able to infer similar, related properties about the same sample [72]. These associations cause us to assume that most large objects are heavier than smaller ones. Warmth, for instance, is a multisensory experience that draws from physical, figurative, and metaphorical concepts. Our perception of materials can be altered by combining modalities, as with the pepper in glass example from the last section. Enhancing the congruence of sensory messages thus

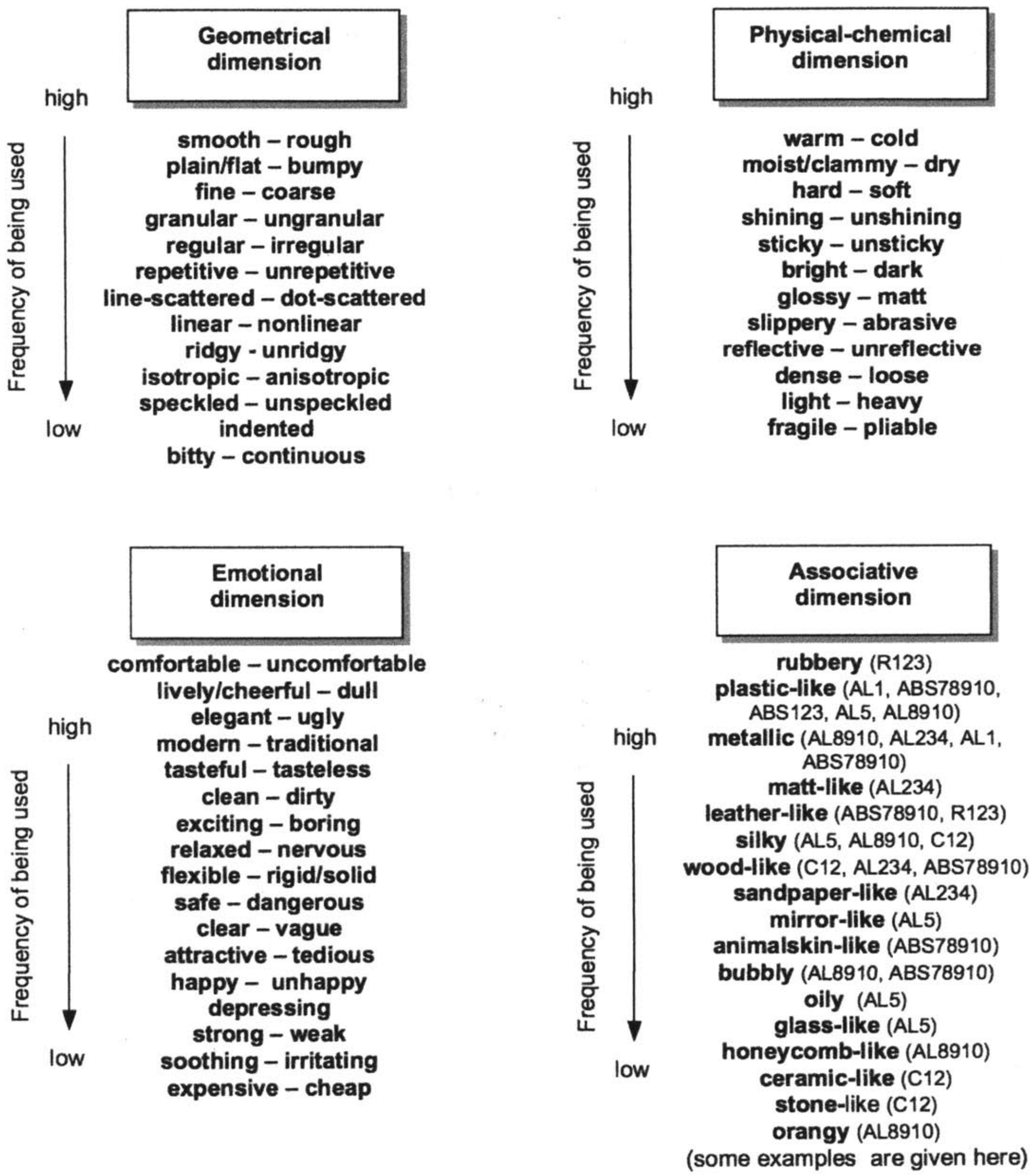


Figure 2-11: The Terminology Collected by Zuo [98]

helps clarify intent and create powerful experiences. Adding emotional congruence could amplify these even more.

2.4 Theories and Thoughts on Emotion

One of the motivations for framing this work in the context of emotions is the intuition we build for the inherent significance of emotions as a means of communication. They are universal in that they are a fundamental part of the average human experience. Much of our interpretation of the world is painted by emotions: they allow us to communicate, establish trust, learn effectively, make decisions, and encode experiences to memory. Designing materials with a consistent emotive and functional meaning could result in objects that resonate powerfully for us. Often, the beginning of the design process is centered around a word or series of words that strive to express a particular character or feel. Many of these words have an inherent emotional tone or association, so by using these as a basis for design, we are associating the emotion to the process as well.

Scholars have engaged in a long-standing debate over what constitutes an emotion and how they ought to be categorized. On a primary level, some theorists argue that emotions have clear bases in biology, while others argue that they are primarily cognitive responses. Darwin situated emotions by noting their adaptive value [20]. James and Lange further built upon this by stating that people experience emotions based on their physiological responses to events and external stimuli [44]. An event triggers a bodily response, which then causes an emotion (such as fear). Cannon and Bard countered this view, arguing that we experience emotions at the same time as we experience physiological responses, and the emotion is not dependent upon the experiences of the body [14]. Lazarus discussed the issue and order of appraisal, where our first response to cognitively evaluate the stimulus (primary appraisal), and that we experience emotions as a result of this appraisal [78]. Averill put forward the idea that emotions cannot be explained strictly on the basis of physiological or cognitive terms [13], and that they are primarily social constructs. Schachter and Singer postulated a two-factor theory, in that emotions require the experience of both a physiological response and the interpretation of that experience [71]. Howard Weiss and Russell Cropanzo presented the Affective Events Theory, arguing that emotions are influenced and caused by events that help us shape attitudes and behaviors [89].

In the space of defining emotions, researchers disagree on whether emotions can be seen as discrete or continuous. Proponents of discrete emotions propose that different emotions stem from distinct neural systems, and that humans have a universal set of emotions that are demonstrated and understood across cultures. Often described analogously to the colors on the color wheel, these emotions can be combined and superposed to create the broad range of emotions we experience. To identify these emotions, techniques such as facial analysis, biological and neurological assessment, and psychological methods are used, resulting in a range of two to eighteen basic emotions [61]. Paul Ekman posits six: anger, disgust, fear, happiness, sadness, and surprise [24]. Silvan Tomkins built Affect Theory, describing nine affect states : desire, happiness, interest, surprise, wonder, and sorrow [83]. Matsumoto presented 22 separate building blocks: joy, anticipation, anger, disgust, sadness, surprise, fear, acceptance, shy, pride, appreciate, calmness, admire, contempt, love, happiness, exciting, regret, ease, discomfort, respect, and like [52]. Robert Plutchik presented acceptance, joy, surprise, anger, fear, disgust, sadness, and anticipation, arguing that they stem from our biological instincts (such as the desire to reproduce). Plutchik's work is presented analogously to the color wheel, and the mixtures are described as dyads. There are 24 proposed dyads, and the basic emotions can be mixed in various proportions. Based on this theory, emotions are often presented in concentric circles, where towards the core lie the more basic components, and along the outer circles lie the more complex emotions that are blends of the inner emotions [65].

The Hourglass Model of Emotion, developed by Erik Cambria, Andrew Livingstone, and Amir Hussain, is based on the ideas brought about by Plutchik. It organizes the basic emotions around four independent dimensions (Pleasantness, Attention, Sensitivity, and Aptitude). Each dimension has six levels of activation, yielding 24 basic emotions. This bioligically-inspired model only examines emotions that correspond to objective natural language opinions, so moral emotions such as guilt, shame, and pride are not incorporated [13].

Comparatively, the dimensional approach to emotions places them on continuous scales, where neurophysiological processes are thought to work together to produce affective states. Emotions are defined based on their position along various dimensions. Most theories include some variation of valence (related to positivity or negativity) and arousal (which addresses the intensity of the emotion). Dimensions allow for a broader interpretation of emotions, where boundaries between them are far less clear, but such an approach obfuscates the process of attempting to quantify stimuli in relation to emotions. However, many researchers employ the dimensional approach as a basis for mapping experimental stimuli in the emotional space. Max Wundt presented three dimensions in 1897: pleasurable-unpleasurable, arousing-subduing, and strain-relaxation [96]. Harold Scholsberg presented pleasant-unpleasant, attention- rejection, and activation level as three axes. In one of the most commonly cited models, James Russell created a circumplex of a two-dimensional space of valence and arousal, which provides a basis

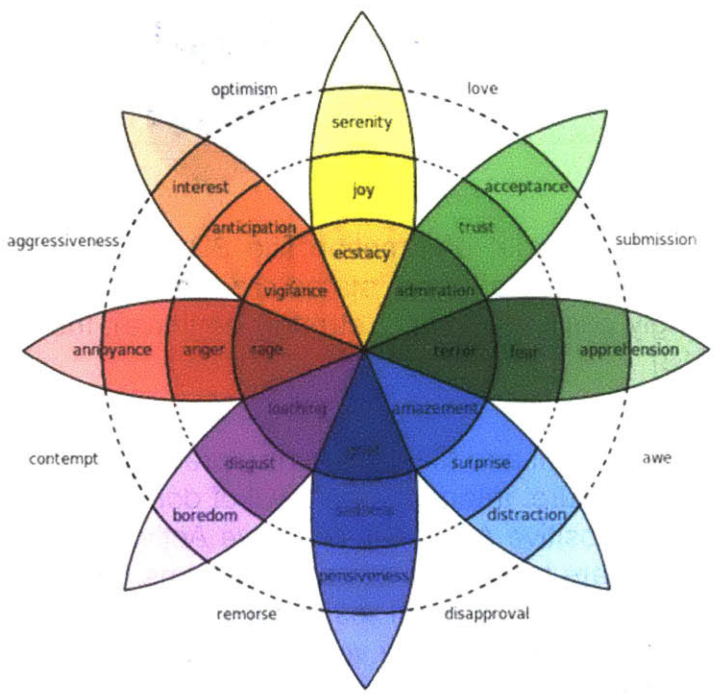


Figure 2-12: Plutchik's Wheel of Emotion [65]

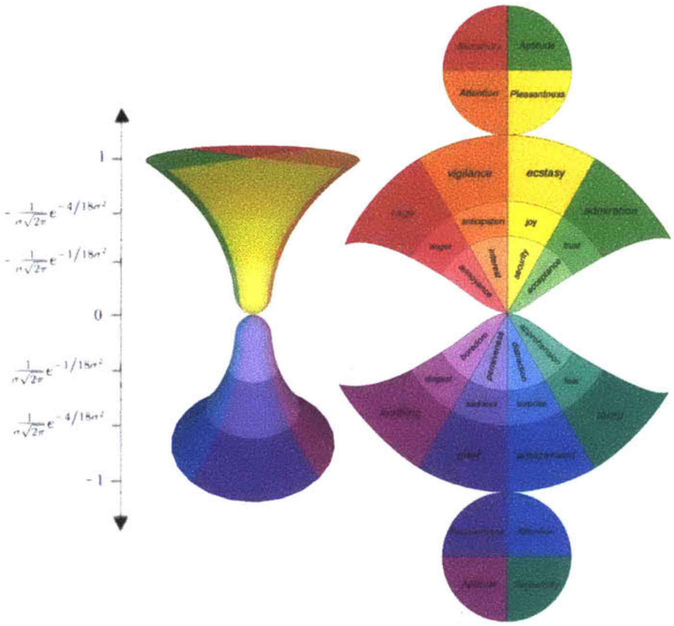


Figure 2-13: Hourglass Model of Emotion:The 3D model and the net of the Hourglass of Emotions: since affective states are represented according to their strength (from strongly positive to null to strongly negative), the model assumes a hourglass shape [13]

for mapping emotion. Russell and Merhabian also presented a Pleasure- Arousal-Dominance scale of pleasure, intensity, and level of dominance [13]. Watson and Telegan presented the Positive Activation-Negative Activation model, where positive and negative affect are treated as separate systems. On the vertical axis lies positive affect, and on the the horizontal lies negative. Valence and arousal present orthogonal dimensions. Finally, a similar vector model of emotion proposes that all emotions have an underlying arousal dimension, and valence determines the direction of the emotion [88].

An interesting addition was made by Lovheim, who proposed a cube formed by axes representing the neurotransmitters dopamine, noradrenaline, and serotonin. At each corner lies on of the eight basic emotions of Tomkins affect theory. The axes do not correlate exactly with a scale of pleasantness, but the model can be used to postulate about biological bases for morality, sociology, and emotion.

As one final layer, Pieter Desmet also examines the ideas of "product emotions," a concept that is slightly different from human emotions. The structure follows a workflow of concern, appraisal, and resulting emotion, where an appraisal of novelty leads to surprise emotions, motive compliance leads to instrumental emotions (such as satisfaction or disappointment), intrinsic pleasantness leads to aesthetic

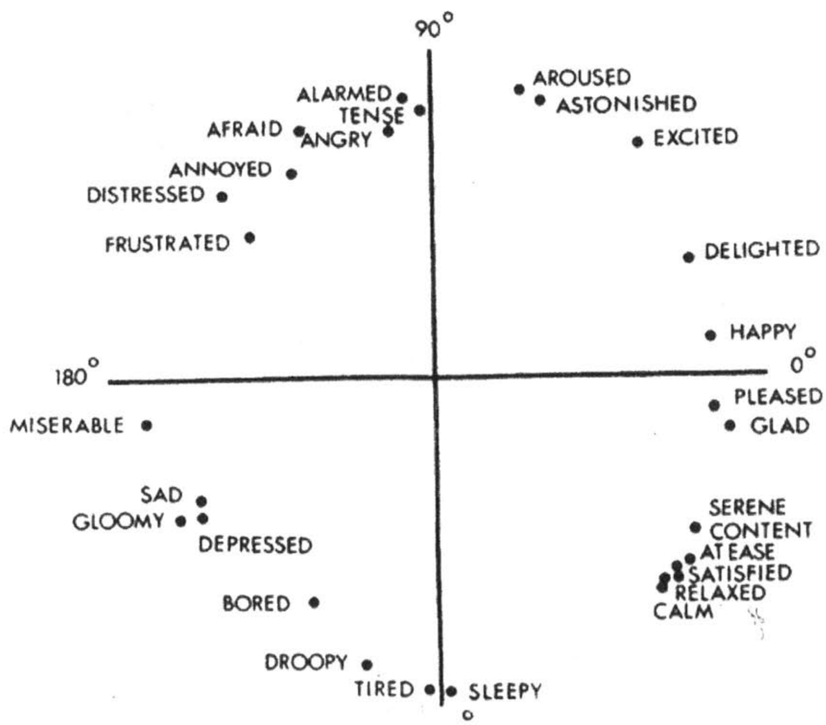


Figure 2-14: Russel Circumplex [66]

emotions (disgust, attraction, etc), legitimacy leads to social emotions (indignation, admiration), and challenge leads to interest emotions (boredom, fascination) [21].

Returning to the idea of words and semantics that designers rely on, Lisa Barett Feldman presented a paradox that arises due to the notion of discrete emotions without any existing scientific guidelines to evaluate when these emotions exist. She argues that our responses are devised as a result of biological and psychological ingredients, such as core affect, conceptual knowledge, and semantic meaning). Eugene Bann presented the idea that people transmit knowledge about emotions through the language around keywords of emotion, so the more specific a language is with regards to emotion, the more distinct the perception of said emotions is.

For my purposes, I used scales such as the Positive and Negative Affect Schedule (which presents participants with distinct emotions that are deemed as positive or negative), Perceived Stress Scale (in which participants are asked to assess their appraisal of situations) [16], and emotional descriptors presented in design research such as the work of Ashby and Johnson. Building off of existing psychometric scales, I frequently evaluated stimuli on dimensions of valence and pleasantness.

3

Motivation and Goals

Why does this matter?

3.1 The State of Materials Design

As introduced in chapter one, materials subtly, but crucially influence human perception and emotion. Gant emphasized that the strategic use of materials is one of the most influential ways through which product designers engender deeper, more emotive connections between their products and their users. The materials that a product is made of influence how users interact with the product [85].

The ability to engineer materials and the formal study of this process has resulted in even more exciting possibilities. It is now possible to fabricate materials made of nanostructures and/or composites that are specifically designed to possess desired properties and interact with specific forms and ranges of energy, as shown in Figure 3-1. But as we are exposed to these new materials, how can we interpret their meaning and determine how they fit into and mold our existing lives?

In chapter two we explored some of the background research that approaches this question and positions it as an important one. So how can we understand how people perceive meaning in materials and how can we collect this data? For digital media, there are numerous ways to reach broad audiences and collect large swathes of information (i.e. the playful interface of Viral Communications GifGif that allows users to vote on the emotive tone of gifs) [68]. Such interfaces could be employed to gain insights on the visual components of samples, but would not support the experiential exploration of the more tactile, visceral, olfactory, and

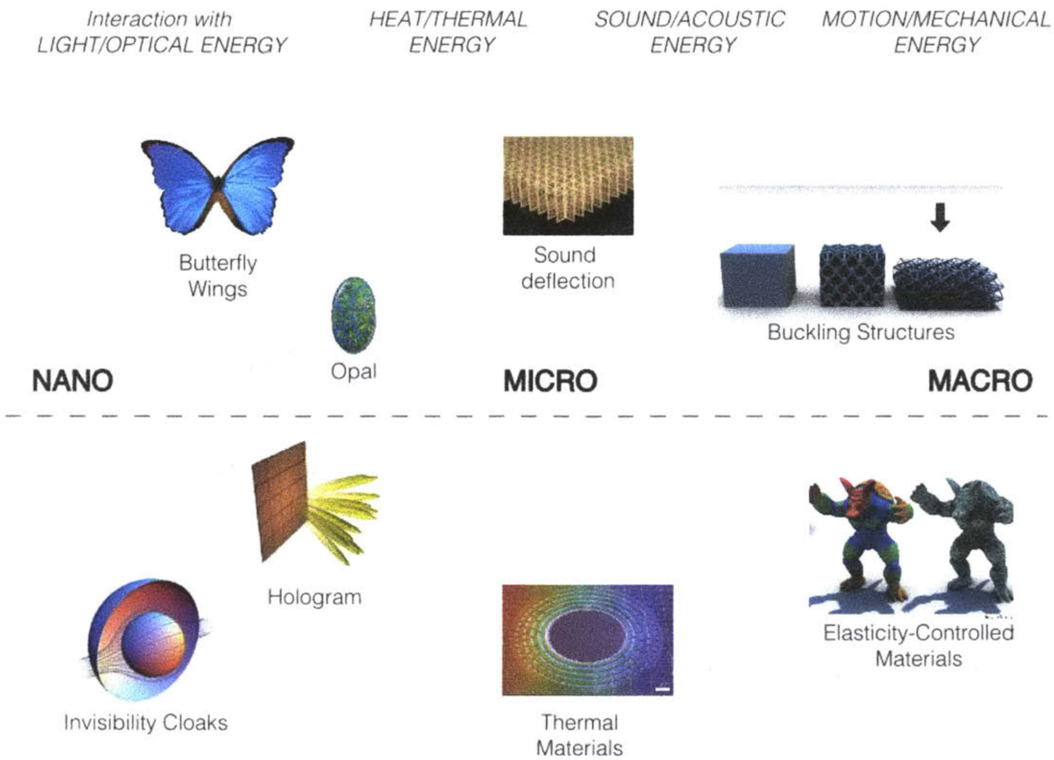


Figure 3-1: Metamaterials interact with different types of energy at different scales. With this class of material systems, properties are derived from structure as the size scale is smaller than the wavelength of external stimuli, allowing for tailored functionality [4, 11, 31, 63, 73, 76]

intangible aspects of the sample. For physical stimuli, there are presently no comparable methods. Traditional design research to understand and categorize the different qualitative properties of materials has relied on extensive and time consuming in-person user studies, where participants can handle and evaluate the physical design samples [42]. While this method provides rich insights into the participants qualitative perceptions of the materials being studied, collecting enough data to make a generalizable conclusion on such a subjective subject would take hundreds, if not thousands, of hours.

Perhaps Elvin Karana explains this conundrum best:

> Developments in materials science and manufacturing technologies have enhanced the variety of applications for materials. People encounter versions of a particular product made of different materials or the same

> material embodied in different products. This has led to an unavoidable transformation of meanings attributed to a certain material. A single material, polypropylene for instance, may be evaluated differently when it is embodied in kitchenware rather than an office accessory. Manzini (1986, p. 3), in his book The Material of Invention, also emphasizes that new technologies have radically altered the meanings that once endowed materials with cultural and physical depth. Accordingly, traditional sayings such as wood is cozy, metal is aloof or plastic is cheap are less relevant and strict in todays design practice. Materials obtain different meanings in different products. Therefore, designers who aim to select a material that will contribute to the meaning they intend to convey in a product are confronted with the difficulty that the materials universe is immense. [40]

The design process is no longer limited to one group of individuals, as number, level, and cost of tools make them ever more accessible. As we move towards tools that allow us to design and create our own materials, having a set of rules with which to evaluate, interpret, and design them will become increasingly important. One way of approaching this problem is by unpacking the ways in which materials create meaning. In this research I aim to understand the more emotive aspects of materials, such as haptic responses to, cognitive evaluation of, and emotive perception of materials to understand how materials communicate meaning. In doing so, I am combining methods from material science, psychology, cognitive science, anthropology, design, and storytelling.

One of the difficulties with this process is the existing rift between the science and design communities: while engineers understand and value functional and technical properties of matter, they often ignore the human element, and designers often do not understand the fundamental technical properties (such as crystal structure) that produce the desired effects. There are many stakeholders involved in the development and use of materials, but often those involved lie on opposite ends of a spectrum between technical and intuitive. As Ezio Manzini stated in *The Material of Invention*, one of the greatest issues surrounding material usage is that of making information coherent that is traditionally confined to fields of research and applications that tend not to communicate with other fields. As it stands, there is a disconnect between the technical community of scientists who develop new compounds and the designers and artists who implement them, and most struggle to see direct overlaps in their fields. Presently, material scientists use precise, technical language based around attributes that can be measured in standard, and specific, ways. The material selection process is governed by equations and databases built on quantitative measurements. Technology is advanced without any significant thought towards immediate human impact. As a result, when a linear model of development in the laboratory spreading slowly to the market is used, new materials can be perceived as intimidating or scary [87], and the adoption of new materials is characterized by a long gestation period, typically of 20 years and above [99]. "Miodownik asserts that there are very few university materials science or engineering departments that 'aim to design materials with a combination of cultural and physical properties'. He puts this down to what he calls the 'facts not opinions' effect of materials scientists being unable to justify researching the cultural properties of materials because of difficulty quantifying them" [90].

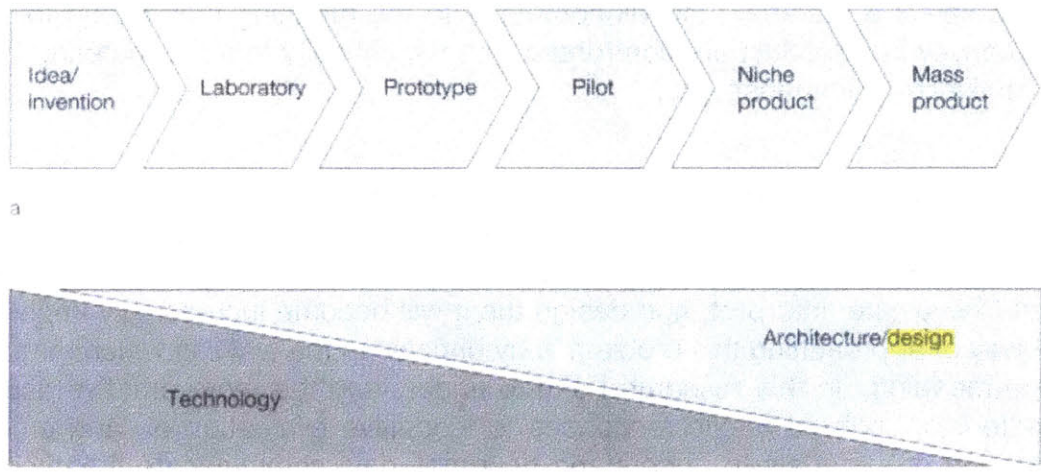


Figure 3-2: The materials process [28]

Those involved in design gain knowledge through practical engagement and experience. By using resources such as material libraries, they are able to explore the intangible aspects of materials, but with novel materials, it can be difficult to develop intuitive knowledge. Mike Ashby and Kara Johnson [9] maintain that industrial designers do not have sufficient access to information of the sort they need to understand the 'personality' of a material; there is little by way of support to help designers determine which materials will "arouse interest, stimulate andhave a personality that resonates with the tastes and aspirations" of a user, aside from 'intuition' and trial-and-error [62]. Creators can find themselves overwhelmed by the number and variety of new materials due to lack of in-depth materials education. In a recent conversation with a pair of designers at IDEO, I was told that one member of the team had recently been handed a binder of carpet samples that was intimidatingly large. When faced with parsing through the samples, the designer simply could not figure out how to distinguish the samples in a reasonable, efficient manner. In many ways, designers serve as gatekeepers of interpretation. By selecting the situations and settings in which compounds are applied, they implicitly form associations, contexts, and meanings for customers and societies. Overtime, these applications become internalized to the character of the material itself. The designers decisions on where and how to include novel materials are central to the general interpretation of these materials, especially in early stages. If designers are unable to effectively familiarize users with a compound, the material will remain mysterious, unfamiliar, and potentially even off-putting. While engineers focus on practical improvements and applications, even the most efficiently performing material may take a long time to reach human consciousness. Many materials go through a slow diffusion process: for instance, carbon fiber, which is now used in products as common as suitcases, was initially used in aerospace and race car applications. It was slowly adopted for high-tech sports gear such as tennis rackets before finally making its way to phone cases and luggage. Indeed, it is often the unexpected uses of materials that prove to be the most interesting. The question that motivates my work is how can we connect the quantitative and qualitative aspects of design in order to bridge this gap. How can we ultimately maximize meaning in design and creation with and of materials, particularly emerging ones?

Designers and engineers could benefit from a better understanding of the language of materials. Scientists consider the structural, chemical and electrical properties of materials to be crucial, and consider sensual and aesthetic properties as secondary, whereas designers focus almost entirely on forming a connection between a product and the users [85]. The use of materials is one of the most impactful ways in which this connection is achieved. While designers have immense knowledge about the aesthetic, intuitive, and performative aspects of compounds [92], they may often feel that they lack the technical vocabulary to engage in the process of creating novel materials. The "engagement of designers with materials relies on knowledge that is innate and tacit, which fail to inform the design of technology" [64]. The existence of material libraries has been proposed as bridge for the communication gap between disciplines [92], but most scientists have never even heard of these establishments [1]. Furthermore, one material librarian we interviewed explicitly mentioned that when attending a Materials Education conference to learn more and explain his work, he found it very difficult to communicate with the other attendees.

Material properties, are in essence, information, and as such they can be used to influence and later judgment. As mentioned above, up until now, researchers have worked to break down physical inputs into technical details, or emotional experiences into perceptual descriptions, but there is rarely a shared language that crosses through all of these domains. It is my aim in this work to examine the viability of such an effort.

[1] Personal Communication, November 4, 2015

3.2 Existing Solutions

In an attempt to understand how we interact with materials, many teams have begun to classify portions of our interactions with materials. Ashby and Johnson spearheaded one of the most influential undertakings in this field, in their work, *Materials and Design*, which unpacked the role of materials and encouraged readers to think deeply about their connection in the material world [9]. In many ways, the book marked the beginning of the incorporation of emotion and other "softer" properties as a serious consideration in product design, and as a subject for academic inquiry. Numerous researchers have tackled portions of a taxonomy to connect some aspects of this process. Ashby and Johnson were two of the first to include aesthetic and perceptual qualities in their list of material properties to consider, Ilse van Kesteren framed user-interaction questions around a lexicon of sensorial properties broken into categories such as "reflection, pressure, sound, etc.," and Zuo proposed a four-dimensional framework for tactile perception (geometrical, physical-chemical, emotional, and associative). Furthermore, many researchers have delved into how to assess meaning on a broader level: Pieter Desmet classified product emotions (surprise, instrumental, aesthetic, social, or interest), Desmet and Hekkert classified experiences (aesthetic, meaning, or emotion-based), and Donald Norman examined types of reactions to objects (visceral, behavioral, and reflective) [22,58]. While many of the taxonomies developed since then are quite extensive, none of them span the full range of experience that I tried to explore. Most of these efforts were based off of extensive user testing, the output of which was a theoretical taxonomy or lexicon, but not any concrete guidelines.

In terms of a more holistic selection tool, there are four existing attempted solutions. Ilse van Kesteren proposed a four-part examination of the material selection process: a questioning tool, picture tool, sampling tool, and relations tool [85]. These pieces were intended as activities to inspire designers through first-hand exploration, and directed the user towards databases to find technical information. Elvin Karana produced a software assistant to provide designers with inspiration and provided them with a framework through which to process and think about materials. The tool attempts to contextualize samples, but it asks you to input the materials and the process is image-based, so there is no physical interaction [40]. The tool does not go into much depth, and instead guides you towards other databases. Hengfeng Zuo created a materials-aesthetics database to link texture to perceived experiences based on user tests. The tool does not extend far beyond that property [98]. Finally, Valentina Rognoli created an expressive- sensorial atlas to encourage dialogue around materials, asking designers to rank uniformly shaped materials based on property values as a learning experience [69].

While many of these tools provide useful insight into the process of understanding materials, they are limited in their scope, specialized, and focus solely on the materials decision part of the process, rather than connecting the designer back to the engineering community or empowering the individual to explore previously unknown options.

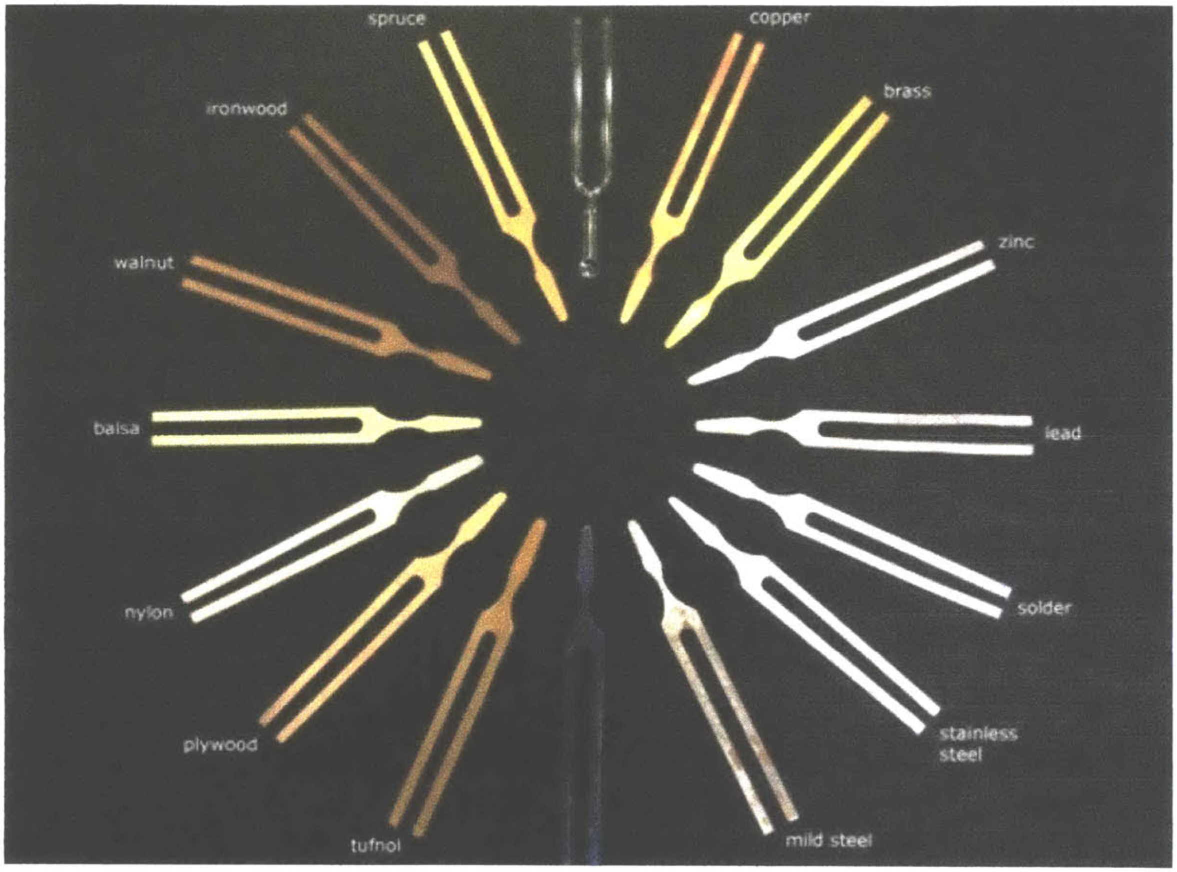


Figure 3-3: Tuning forks produced at the Institute of Making to demonstrate the "performance" of material properties related to acoustics [91]

In terms of exploring the emotive aspects of materials through fabrication, Sarah Wilkes and a team at the Institute of Making are now beginning a venture (called PhysFeel) to explore the relationship between physical properties of materials and emotions in the context of mental health and wellbeing assessments. The team is beginning by enabling people to communicate emotions non-verbally using physical stimuli to determine if there are correlations between the material and their selection to communication emotions. Zoe Laughlin, also at the Institute of Making, is attempting to develop a sensoaesthetic theory of materials through scientific methodology. In two particularly intriguing experiments, the team has explored sound and taste. In the first, they tested the comparative acoustic properties of different materials through tuning forks of identical shape made from varying materials. The tuning forks were used to demonstrate the effects of materiality on sound, with exact frequency produced by each fork measured and the shift in pitch attributed to the change in materials [91]. In a second experiment, the team explored the physical factors that define taste by asking volunteers to taste spoons which had been coated with seven different types of metal: zinc, copper, stainless steel, gold, tin, chrome, and silver. This work in sensoaesthetics looks for correlations between measurable properties and subjective physical sensations that directly relate to those physical properties [92], thus comparing physical properties to physical sensations.

In her PhD work, Elvin Karana collected a set of descriptive words to create the aforementioned software tool. She describes the process below:

> For this aim, we asked people to describe materials (materials as words, material samples and materials in products) (Chapter 2). In addition, we explored several sources (design magazines, materials selection books, etc.) in order to collect items used for describing materials. We came up with 687 descriptive items and classified them into seven descriptive categories: (1) use descriptions, (2) manufacturing process descriptions, (3) technical descriptions, (4) sensorial descriptions, (5) expressive/ semantic descriptions, (6) associative descriptions, and (7) emotional descriptions. We utilized the three experiential categories of product experience in peoples material descriptions: aesthetic experience; experience of meaning and emotional experience. On the basis of these experiential categories, we introduced the term 'materials experience', with which we emphasized that materials- like products- are used for creating certain experiences. [40]

While some initial steps, such as the determination of materials experience, have been taken to create a shared foundation between designers and engineers, very little research has been completed that has taken a scientific approach in the exploration, and few researchers have extended their knowledge towards fabrication or application to new materials.

3.3 The Scope of This Work

In his book *Nanomaterials, Nanotechnologies and Design*, Ashby poses a series of intriguing questions: In thinking about how we might use nanomaterials in design, it is important to step back and not define the issue simply as a technology transfer problem a self-limiting approach- but rather to think about it in more fundamental terms. What is the role of material in design? How do material properties influence the shape and form of objects and environments? What are we trying to do when we use a specific material? What role do we expect materials to play? [75]

As explained earlier, which such a broad range of possible materials, having a way to parse through choices based on conveyed and embodied meaning is crucial; understanding the emotive meaning is one way of filtering through choices. Designing materials with a consistent emotive and functional meaning could result in powerful material experiences. To develop a basis for connecting material properties that operate across scales, I am referring to some concepts of cross-modal mapping and synesthesia as a method of framing. In such phenomena, experiences of one sense combine with another to create multi-model, sensorially rich experiences that are incredibly moving. In framing this work, I rely on the following premise: emotions are based on sensorial inputs, which are based in experiences, which are fed back into emotions, so they all influence each other like a circuit. For this reason, none of this work is meant to exist in a vacuum, instead it is a thought process and system, a conversation starter rather than answers. Any such endeavor would require rigorous methodology. This thesis is an attempt to establish that.

To begin this research, we must first determine a set of quantifiable and measurable properties of materials that are salient to human- material interfaces. Such properties can then be mapped to the senses, allowing researchers to ascertain the perceptual dimensions of materials. In the following chapters, I will outline experiments that take this first step.

The language of quantitative and qualitative aspects of materials is vastly different. By exploring materials in terms of the more universal foundation of human emotion, I seek to encourage a shared language across disciplines. In doing so, I hope to allow designers to understand more technical aspects of development, and give engineers tools with which to contemplate the user dimension of materials, thus allowing a more symbiotic process of technical progression. "If designers can understand the unique properties of novel materials and reinterpret the opportunities provided by them, they can shape future material experiences and, by steering material development, creating technically and emotionally innovative materials" [99].

As stated by designer Julia Lohmann, "when communicating through objects, the meaning is created through the materiality of the object, the materials become the words and the design becomes the syntax. The piece speaks without the detour of language" [99]. The materials development process is evolving; today things are different - competition between families of materials has led each family to extend its characteristics and broaden its jurisdiction in space [50]. While creating a system to quantify responses to existing samples has immense potential, material scientists are now able to create systems with functionality that goes far beyond the capabilities of any one material. Scientists develop arrangements, structures, and combinations that capitalize on specific properties and couple them to other compounds that would not be found in nature. Generally speaking, in the space of properties every point - that is, every possible combination of properties- is now occupied by one or more materials, which complicates the process of design with and selection of materials. It therefore stands to reason that that a key distinguishing factor could ultimately be the emotional properties and implications.

For those without the resources to conduct time intensive user studies for every project and without the intuitive knowledge of a professional, it can be very difficult to predict the implications of materials and their impact on interaction. The development of an effective methodology and mapped vocabulary aims to lower the barriers of fabrication of engaging objects. By incorporating qualities that were not previously quantifiable, I aim to encourage a more interactive design process that allows for the production of experiences that are tailored to an individual preference. The lasting value of this work will be a framework for conversations around material issues. Using this process, we can make things which have a consistent aesthetic and emotional meaning. If I can, for instance, better understand why a squishy material such as silly putty or a stressball is pleasant, I can build materials intended to alter mood. Such a process further allows us to go beyond: if we can say that some property relates to a desirable effect, it might imply that we should design materials using that to evoke specific reactions. This work has implications for many potential applications, but one of the most intriguing lies with design and wellbeing- creating products with specific emotional intentions can be used to promote positive wellbeing and mental health, and to generally create positive user experiences. Through this work, I ultimately hope to connect materials creators, users, and designers, enabling engagement with and communication through the physical world.

Here, we aim to determine a set of quantifiable and measurable properties of materials that are salient to human-object interfaces, (e.g. tactile, mechanical, optical properties, etc). Through mapping these traditional material properties to their more qualitative physiological, emotional, psychological and intellectual reactions, we hope to build a design language framework that links the physical and perceptual experiences of the design properties of materials.

Scientists describe attributes as extrinsic or intrinsic to a material: intrinsic values such as density or conductivity are inherent to the compound itself, whereas extrinsic properties such as weight or volume (though materials can be labeled as "extrinsic" if they are doped or processed to posses certain aspects of a second material) are dependent on size or amount. A question that is raised with this work, then, is if there is an analogous understanding of the value and meaning of materials? It would be unrealistic to assume that the examination of materials in one (or even a few) contexts could capture our understanding of materials in every context, yet there are some more "universal" material qualities. Hengfeng Zuo shares that "the correlation between emotional responses and outside stimuli are dynamic and complicated. However, it still makes sense to seek some general phenomena about the correlation between emotional responses and the perceived...attributes of materials, even if under controlled conditions and with material samples. The results of such research will serve as reference for designers to select materials or textures for any new product development where no existing products can be used as a reference" [97]. As stated by Karana in her PhD thesis,

> The study also showed that people have ideas about materials even before their embodiment in a product. It was one of the very first questions raised in Chapter 1: can we talk about an intrinsic character or an inherited meaning of a material? At first sight, yes we can. We came across several examples during the studies conducted across four years. When people are asked to describe wood, for instance, they do not only talk about its colour, its smell, or its ease of carving, but also its appropriateness for cozy environments, its association with hand-craftsmanship, or nostalgic and antique artifacts. These characteristics behave as if they are woods intrinsic characteristics, which are primarily constructed by common knowledge, social interaction and prevailing use of a material in certain contexts [40].

Though Karana continues to explain the context, and cultural dependencies of material implications, there are some connotations that seem to be universal in many contexts.

Hekkert and Karana explain this by demarcating meanings of materials into two categories: universal and learned meanings. They explain the universal material meanings as "the material-meaning associations which are, by their sensorimotor nature, very robust and persistent and not very sensitive to cultural or individual differences" [41]. They offer several examples: Wood is literally warm to the touch and therefore perceived as inviting and cozy, whereas stone or steel is generally cold to the touch and thus tends to be perceived as more distant. Or, when a material is rough, people will perceive it as more natural than when it is smooth, and transparent materials are most likely, or should we say naturally, seen as fragile. Yet, for many new materials with a much shorter history than, for example, wood or steel, the meanings still have to be learned [99].

However, as stated above, as the ability to engineer materials has expanded in scope, the definition of a traditional material has become more complex. "Nevertheless, the evolving science of materials and manufacturing technologies has provided designers with an enormous number of possibilities in their material choices. This has led to an increase in the variety of applications for materials in product design over the last decade. A single kind of metal, for instance, may be embodied in a dining plate as well as in an office accessory. The meanings attributed to this particular metal may differ considerably in each case. Therefore, to sustain that a specific material has a definite or an intrinsic character becomes difficult (e.g. "plastics are cheap surrogate materials") [40].

As such, this thesis is written as documentation of a process, and as part of a larger effort to explore the viability of a such a field and justify more research in the area. Many researchers have explored the effect of structure on optical properties, the role of personality in interpreting visual stimuli, or, in Philippa Mothersill's case, the emotive response to three-dimensional designs there is no one theoretical framework to bring these fields together. For example, what if scientists developing new materials for a health application could also incorporate physical, tactile and optical properties that were perceived as comforting, as well as being functionally therapeutic? What if designers could more deeply understand their users' psychological reactions to the materials they choose and directly link this knowledge to the fabrication systems they use in their design process? What if we could understand the very structural essences of materials that can evoke a certain emotive reaction and develop metamaterials that could generate evocative perceptual qualities that no naturally-occurring material could?

Through this work, I hope to identify what properties of matter can be altered to produce interactions to evoke specific emotions as an attempt to understand how emotions can be used to classify materials. Ultimately, I seek to connect the qualitative and quantitative design elements in this domain. To do so, I explored the question from two angles. In the first study, I took a broad approach to prove that material properties do indeed matter. In examining dice, I asked if there is an ideal material for a context and how we can identify which properties determine this. In the second study, I focused on a narrow set of properties to examine how perception and preference change with time, and whether materials can directly impact perception and behavior.

In this thesis, I started with broad study as a foundation from which to determine what types of questions could help reveal connections between the quantitative and the qualitative. This led to relations that indicate that specific attributes are related to specific properties. I have determined that this method should be considered as part of a broader discussion due to the viability of results of the study. Ideally, this work will open up a discussion for others to use this methodology and collectively understand the language of materials.

Once the connection between material properties and perceived properties has been established, the design guidelines could be tested as a next step. We could build an object using these constraints and ask individuals compare it with other objects fabricated in a more traditional manner. The guidelines would then be deemed useful if using them resulted in an object with the intended perceived properties.

There were, of course, limitations to this work that stem from time, ability, and resources. Many of the samples were produced in-house (as were some of the materials, with limited success) as a result, many of the materials used were relatively standard, and manufacturing and fabrication imperfections may have affected user responses. Furthermore, for the sake of practicality and safety, some limitations on tests were inevitable. While I considered using the waterjet to cut a thick piece of aluminum to really provide interesting thermal properties and providing extremely rough sandpaper as a sample, the reality is that I would not have been able to entice users to carry such a piece around for a week as the study called for. Furthermore, each of these studies would have benefited from more ethnographic observation, deeper dives into historical context, and a more culturally diverse user base. At some point, I hope to address these limitations, and consider attempting to map people to their material preferences.

3.4 Audience and Reach

This thesis was undertaken with the goal of determining if a new field can emerge from the examination of materials through a new lens. I intended these experiments to serve as an initial exploration towards establishing a comprehensive understanding of the range of material properties that can be controlled and combined to evoke emotional, as well as functional, reactions. Ultimately, I hope this exploration can lay the foundation to allow other scientists, designers, and researchers to contribute to this area of research.

As a starting point, I spoke with designers, librarians, students, practicing engineers, psychologists, and statisticians. There are methods from all of their practices incorporated in my process and thinking.

Much of this work was completed as a testing ground for myself, but the outcomes should resonate with those curious about engineering, those starting out as new designers, those involved in marketing and consumer products, or those interested in understanding more about how we converse with our surroundings through the subtle language of the objects and environments around us.

4

Storytelling with Materials

Deriving Meaning from the Physical

"When brand is built from the inside-out, elements of materiality and making matter most. Design plays the role of connecting materials to a bigger story."

– Mike Ashby and Kara Johnson, *Materials and Design*, [9]

Often we find that the richness of materials stems from their ability to provide a personality or craft a story around an existing form, or in some cases, to weave a story where none inherently existed. As materials age or gracefully degrade with age, these stories become more and more ingrained in our interpretation of their connection to our lives. In the first experiment, for instance, one user spoke of a cutting board with characteristic rings that have formed in a trough from frequent use. Though objectively this acts as a sign of wear and imperfection, to the user it is a visible signal of his attachment for the wooden board. While initially the weight and texture of the board made it appealing, the rings now provide an interesting visual effect and a constant reminder of the history it bears. He noted, interestingly, that this is the only argument he really has with his wife, indicating, again, that our material attachments can be very important. He reported that this is the only fight he's ever had with his wife.

Though typically materials reinforce memories or the characteristics implied by form, the ability of materials to infuse/tinge an environment or object with personality provides interesting opportunities for crafting stories. In a thought experiment with my friend Peregrine, we attempted to test this concept. What if, for example, we could make the stereotypically "trashy" form of a trashcan seem classy simply by altering a material? Perhaps by swapping out the traditional metal (particularly the thin, grey sheets which can easily become rusty with something perceived as natural and rare such as wood or stone. (A quick google search confirmed this hunch- an HGTV blog linked to the Treela Waste Can by Umbra, which imitates a wood finish and other similar ones purportedly hand-covered in yarn [12]). Similarly, how would you make something seemingly expensive come across as "trashy"? Perhaps by using a crumbly foam or cheap, common-looking plastic. In considering the interplay between material, form, color, and marketing, it becomes clear that materials can be immensely powerful. A Walmart sign could theoretically be made to seem less commercial by using recycled wood and metal from trash in Brooklyn, and then building a story around the artisans who hand selected and molded these elements into shape. There is a clear sense of surprise derived from expecting a specific material and realizing that in reality, it is something else entirely.

In many ways, designers serve as the gatekeepers of interpretation. By selecting the situations and settings in which different compounds are applied, they implicitly form associations and contexts for customers and societies. Overtime, these applications become internalized as the character of the material itself. It is now hardly possible to look at glass without thinking of windows and skyscrapers, or to thing of wood without envisioning furniture, or to see concrete without imagining a sidewalk. As such, the designers decisions on where and how to include novel materials is central to their general interpretation, especially in early stages. If designers are unable to effectively familiarize users with a compound, the material will remain mysterious, unfamiliar, and potentially even fear-inducing (depending on the nature of the chemicals involved and the process used to make it). While engineers focus on practical improvements and applications, even the most efficiently performing material may take a long time to reach human consciousness. Indeed, it is often the unexpected uses of materials that prove to be the most interesting. "Thus materials have two overlapping roles: that of providing technical functionality and that of creating product personality" [9].

4.1 Metaphors and Personality

Much of the richness of material interaction stems from metaphors: the metaphors we use to envision future products, the metaphors we use to describe materials, and the metaphors we use to describe personality. As Ackerman posits, "physical-to-mental scaffolding" is reflected in our use of metaphors, relating to the manner in which touching objects may similarly cue the process of physical sensation and touch-related conceptual processing as mentioned in Chapter 2 [6]. The language we use to describe our world and our interactions demonstrates this connection: we associate holding with caring, as in the phrase "the world is in our hands" [6], and the experience of weight is metaphorically related to seriousness or importance, as in "the gravity of the situation or "weight on his/her shoulders." With some descriptors we explicitly call on material metaphors, such as our experience of "rough" days.

There are some means through which was already intuitively apply material properties towards emotional meanings. For instance, consider what is brought to mind by the concept of a "warm" person versus a "cold" one. We describe people as "earthy" or "woodsy," "sharp" and "dull." Schifferstein and Wastiels delve into some of the literal and figurative associations we have with the concept of warmth:

> For understanding multisensory experiences, it is important to realize that they are not based solely on the information people perceive through their senses. The different meanings associated with the warmth concept are numerous. They relate to enthusiasm, liveliness, excitement, friendliness, sincerity, loving, passion, arousal (The American Heritage Dictionary of English Language, 2009), affection and tenderness, comfort and coziness, sexuality, or anger (Fenko et al., 2010b). Things that were once alive and warm, like the fur of a polar bear rug, or the leather of a chair, may carry an association with previous life (Heschong, 1979). In addition, materials that keep our bodies warm, like a woolen or fleece scarf, are associated with warmth (Fenko et al., 2010b). These cognitive associations affect the way in which people perceive, experience, and evaluate materials. Hence, for grasping the multisensory experience of the warmth of a material the product function and the evocation of associations should be taken into consideration. [72]

If we then add to this the more abstract layer of meaning we then apply to materials, it becomes apparent that there are many emotional stories we tell with materials. As part of the dice study, I asked subjects to describe an object that had meaning to them (usually their favorite object). One user perfectly captured the importance of materials in her description:

> One summer I was in Seattle and I happened on this red heart thing it was made out of this really heavy carving material and it was red with white chiseled dots. I picked it up and it was heavy. I really liked how it felt in my hand, and how it fit in my hand. I was feeling kind of sad, I had just gone through a break up, and associated holding

> that heavy object with independence. I remember when I was writing in my journal, I thought the break up would ruin my summer. I would sit on the porch and write and hold it, but for like many many months after that was super symbolic and brought positive associations with independence. Something about the size and heavinessI still associate it with independence, though eventually I needed it less and less.[1]

While this participant provided a poignant tale of how material properties turned into powerful associations, in the form of an object, materials have been assigned roles even within the making process. In her studies of material literacy in the creation process, Dr. Ann-Sophie Lehmann describes the personification of raw materials: "In addition to low value, clay was labelled as a feminine material. Not only because it was obtained from the female element par excellence earth but also because just as colourful pigments were said to be pleasurable and deceitful like a woman, clay was likened to a woman for its forgiving softness: unlike with bronze, marble, stone, or even less costly wood, mistakes in sculpting could easily be mended" [45]. She continues to explain how the metaphors of inferiority and gender-just like the male superiority of hard marble or dangerous, shiny bronze initially stem from the marginalization of materials by artists.

The connection between personality and materials is explicitly linked in the Wu Xing practice of Chinese astrology, where individuals personalities are linked directly to "elements or changing states of being." In one basic website describing this association, the elements are summarized as follows: The Metal-type person is righteous, the Water-type person is smart, the Wood-type person is kind, the Fire-type person is polite and the Earth-type person is trustful. Much like colors on the color wheel, these elements can be mixed to achieve nuanced traits. The website even explicitly states that "Metal is the substance in which internal particles squeeze and condense together. There is a force from the outside to the inside that keeps Metal hard. Metal reflects light, so it is shiny. It may have a clear sound when it's hit. Therefore, a Metal-type person has great strength, discipline and enough courage to aid needy people, which may make them famous" [7].

While for most people the meanings of materials are not as explicitly outlined, we frequently use metaphors to describe our interaction with the physical world, and thus give them emotive hues.

[1] Participant, Personal Communication, 2016

4.2 Crafting Emotional Spaces

Juhaani Pallasmaa provides one of the most poetic desriptions of the storytelling power of materials in his work on the Architecture of the Senses [62]. He begins by describing the sensual nature of architecture and the idea of the accumulated history of places. In the piece he focuses on seven sense-based properties, based on eye, ear, nose, skin, tongue, skeleton, and muscle.

I was first drawn to this piece because of the idea that materials allow for the realization of sensorial experiences, just as the difference between an empty room and one filled with furniture is reflection in the way sound moves through the space. Pallasmaa discusses materials in the context of aging and use and building for memory. One of the most thought-provoking quotes is the idea that interior details embody a collection of stories: the "door handle is the handshake of the buildingallowing us to shake the hand of countless generations." In his descriptions, he encourages us to think about experience beyond the agenda of the eyes [51]. The interior of a space acts a repository for embodied sensory experiences, and authenticity is derived from the alignment of architecture with the inherent wisdom of the body [62]. The imagery used to explain the existence of matter in the continuum of time and the contrast between natural materials that are enriched with age and modern ones that cannot convey that information is a remarkable commentary on the character and communication of materials.

As mentioned earlier, our interpretation of sensory materials is our primary means of interpreting material properties. Pallasmaa discusses the traditional hierarchy of the senses, where vision is often regarded as the highest sense, and touch is one of the basest, but he mentions that eyes are the sense of separation, while touch is the sense of nearness and intimacy. Touch can be thought of as unconscious vision, and sight can be thought of as the touch of the eye [62]. While sight often isolates us, sound can unite us, as in the power of a round of applause, through which a space can become instantly emotionally charged. He similarly describes the odor memory of a space; the way that scent can be used to represent a facet of life. Abandoned houses maintain a hollow smell and an empty sound, and Pallasmaa muses that this can be attributed to senses reinforcing each other, much like the sensory modalities examined earlier. The senses do not only mediate information, they are also a means of articulating sensory thought, and thus the senses can be thought of as architectural media. Thus, "the strong identity between the skin and home [means that] the experience of home is essentially an experience of warmth" [62], as mediated by the materials within it.

Authentic architectural experience is grounded in the ability of the body to find resonance in a space, and Pallasmaa charges architects with the timeless task of creating embodied existential metaphors, though this can be expanded to the interaction of humans with any material interface. It is through metaphors that we learn and derive meaning.

This led me to examine the material diversity of the environments around me: in my office alone, I recognized 28 separate materials. Spaces such as homes, coffee shops, and stores had a plethora of material and thus provided an immense amount of stimulation, whereas spaces intended for more transcience or single functionalities, such as the lobby of bank with an ATM, a classroom, a Laundromat, and some older libraries tended to have a lower diversity of materials, and thus, provided a less rich sensory experience (though, if the materials are selected for pleasure, this can be a relaxing experience).

We experience extremely different sensations when we walk into different environments, but what makes us feel certain ways in certain spaces? What cues can we take from the design of spaces to understand the implications of materials? Many of the homes I interact with are warm and study, full of soft objects and wooden surfaces. Saunas shroud us in heat and steam and darkness, providing a relaxing hideaway. Many modern corporations have cold, smooth, elegant appearances, maintaining a clean and formal feel through their material choices. If we move to an even more abstract layer, environments that promote sleepiness tend to be dark, warm, and soft (during the dice experiment, when mapping the samples, one user astutely mentioned that comforting is the combination of happy and sleepy). When we want to be woken up we seek bright, shiny environments (similarly, traffic signs tend to involve highly reflective surfaces that promote alertness).

In the following experiments, I attempted to unpack some of the properties that fuel these sensations, associations, and stories.

5

Using Dice to Establish Material Matters

Initial Explorations

This work experiment was reviewed and cleared by the Internal Review Board (COUHES) under protocol number #1601348759

5.1 Approach

So much of this work relies on the premise that material properties are central to our evaluation of objects, and that they impact us in predictable manners from which we can draw patterns. With this first set of experiments, I strove to quantitatively prove that. I also needed to carry out the entire process of both understanding the technical properties useful to engineers and the perceptual, psychophysical, and qualitative properties useful to designers for a specific object. In doing so, I was able to develop a process that consisted of the following:

1. **Select object based on desired exploration:** Is there one property to be explore? One story? One cultural context? In this case I wanted to understand on a broad level how our preconceived understanding of effective dice impacted our interpretations of dice of different materials. In other studies, researchers have examined how physical stimuli impacted behavior, how alteration of a physical property influenced which version of a product is favored, etc.

2. **Select relevant technical properties to examine:** This is based on a combination of intuition, literature review, and observation. In this case I predicted which factors of dice interactions were most memorable and impactful during use, and extrapolated the associated technical properties to test.

3. **Select the scope of materials to be examined and define a sample set:** This is an incredibly crucial process. Limitations in the range of materials tested is one of the largest sources of error in multielegant scaling examinations. In order to appropriately select the samples used for this study, I produced graphs to map out the variability between potential samples to ensure that a broad range of properties was represented.

4. **Select and acquire access to the tools needed to effectively measure these properties:** This is an extremely nontrivial process- even at a research institution such as MIT, it can be difficult to track down the necessary instruments, and to determine which provides the best balance of accuracy and time efficiency. It can take weeks to get trained on all of the necessary aspects of a system, especially those contained in specialized environments like cleanrooms (as many of those used here were). It can also take time to determine what the correct level of precision is, and which testing techniques are too involved and specific to be directly applicable or well-suited to user studies.

5. **Measure the relevant properties:** Again, this is an extremely nontrivial process. To accurately deduce values, many, many measurements are needed - hundreds of measurements were recorded for roughness (three measurements per side by the number of sides by the number of dice) and for dice drop, which can be laborious and time consuming. These properties then need to be analyzed, tabulated, and interpreted.

6. **Design questions and activities to gauge the emotive aspects of the materials:** Select relevant adjectives from existing literature, select relevant tasks, and establish an appropriate method, scope, and length. In-person studies, for instance, provide an opportunity for rich stories, but on-line surveys allow for more rapid and efficient collection of information. It is also important to strike a balance between collecting all of the necessary information and fatiguing the user, especially if they are uncompensated. Determining effective compensation and obtaining approval from the Internal Review Board is also part of this process.

7. **Conduct multiple rounds of testing:** Pre-test the study on a small scale to determine whether the questions and methods are effective. It is useful to ask respondents what they think the experimental questions were at the end

of the study to see if the correct conditions were tested, though the purpose should not be overly obvious.

8. **Select analysis methods:** For many researchers, this is one of the first steps of the process. While I had a plan for comprehensive analysis beforehand due to existing literature in relevant fields, during the course of collecting stories and observing interactions, other relevant methods became apparent. With qualitative questions, it can be useful to analyze as the study progresses and pivot as necessary.

9. **Analyze results.**

10. **Visualize results and use findings to select the next experiment.**

One of the primary challenges with this work is capturing the richness of emotion, while still uncovering insights that provide useful guidelines and points of discussion in a non-reductive manner. Existing work oscillates between oversimplified models that map stimuli to specifically selected emotions and vague qualitative work that is difficult to translate beyond the initial experiment. In reality, some of the most powerful emotions are not purely "happy" or "sad," but rather more along the lines of bittersweet.

In an attempt to understand the fundamentals of how people connect to materials, I also adopted a "feelings first" approach in an effort to crowd-source the feelings relevant to the such a discussion. Prior to providing users with a pre-selected set of adjectives, I allowed them to define, map, and associate the samples freely.

5.2 Using Dice to Establish Material Matters

Through the first experiment, I strove to understand if material properties do indeed matter, and to demonstrate their effect if so. My secondary goal with this experiment was to learn how to conduct an effective user study to connect qualitative information with quantitative techniques and metrics in a rigorous way. The primary questions behind this first exploration were as follows:
Do material properties matter? If so, which ones?
Can we alter perception with these properties
Can we map people to materials

Along the way I needed to figure out where the data started to spread to recognize and focus on those properties for round two of testing. I needed to figure out and draw what the plots would look like for these (i.e. as this property increases, how will people react). The end goal was to develop plots to figure out what questions to ask to gauge whether the properties had impact.

As a first step towards this, user testing is needed to answer questions such as:

1. *Do material differences impact preference? Are these differences perceptible to users?*
2. *Will different individuals prefer different materials?*
3. *Will certain properties be more relevant? Can these properties be manipulated to evoke specific reactions?*

5.2.1 Reasoning

The form of a product or object is extremely relevant to perception, a concept that has been extensively demonstrated in practice and in literature [56]. A local practicing designer described the levels through which we interpret and differentiate products, where shape is a first order element that can be recognized from far away, form is a second level of recognition, and elements such as pattern, stripes, and texture follow. Then eventually the user has to touch the object to evaluate further properties such as the weight, feel, or smell.[1] Thus, the form had to be carefully selected to limit the variables in question. In this experiment, I aimed to control for shape, size, and color, though variations in color did occur due to natural material differences. Most pieces were grey or white, but all pieces stayed in the realm of neutral colors. The variables tested, then, were the materials themselves, and the people responding to the samples.

Dice pieces were selected as the first object for testing. The built-in affordances for dice are very strong: people are familiar with the form and know how to roll, hold, and interact with them. They allow for the tactile interactions that occur as one places dice in their palm in the moments before rolling a turn. Physical effects of the material properties are also invited: the physics of motion of the dice are observed as they roll and collide with each other and with the surface, the weight is perceived as they fall and bounce off of the surface, etc. Dice have well anticipated interactions with each other and with the board, and they provide opportunities for visual and auditory interactions as one observes the result and hears the satisfying click of a die finding its final position. We are subconsciously primed to notice

[1] Jason, Personal Communication, November 18, 2015

material properties of dice- we listen for the sound of a good pair of dice, we look for the response that determines the fate of the game, we observe and evaluate the bounce, and we hold them in our palms.

While a more outlandish or novel shape may have have detracted focus from the primary questions of interest, the familiarity of this form was intended to allow users to focus on the differences in the materials of which the dice were comprised. As such, the central question for this test was *What makes a material desirable as a dice?*

In selecting dice, a set of actions were proposed for the user; stacking, rolling, bouncing, dropping, building, holding, sliding, and squeezing are all afforded by this shape and its connotations.

5.2.2 Limitations

Since this experiment was conducted with real human subjects, certain limitations were in place. By selecting dice as the form, preconceived notions and biases were introduced in terms of how the samples should respond. Participants were expected to be inclined towards rigid, heavy objects that make a particular noise, and biased against soft materials. As such, follow-up experiments were considered to account for this bias and explore a different form.

A second, crucial, limitation was that all dangerous or toxic materials were excluded. Expensive and rare materials were inaccessible for the purposes of this study, as were materials that are difficult to process and work with. While size and shape were effectively controlled, color could only be controlled with moderate success due to natural material variations.

5.2.3 Hypotheses

Initial hypotheses for this experiment were as follows:

1. Material properties do matter and are perceptible, and thus the best and most desirable dice can be predicted using these properties. Hypotheses for these properties are displayed in Figure 5-1 through Figure 5-6

2. Different "groups" will prefer different material types.

3. The most relevant and salient properties will be the sound produced, surface roughness, shininess, density, stiffness and coefficient of restitution, and thermal conductivity.

The false assumption was made that when variance was necessary due to manufacturing, it was better to preserve shape than color. The brass die appeared gold, and brass proved to be an outlier in many of the rankings. This affected the selection process significantly, and is reflected in the data.

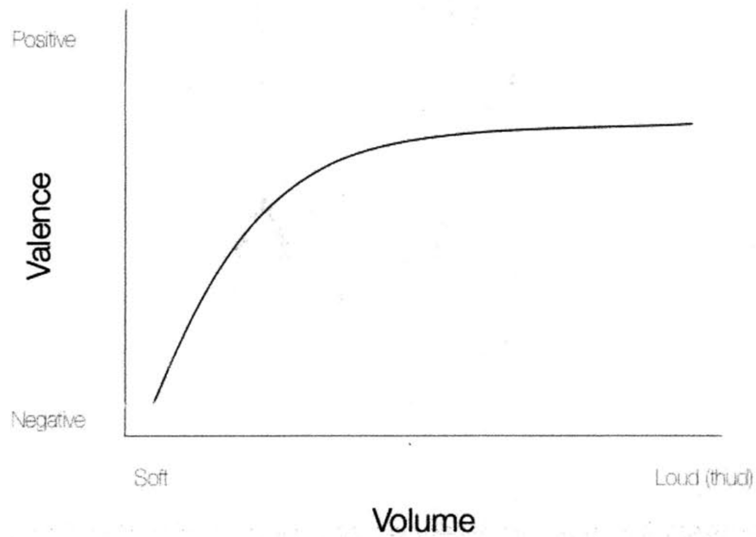


Figure 5-1: Hypothesis for user preferences of sound of dice drops. The logic was that dice that sounded too "soft" would be perceived as fake, but that after a certain point, preference would no longer increase with volume

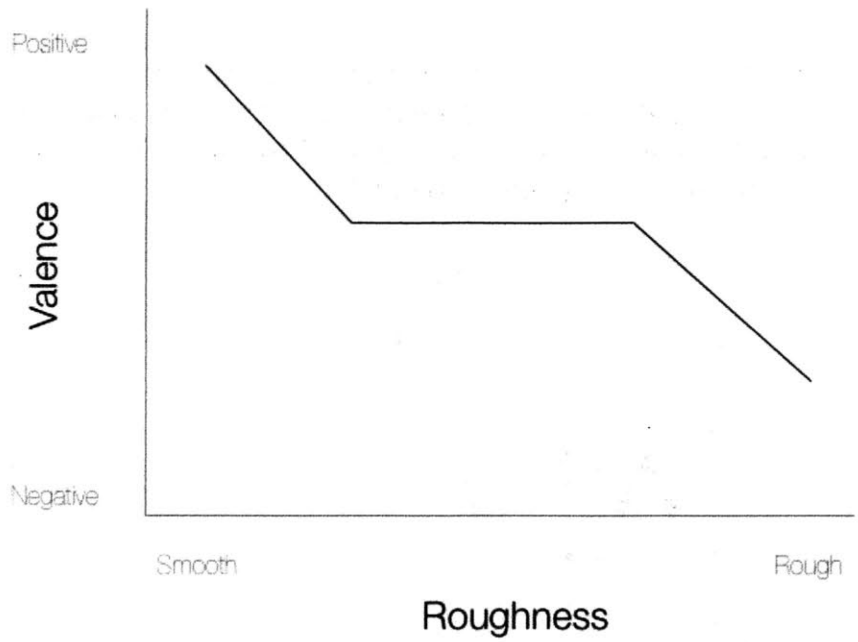


Figure 5-2: Hypothesis for user preferences of roughness of the dice surface. The prediction was that smooth dice would be received most favorably, things with moderate roughness would be moderately pleasant, and rough samples would not be received well.

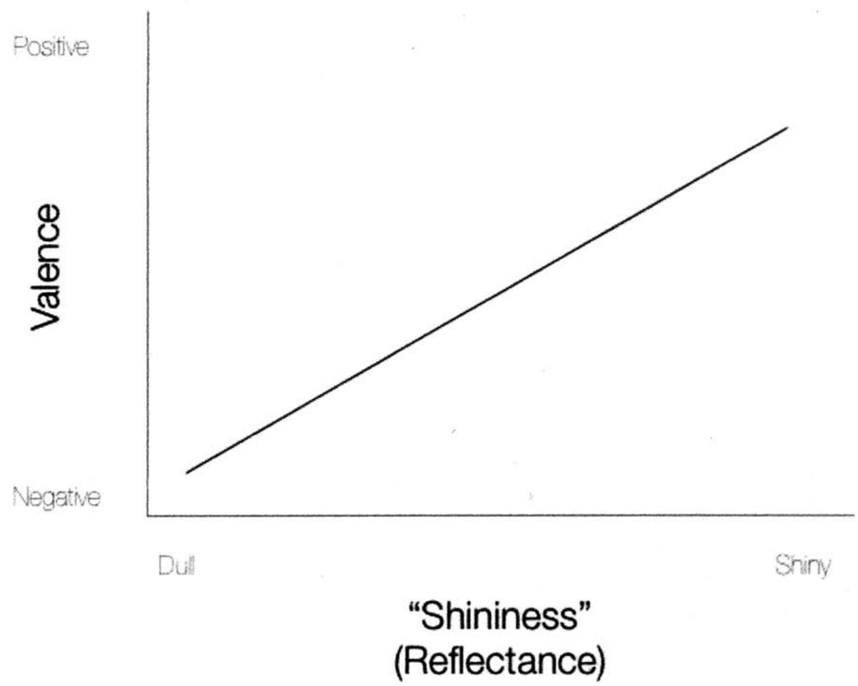


Figure 5-3: Hypothesis for user preferences of the "shine" of the dice. Preference was assumed to increase with shine, as long as the dice did not appear fake.

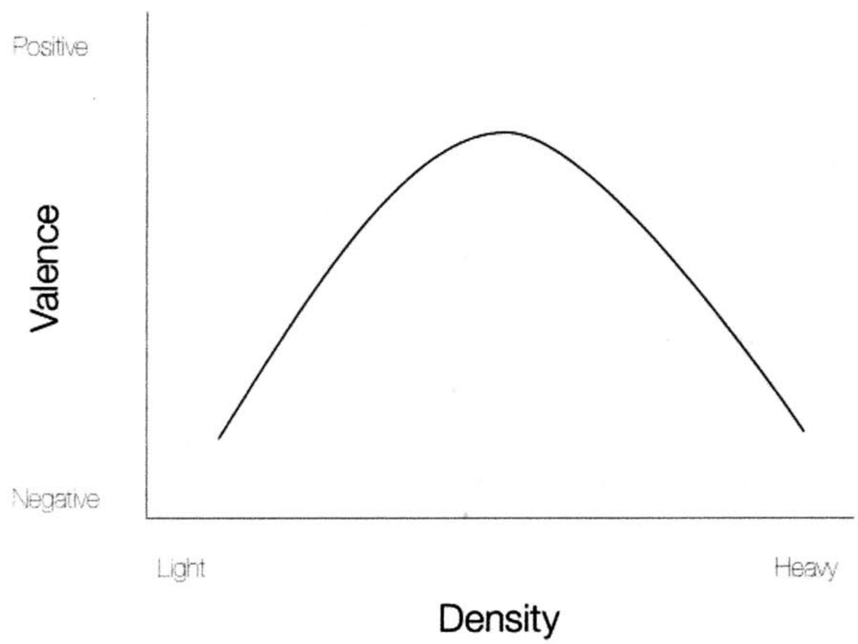


Figure 5-4: Hypothesis for user preferences for the density of the samples. At the lower end, dice may come across as fake. At the peak of the parabola lies the 'ideal' roll, but as dice become increasingly heavy, they no longer roll well.

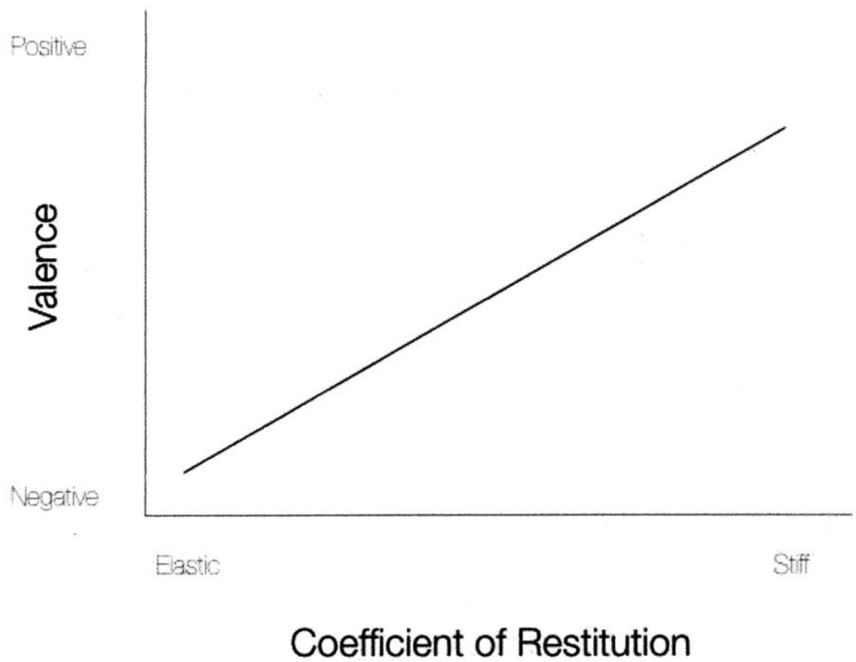


Figure 5-5: Hypothesis for user preferences for coefficient of restitution or bounce of the dice. The assumption was that elastic dice would not roll well, and that stiffer dice would bounce in a more 'expected manner' and have better inelastic collisions.

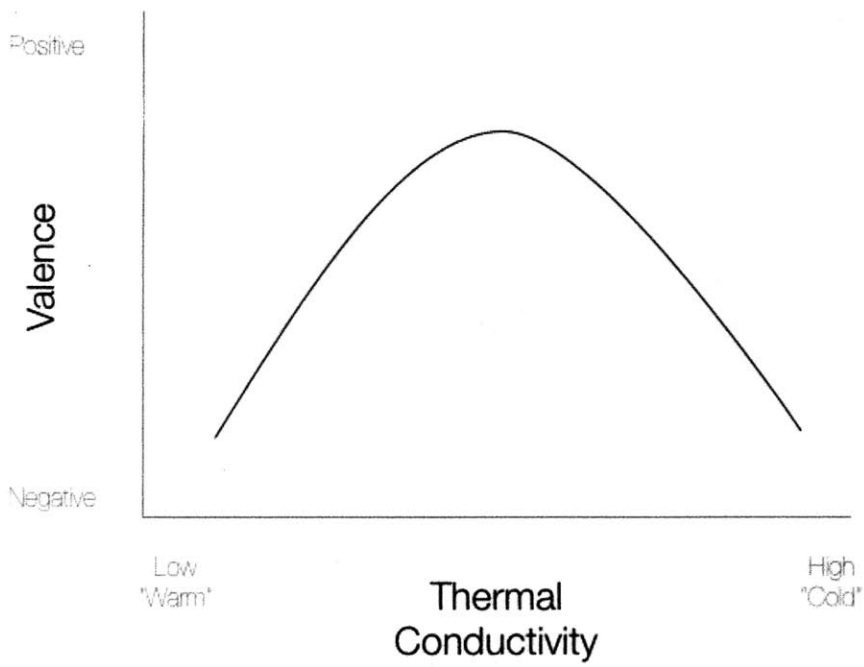


Figure 5-6: Hypothesis for user preferences for the thermal conductivity of the dice. At the lower end, if dice seem to 'warm,' they may be unpleasant, but if they are too 'cold,' they will also seem undesirable. There is theoretically an ideal midpoint.

Figure 5-7: Dice samples used in the experiments

5.2.4 Material Samples and Testing

Materials were selected to create the best possible separation of variables and represent a broad range of physical properties, as demonstrated in Figure 5-8. Samples were limited by cost, availability of materials, and ease of construction (in addition to the limitations listed in the sections above). The values of properties that were previously deemed salient were collected from Material Data Sheets provided by the manufacturers, and this information was used in conjunction with cost and practicality considerations (ease of manufacturing, availability, color adaptability, etc) were used to reduce the sample size. Materials with properties that were too similar were eliminated, so that a broad spectrum of properties was represented. Practicality or functionality as a die was not a primary consideration, though it was a consideration in the study design and informed the hypotheses. The "standard" resin die was included as a benchmark or control for all evaluations.

Samples what were first selected are as follows: alumide, elastoplastic, unpolished strong flexible plastic, polished strong flexible plastic, brass, silicone rubber, opalite, standard, foam, zinc alloy, wood, aluminum, pearl marble acrylic, clear acrylic, rubber, sandstone, Play-doh, a second type of wood, and banded onyx. In the first round of testing, all samples were included. Eventually, some samples were removed as similarities between them were too great for users to perceptibly differentiate (as with the zinc alloy and the brass alloy samples). Samples made of the same material were also eliminated (with the exception of the polished vs. unpolished plastic which were retained to explore the role of surface differences). Other samples were removed because the variation of shape or size was too great for them to be effectively compared to the other samples (as with the rubber die). Finally, the Play-doh sample was removed as it proved to be too distracting for participants - they often spent the majority of the time fiddling with it and deforming the sample. Play-doh was effective for drawing out connotations as almost every surveyed individual had interacted with Play-doh during their childhood.

Initially, two types of wood samples were examined, but the "more natural" seeming sample was retained and the other was cut. Numerous types of acrylic were initially examined, but "pearl marbled acrylic" was removed in favor of clear acrylic. Two variations of zinc alloy were narrowed down to one that more closely matched the shape of the other samples. Two rubber samples were narrowed down to one that varied more drastically from the behavior of of the other samples (since variation of samples was a key criteria for selection). Play-doh was also removed from the sample pool as participants recognition of the sample ultimately caused them to become distracted from the initial task and instead play with the substance. Also, samples made of this material barely held their form when examined.

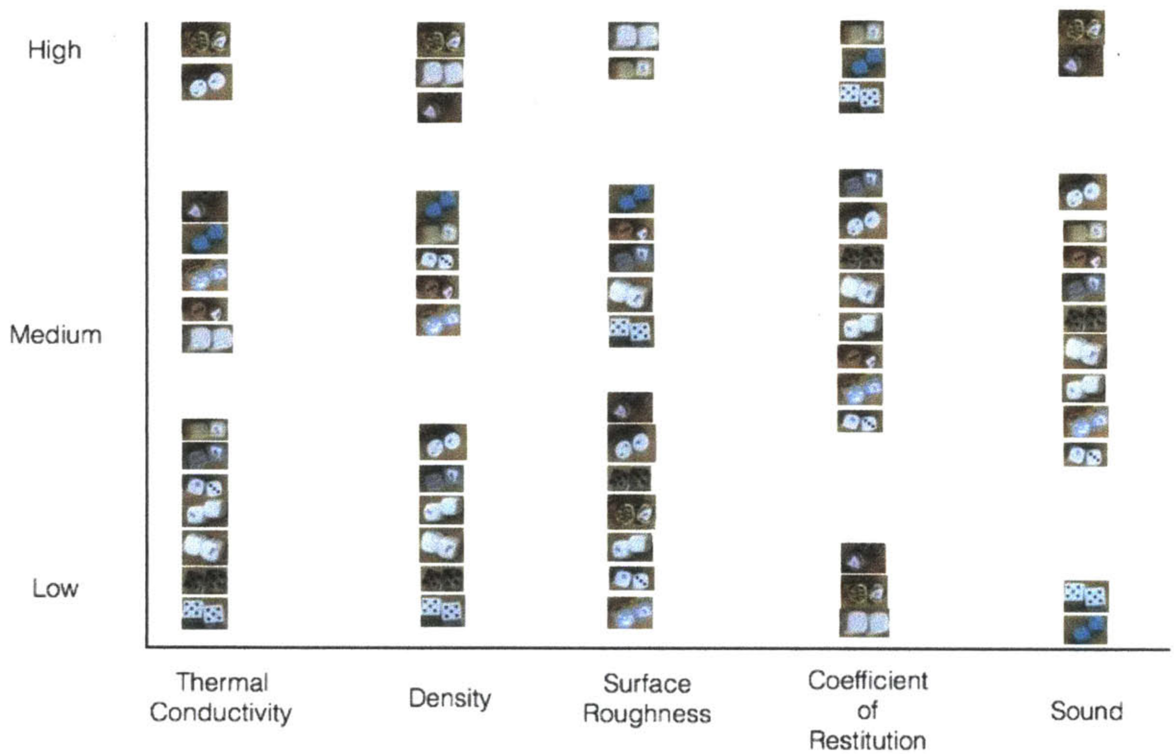


Figure 5-8: Plotting the samples along salient properties

Figure 5-9: Dice samples used in the experiments

5.2.5 Materials Testing Techniques

Measured properties were selected based on ease of acquisition and relevance to perception and evaluation of dice. Based on the previously stated assumptions, the following properties were measured:

5.2.5.1 Coefficient of Restitution

For this work, coefficient of restitution (COR) was determined to be a good measure of hardness, elasticity, stiffness, and Poisson's ratio, which manifested in the bounce that users observed during testing. An adaptation of a normal ball-drop test was used for calculations of COR. 560 videos were collected of the 14 samples to accurately calculate this information. Please see A for experimental details and calculation methodology.

Coefficient of restitution is defined using the parameter e, where

$$e = v_1/v_2 \tag{5.1}$$

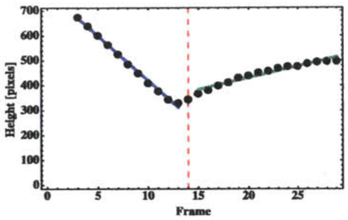
v_1 and v_2 indicate incident and outgoing velocity respectively. [27]

Materials with larger Young's Modulus numbers require a larger force to deform by the same amount. For example, "given the much larger Young's Modulus value for aluminum compared to the various types of wood, it is obvious that the various types of wood deform much more than the aluminum, absorbing much more energy and lowering the velocity of the ball as it leaves the bat. Meanwhile, this lack of deformation in the aluminum represents the so-called 'trampoline effect' which causes the ball to collide more elastically and have a higher velocity after collision. While the mass of the two objects and their velocities have an impact on the speed with which the ball leaves the bat, in this model, the spring constant can be accounted for by considering it to be the elastic modulus, or Young's Modulus, of the bat material." [2]

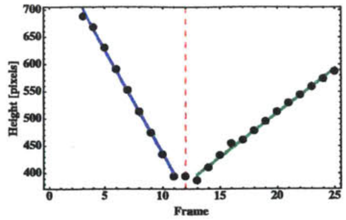
Traditional drop tests are conducted on a slab of wood or steel. For the purposes of this testing, a thick wooden slab was utilized. This was the same surface that participants were asked to use as a base for dice interactions during the user study.

Table 5.1: COR Values for Die Drops

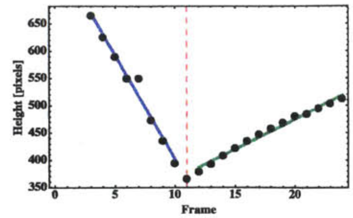
Alumide	ElastoPlastic	Strong Flexible Plastic-Polished	Strong Flexible Plastic-Unpolished	Brass	Silicone	Wood
0.443	0.679	0.480	0.465	0.132	0.738	0.492
Opalite	**Standard**	**Foam**	**Aluminum**	**Acrylic**	**Sandstone**	**Onyx**
0.403	0.254	0.343	0.309	0.317	0.349	0.179



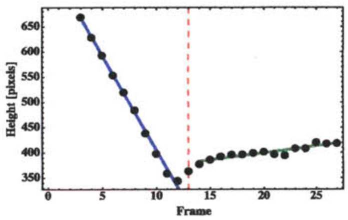
(a) COR plot for Acrylic



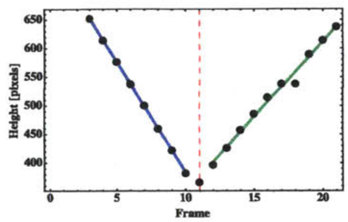
(b) COR plot for Alumide



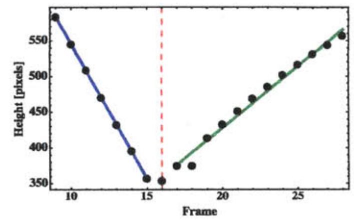
(c) COR plot for Aluminum



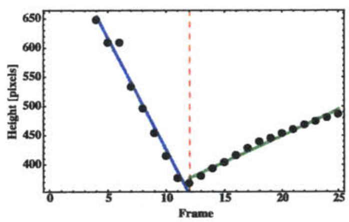
(d) COR plot for Brass



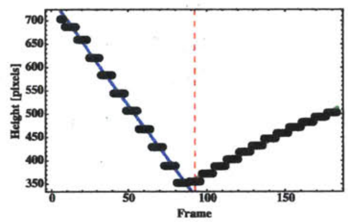
(e) COR plot for Elasto-plastic



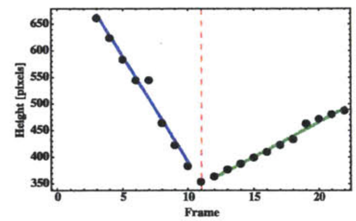
(f) COR plot for Foam



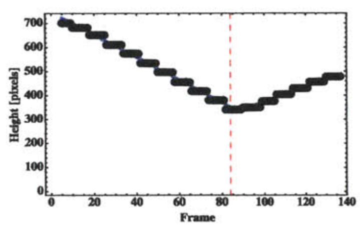
(g) COR plot for Onyx



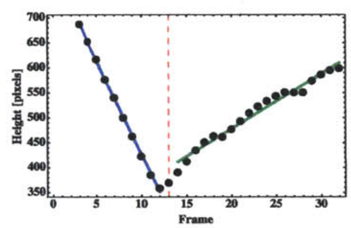
(h) COR plot for Opalite



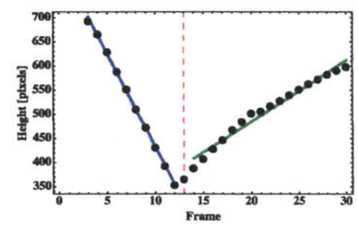
(i) COR plot for Sandstone



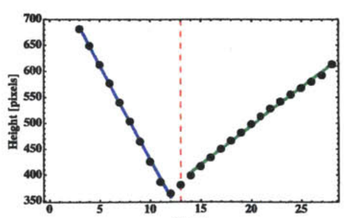
(j) COR plot for Silicone



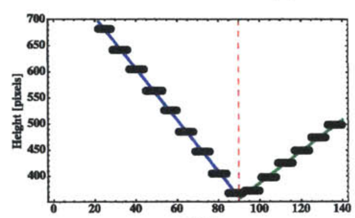
(k) COR plot for Standard dice



(l) COR plot for SFP-P



(m) COR plot for SFP-U



(n) COR plot for Wood

Figure 5-10: COR plots

5.2.5.2 Surface Roughness

Due to differences between perception of micro and macro roughness, surface roughness was measured using both Atomic Force Microscopy (AFM) for micro measurements and profilometry. Other researchers have also used image analysis to determine surface features [26] for macro roughness, but for the purposes of this experiment, contact measurements were used.

AFM is an extremely high resolution method used to understand samples by probing the surface. The resolution is significantly better than the diffraction limit, and, as the name suggests, can image down to the nanometer scale of individual atoms due to interactions between the tip and the material. There are multiple modes of imaging, and both contact mode (where the tip is moved along the surface) and non-contact mode (where the cantilever is oscillated at resonance above the surface and Van der Waals interactions are used to understand the distance between the tip and surface) were used. Non-contact mode is often preferred as it does not damage the tip or the surface. Initially, AFM testing was used to obtain roughness values for each die, however two obstructive issues arose. The first is that AFM imaging is actually potentially too sensitive for this application, and the piezoelectric element had extreme difficulty responding adequately to surface interactions with the sample, making it difficult to get accurate readings. The second is that the process was exceptionally time consuming, with calibrations and measurements of each die taking up to four hours, partially due to the nature of the sample in comparison to samples traditionally prepared for the AFM.

The AFMs used for this process included the Asylum model located in the Center for Nanoscale Systems at Harvard, and the Agilent model located in the Center for Bits and Atoms at MIT. Prashant Patil was extremely helpful and spent many hours training me on this machine.

After many hours of struggling with AFM measurements, a Dektak3 Profilometer was utilized instead. 232 measurements of roughness were collected on this system. The Dektak is located in the NanoStructures Laboratory cleanroom that is part of the Microsystems Technology Laboratories. Profilometers are typically used for measuring the step height or trench depth of features on a wafer, though many also use this tool to measure surface roughness. They operate by dragging a stylus over the sample to record the surface profile. Multiple measures of roughness were recorded, including the step height, mean roughness depth (Rz), root mean squared (RMS), and arithmetic average values (Ra). Please see C for measured values. Alternative methods could include optical measurements of the surface profile and image analysis, or measurement of the coefficient of friction as a proxy. [23]

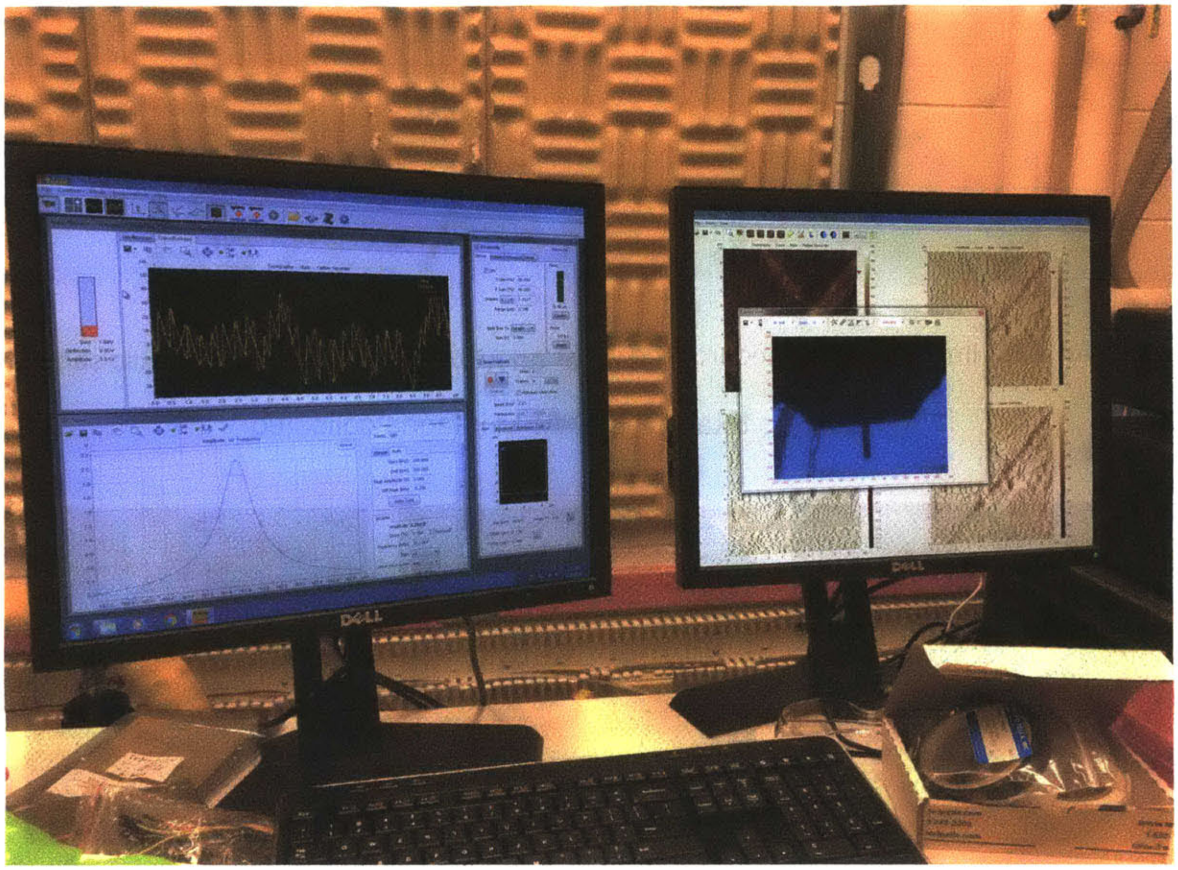
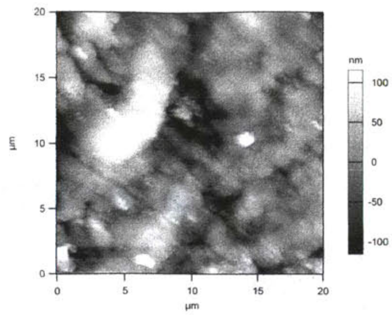


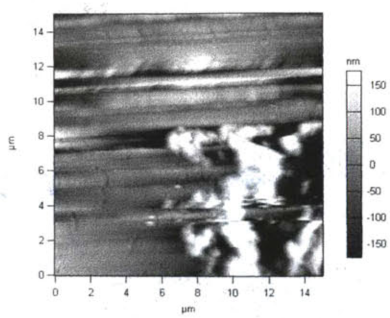
Figure 5-11: AFM Set-Up

5.2.5.3 Reflectance

Often, glossmeters are used to reproducibly measure the shine of a surface. Sunny Jolly helped me assemble a similar set up for examining the amount of incident light reflected off of the die surfaces using a laser, mirror, and photodector connected to a powermeter. A laser was placed at 60° from the center line, a clamp was used to hold the dice, and a powermeter was used to read the values from the photodetector. 60 ° was selected as the angle based on existing literature that demonstrated that some samples are most effectively measured at low angles (approximately 30 °) and others are most effectively measured at high angles (around 80), but all samples are measurable at around 60°. The alignment was calibrated using a mirror. For these measurements, green laser light was used for these measurements- white light was the initially intended plan, but unfortunately the blue aspect of the laser system was nonfunctional.



(a) An AFM image of the standard dice



(b) An AFM image of the elastoplastic sample

Figure 5-12: Examples of AFM images collected

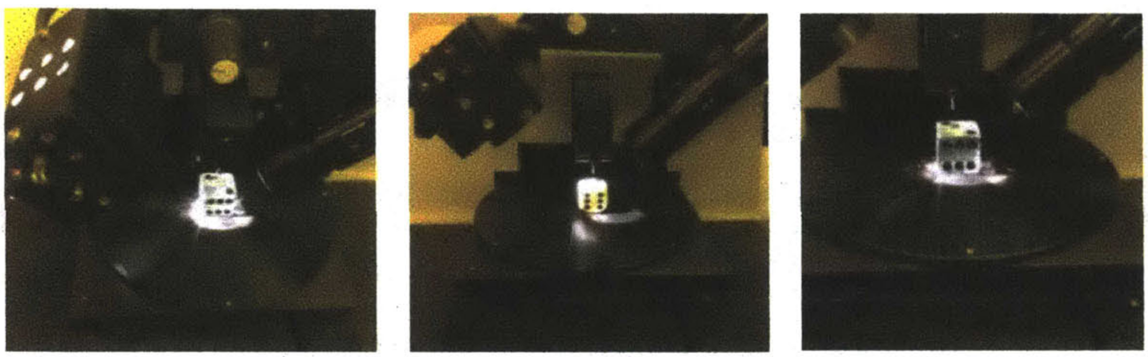


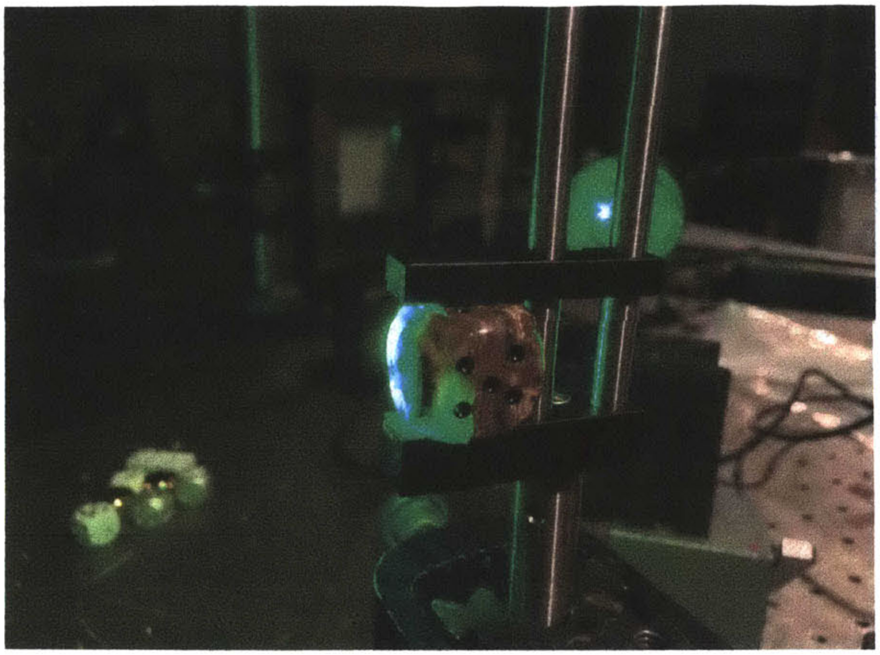
Figure 5-13: DekTak Profilometer in use

5.2.5.4 Density

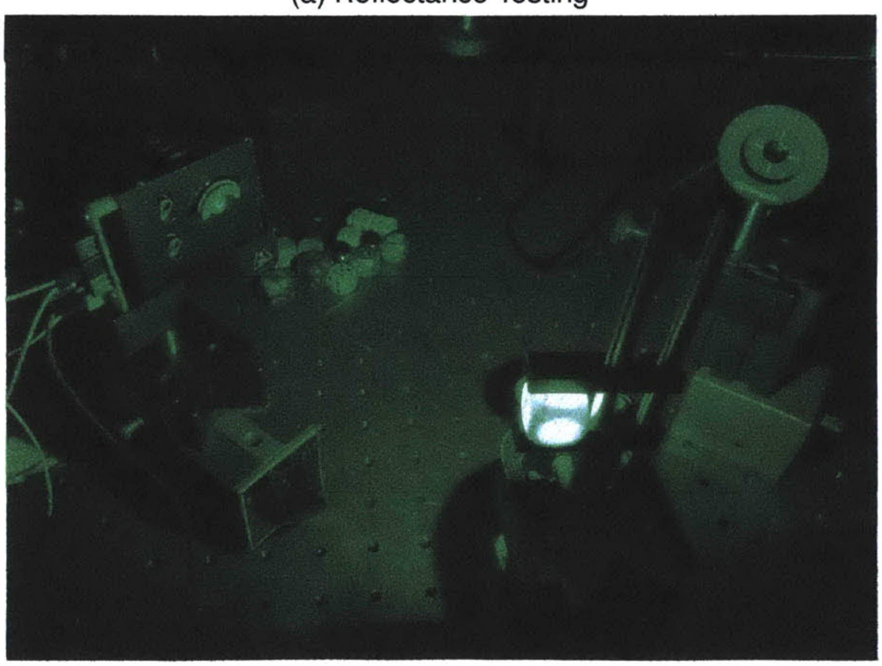
Weight measurements were carried out on a scale that is accurate to the milligram. Volumes were calculated by measuring sides of the dice, and corroborated using water displacement.

Table 5.2: Density Values for Dice

Alumide	**ElastoPlastic**	**Strong Flexible Plastic-Polished**	**Strong Flexible Plastic-Unpolished**	**Brass**	**Silicone**	**Wood**
1.246	0.863	0.863	0.822	6.230	1.272	0.747
Opalite	**Standard**	**Foam**	**Aluminum**	**Acrylic**	**Sandstone**	**Onyx**
2.1164	1.246	0.268	2.490	1.058	1.48	2.30

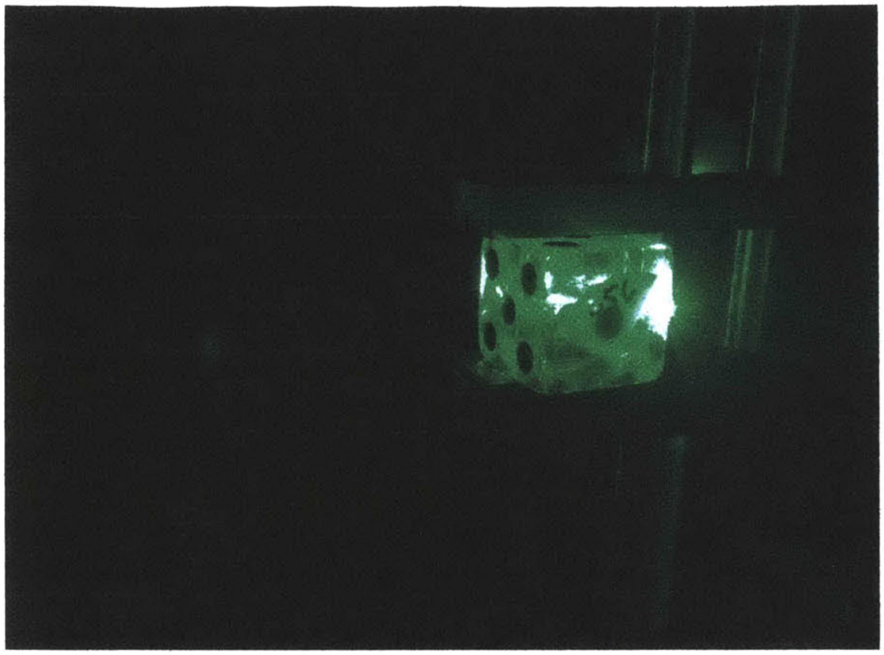


(a) Reflectance Testing



(b) Dice setup in reflectance testing

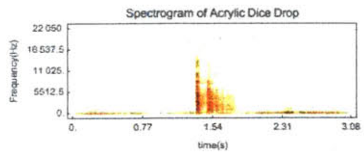
Figure 5-14: Images from testing reflectance



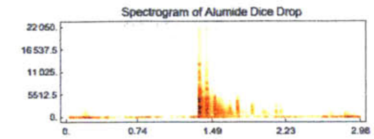
(a) Reflectance Testing

(b) Dice setup in reflectance testing

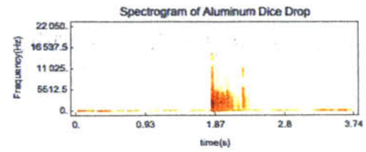
Figure 5-15: Images from testing reflectance



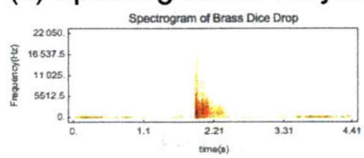
(a) Spectrogram for Acrylic



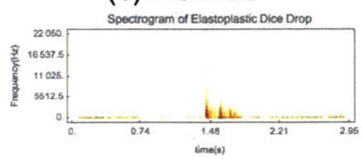
(b) Alumide



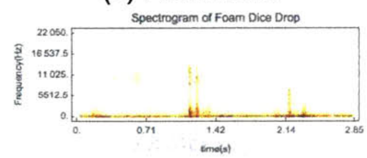
(c) Aluminum



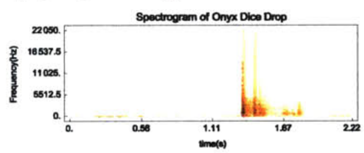
(d) Spectrogram for Brass



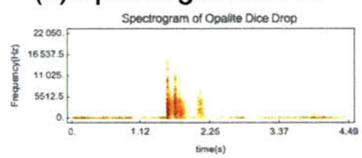
(e) Spectrogram for EP



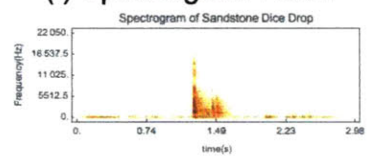
(f) Spectrogram Foam



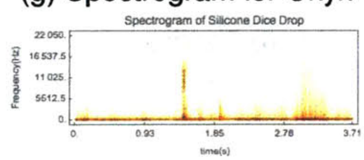
(g) Spectrogram for Onyx



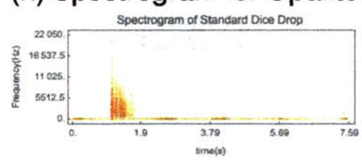
(h) Spectrogram for Opalite



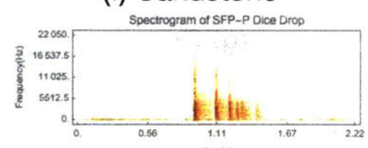
(i) Sandstone



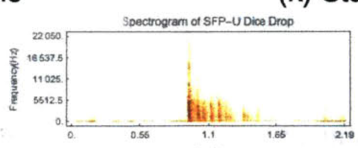
(j) Silicone



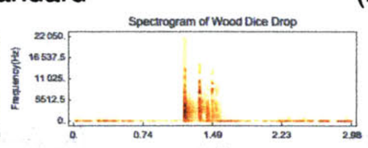
(k) Standard



(l) SFP-P

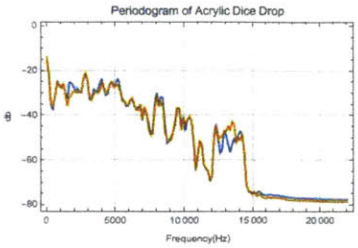


(m) SFP-U

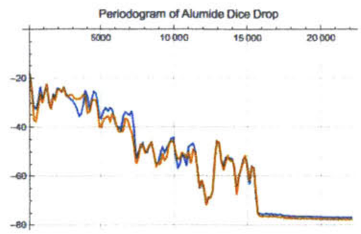


(n) Wood

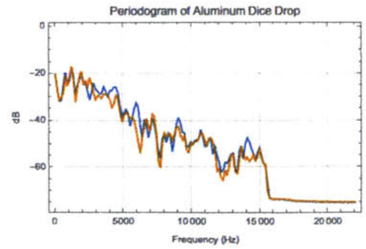
Figure 5-16: Spectrograms of the dice drops



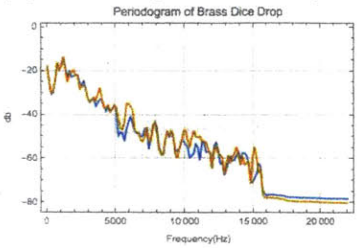
(a) Periodogram for Acrylic



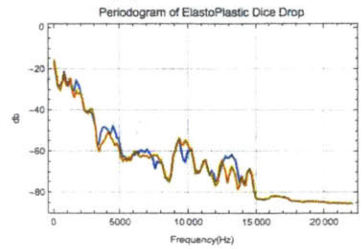
(b) Alumide



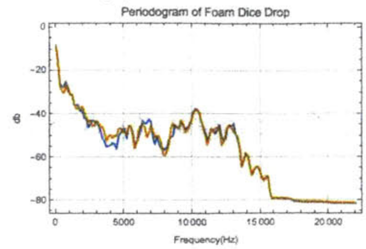
(c) Aluminum



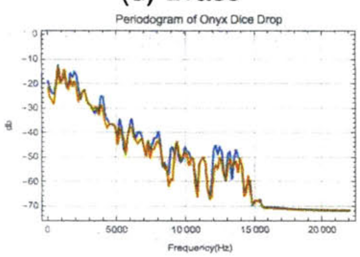
(d) Brass



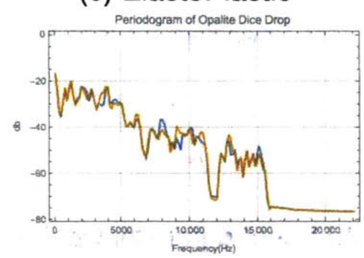
(e) ElastoPlastic



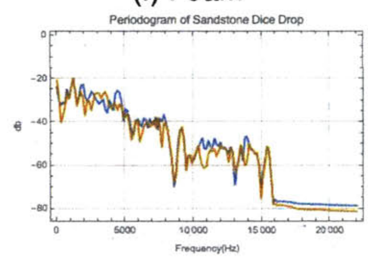
(f) Foam



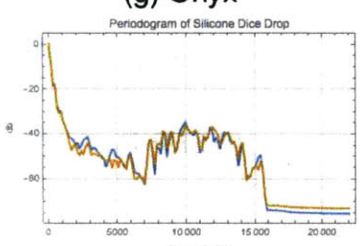
(g) Onyx



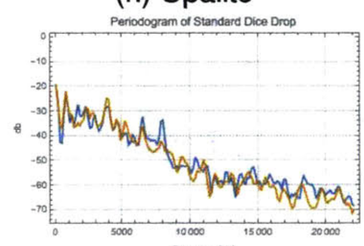
(h) Opalite



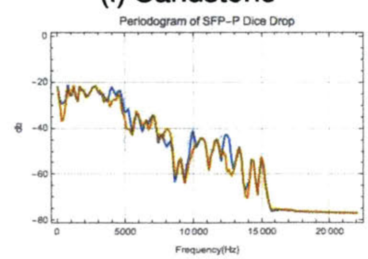
(i) Sandstone



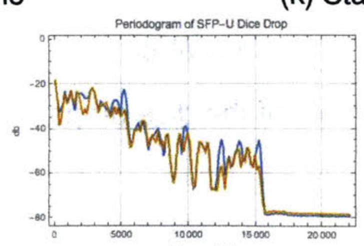
(j) Silicone



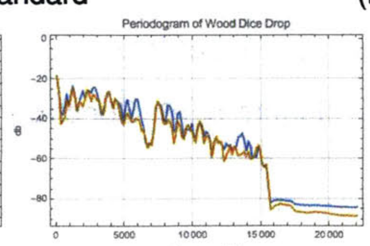
(k) Standard



(l) SFP-P



(m) SFP-U



(n) Wood

Figure 5-17: Periodograms of the dice drops

5.2.5.5 Sound

Dice drops were recorded using a Zoom audio recorder that was rented from the Lewis Music Library. As it is difficult to generate one numerical property to represent the nuances of sound, spectrograms and periodograms were produced instead to visual some of the differences between the bounces . The spectrograms (shown in Figure 5-16) visually represent the time variation of frequencies in a sound, where brightness indicates amplitude. These visualizations can also be used to interpret how pitch moves up and down over the course of the signal. Periodograms (shown in Figure 5-17) are visualizaation of the squared magnitude of Fourier Transforms of the spectrum.

An alternative analysis method could be a qualitative examination the rolls.

5.2.5.6 Existing Material Properties

Where it was consistently possible across samples, manufacturer-collected values of samples were used rather than repeating measurements. However, this method was only valid for properties which were available across all samples. Thermal conductivity was pulled from manufacturer available values due to equipment and time limitations. With consumer items such as dice, it is often difficult to acquire these values from the manufacturer as standard consumers do not need to know these values, so it took a significant amount of time to track down the appropriate measurements.

A significant limitation of this experiment stems from the fact that our perception of physical stimuli such as temperature originates in a complex set of interactions. The temperature we perceive is derived from the contact temperature, initial material conditions, thermal conductivity, density, thermal effusivity and heat capacity. The geometry of the piece also impacts our thermal perception, as thick slabs will conduct heat away from the finger more easily than thin films. The roughness of the surface can also prevent intimate contact between the finger tip and the surface, thus diminishing the perception of surface temperature. As a starting point, Wastiels investigated the correlations between specific physical parameters of materials and the perception of warmth for different sensory modalities. In future experiments, a more rigorous multivariate assessment of properties must be examined. [99]

5.2.6 Drawing from Haptics

Many of the techniques used in this survey were adapted from work done regarding research on haptics and robotics. Specifically, many cues were taken from the work of Katherine Kuchenbecker and her team at the University of Pennsylvania. This experiment drew on multielegant scaling and principle component analysis work, with the addition of some techniques from psychology and materials science. Users were surveyed on both qualitative and emotional factors to try to connect central qualitative and quantitative factors attributable to reaction to the samples. Questions were drawn from Collier's research on Affective Synesthesia and Karana's work on Material Driven Design, while the vocabulary for the Semantic Differential scales was drawn from Ashby and Johnsons seminal book [9,17,39]. Other questions were conceived by the experimenter.

Kuchenbecker's work has primarily focused on tactile perception and haptics. Robots created by her group use temperature, pressure, and fingertip deformation to learn and understand the meaning of haptic adjectives as the robots learn through physical experience. To create a lexicon from which to base such work, human subjects were used to establish "ground truths." Ground truth data is needed to help robots associate quantitative data with subjective ratings of how objects feel. Similarly, the goal with this experiment was to draw conclusions from observing human interaction with samples and asking participants to label and define aspects of their experience. The subjects in "Using Robotic Exploratory Procedures to Learn the Meaning of Haptic Adjectives" were asked to complete actions such as grasping, shaking, dropping, and flipping, many of which were replicated with the dice. Correspondence analysis was used to create structure from the results of these experiments [15]. This technique posits descriptors in an "n-elegant" space, where the distance between stimuli represents perceived dissimilarity and the location of descriptors represents their degree of association with stimuli [15]. It can be used to visualize latent relationships between stimuli. By comparing the resulting plot with the pre-determined adjective space, researchers were able to find highly salient object properties that have a greater proportion of feature variance attributable to this dimension.

Similar methods were outlined by Okamoto. There are three primary methods of data collection that have been successfully utilized to understand tactile perception. The first is semantic differential, in which materials are rated one by one using a scale of bipolar adjectives (i.e. smooth to rough). Originally developed by Osgood, it is frequently used with five or seven grades. It is extremely beneficial for interpreting fundamental factors and precluding the need for future experiments, but it is limited by the adjectives that are chosen by the experimenters. If adjectives from certain dimensions are left out, that dimension will not be uncovered. Semantic differential information is usually analyzed with Factor Analysis or Principal Component Analysis. The second method of data collection is similarity estimation. Three varieties are often employed: ratio judgement (where participants use arithmetic values to estimate the perceptual distance between pairs of stimuli), grading (where similarity between samples is evaluated on a gradated scale), and visual analog (where participants mark along a line based on perceived relative distances between samples) [60]. In similarity estimation, the number of dimensions is not limited by the adjectives used, but the process is extremely costly in terms of time and number of trials as all possible pairs need to be tested [60]. Usually, samples must be limited for practicality. The third method is classification, in which a set of stimuli are grouped by the participant based on similarities of the material. Dissimilarity scores can then be calculated, and geometric distances can be used to establish perceptual grouping. This method is much more user-friendly in terms of time, but it limits the user to two dimensions as it is formed on one plane, and thus loses much of the nuance of other techniques [60]. Both similarity estimation and classification studies are typically evaluated using multielegant scaling, where the distances are analyzed from gross perceptual distances.

In factor analysis, correlations between variables are interpreted to reveal inherent factors. It is used as a means of reducing variables and revealing structure in the data. Factors are intended to represent a large percentage of variation in the data. Principal component analysis is often used similarly and employs orthogonal transformation, where factors are extracted one at a time, and all factors are orthogonal. The first principal component accounts for the largest amount of variance. Multielegant scaling, by contrast places the samples on an n-elegant space in a manner that maintains perceptual distances [60]. Individual axes do not correspond to an individual dimension. In both methods, common materials are often represented more effectively, and data that is less dense is often overlooked [60]. Some experimenters will validate data after experimentation by asking participants to rate materials using adjectives, where properties are confirmed by using correlations between these ratings and scores of individual dimensions, or by using physical property information to examine correlations between the exposed dimensions and physical values. For this study, physical properties of materials were collected in conjunction with user ratings.

5.3 Methods, Survey, and Procedure

The survey was broken into three components in order to capture the maximum amount of useful information, while keeping in mind the time constraints and attention span of the participants. The first segment was an open-ended, interview-style conversation about the materials. The second portion focused on ranking the samples based on material properties to establish whether or not participants could perceive differences effectively, and to see whether any properties were correlated. The third portion relied on both semantic differential scales and open-ended mapping. Through the opening interview-style questions and the mapping portions, the experimenter intended to give the participant an opportunity to articulate their observations and connotations without bias and without using reductive labels. The semantic differential scales were used to acquire more concrete relations to emotional adjectives afterwards and attempt to unpack any possible trends. Vocabulary for this was drawn directly from the findings of Ashby and Johnson in Materials and Design [9] to attempt to capture a broad range of thematic words. The second portion (ranked data) was also used as a means of getting participants familiar with the dice and causing them to consciously consider properties (such as sound) that they may otherwise have ignored.

The order of parts was determined through various iterations during pre-testing. The open-ended section was placed first to frame the discussion and capture user's unbiased thoughts before they thoroughly explored the samples along dimensions articulated by the experimenter. The ranking came before the semantic differential and mapping as familiarity with the samples helped ease the process and shorten response time for the extensive questioning in the third portion. See B for further details.

The interaction procedure for participants was as follows:

1. Recruitment: Participants were primarily recruited via email or word of mouth. Some participants were reached via publicly available email listserves, or publicly acknowledged groups (i.e. reading groups, athletic teams, Boston Symphony Orchestra, publicly acknowledged lab groups, etc.). Participants fell within the age range of 18-65.
2. Participant tasks: Suggested actions were provided for each sample set. For dice, this included stack, roll, bounce, drop, build, hold, slides, or squeeze. However, participants could also focus solely on visual examination if they preferred to. After participants explored the samples, they were asked a series of open-ended questions about the pieces. These questions were followed by a series of prompts in which they were asked to rank the pieces. For the ranking and quantitative questions, they were given a paper survey to complete.
3. Length of interaction: The entire process was estimated to take between 45 minutes and 90 minutes, though it was clearly articulated that participants could choose to stop at any point. At the end, participants were asked if they

would be interested in participating in a follow-up study (either to examine the second set of samples or for the purpose of future examinations in which recording might be included).

4. Design samples and questions: B includes an example selection of questions that were be asked in our first experiment. Design samples and questions being tested were expected to vary over time as the investigators experimented with other variables in their research.

Participants were recruited through a combination of direct recruitment over email and in-person, through personal contacts, course lists, and public email listings. Many iterations were needed to arrive at a useful survey. The iterations are described in the sections below.

5.3.1 Alpha Version

In the preliminary ("pre-test" version) of the experiment, the experimenter attempted to capture all possible information for similarity estimation, classification, and semantic differential. Understandably, this proved to be extremely taxing on both participants and experimenter, with the entire process taking almost four hours.

Initial open-ended questions included the following:

1. If we were to discuss the concept of dice, what properties would you consider desirable? why?
2. Feel free to stack, roll, bounce, drop, build with, hold, slide, or squeeze the pieces. Definitely feel free to roll them, but as you do, be careful not to throw them too hard (some of them are moderately delicate.). Use the amount of force you would when normally rolling dice.
3. Examine samples in any order you would like. Describe each sample in your own words.
4. What are your initial reactions? What did you notice about it first? what attracted it to you? Why did you pick it up when you did?
5. What sensorial properties played a role here?
6. What does this die remind you of?
7. Have you interacted with this sample before? Have you interacted with this material before?

8. does this bring up any emotional connotations for you? what emotion is called to mind? Such as surprise, love, hate, fear, relaxation, etc
9. What are the most and least pleasing aspects of this material or this sample?
10. now, in thinking about the MATERIAL, and not the die, what might you use this material for?
11. What context might you see this material in?
12. Is the material associated with any other material due to its similar aesthetics?
13. Does this material evoke any kind of meaning?
14. How effective was this sample as a die?
15. Do you have any further comments on this sample?
16. Which dice set did you like best? Which did you like least? Why?
17. Were any of them surprising?
18. Would you like to see dice of any other material?
19. If you could change anything about your favorite dice, what would it be?
20. What would a happy die look like?
21. A sad one?
22. A tired one?
23. An energetic one?
24. What would a feminine die look like? A masculine one?
25. What would a die for your grandparents looklike?
26. What about for your best friend?

Ranking questions included the following:

1. Rank these samples based on (loudness) of sound produced when you roll them (soft to loud).
2. Rank these samples based on how warm they feel (cold to warm).

3. Rank these samples based on how hard they seem (soft to hard).
4. Rank these samples based on how shiny they are (dull to shiny).
5. Rank these samples based on how rough they are (smooth to rough).
6. Rank the samples based on how heavy they feel (light to heavy).

It quickly became apparent that participants without a design background had significant difficulty answering questions that asked them to describe concepts such as "sensorial properties." Furthermore, many users had difficulty responding when they were explicitly asked whether specific sample materials evoked any meaning or had any emotional implications. In future versions, this question was no longer asked explicitly, and instead participants were asked if samples and materials reminded them of anything or any contexts, which was met with much more success.

The in-depth interview portion was emphasized in this version, so users were unable to functionally make it through the semantic differential part due to exhaustion and loss of attention. The survey was cut down significantly through two more iterations. The initial version was conducted entirely on paper.

5.3.2 Beta Version

In this version, the in-depth questions were cut down to incorporate the seven seemingly most relevant ones based on previous user responses, but some questions were skipped as users incorporated elements of multiple questions in response to one question. The most significant alteration was that the third part was trimmed to eliminate bipolar pairs that seemed very similar both in connotation and in previous user response. From the initial Ashby and Johnson list, 13 pairs were ultimately used. A Likert-style scale was used for evaluation.

Furthermore, some dice samples were removed to eliminate pieces that did not significantly contribute unique property combinations or material compositions, based on the ability or inability of participants to distinguish between the materials in the initial round, as described in subsection 5.2.4.

5.3.3 Final Test

In the third iteration of the test, it was determined that the primary purpose of the ranking portion was to familiarize the users with the samples, so for the future surveys, two to three material samples were selected at random from the initial set of

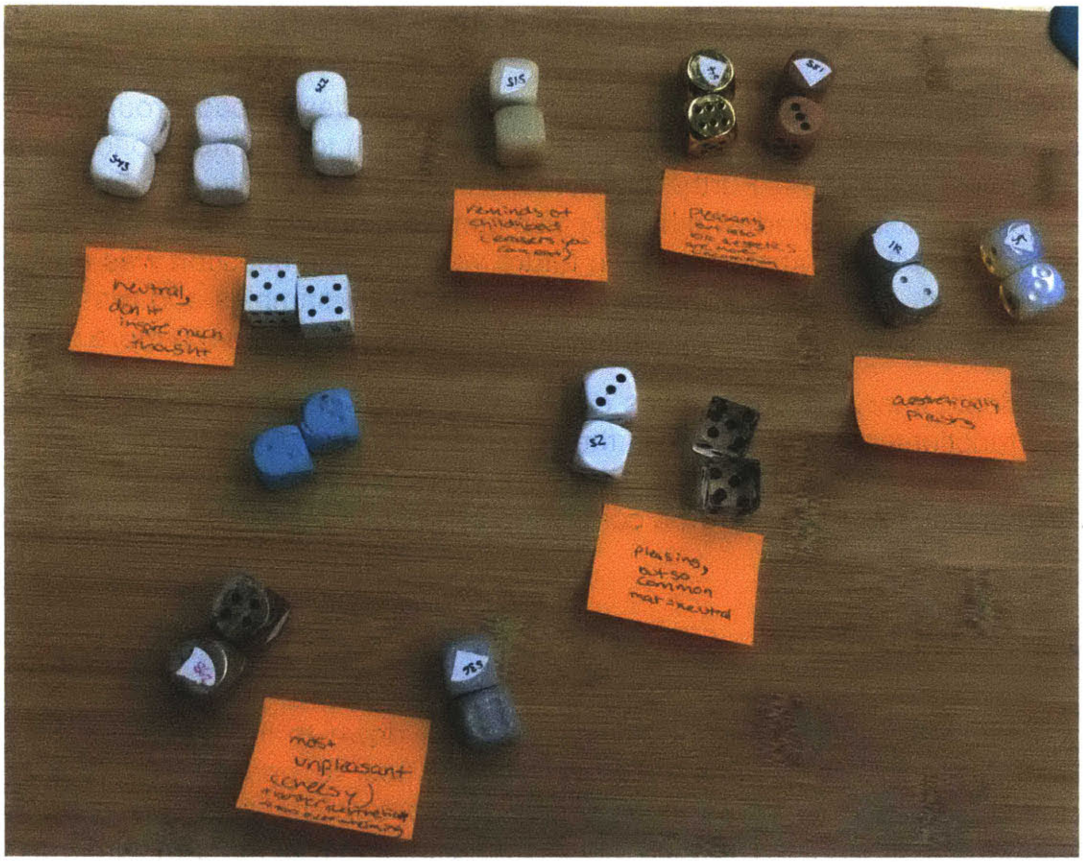


Figure 5-18: User-produced mapping

six for each participant, shortening the length of the test. The consolidated semantic differential section was digitized, as was the demographic section, for speed of use both for the participant and for the examiner when analysis occurred. The demographic section was expanded to include open-ended spaces for users to include words they identify with, in addition to traditional, pre-determined categories.

In total, 15 participants completed the study. This is realistically not a large enough sample size with which to parse out demographic data, but it provided a platform from which different methods of analysis and clustering could be explored.

5.4 Results

5.4.1 Procedure for Analysis

The majority of the analysis for both experiments was conducted using the scikit library in Python. An immense amount of information was collected during the experiment, and multiple modes of analysis were used. Initially, rankings of samples from the bipolar adjective sets in section three with plotted against eachother, as explained in subsection 5.4.2. Pearson correlation values were calculated to examine the relation between these attributes, which is explored in subsection 5.4.3 and subsection 5.4.4. Material properties were correlated with these attribute descriptions to uncover any fabrication trends. PCA and K means (subsection 5.4.5, subsection 5.4.6) clustering tests were performed to evaluate the underlying structure of the data set. Ranked data was analyzed, but ultimately, due to the decision to provide participants with only 2-3 ranking questions in the interest of time, an inadequate number of answers was collected for this question. Finally, the open-ended responses and stories were collected and categorized in subsection 5.4.8.

5.4.2 Attribute Correlations

As a starting point for analysis, the data was restructured by taking the average of all user responses for each sample for each adjective word, and then plotting those adjective pairs against each other. The average ranking of each material along each attribute was a basis for the majority of the calculations explained in this chapter.

	Pleasing	Masculine	Classic	Cozy	Aggressive	Mature	Futuristic	Exclusive	Rugged	Elegant	Friendly	Formal	Humorous
Pleasing		0.368	0.027	0.564	0.696	0.402	-0.165	0.426	0.514	0.932	0.235	0.769	-0.184
Masculine	0.368		0.089	-0.128	0.462	0.465	-0.152	0.214	0.586	0.214	-0.216	0.297	-0.480
Classic	0.027	0.089		-0.030	-0.234	0.243	-0.691	-0.768	-0.126	-0.050	0.622	0.107	-0.330
Cozy	0.564	-0.128	-0.030		0.121	0.058	-0.408	0.218	0.016	0.453	0.582	0.153	0.525
Aggressive	0.696	0.462	-0.234	0.121		0.394	0.094	0.713	0.716	0.703	-0.366	0.815	-0.098
Mature	0.402	0.465	0.243	0.058	0.394		-0.523	0.128	0.672	0.525	-0.142	0.586	-0.533
Futuristic	-0.165	-0.152	-0.691	-0.408	0.094	-0.523		0.347	0.017	0.347	-0.511	-0.212	0.005
Exclusive	0.426	0.214	-0.768	0.218	0.713	0.128	0.347		0.446	0.480	-0.584	0.419	0.223
Rugged	0.514	0.586	-0.126	0.016	0.716	0.672	0.017	0.446		0.575	-0.379	0.575	-0.384
Elegant	0.932	0.214	-0.050	0.453	0.703	0.525	-0.123	0.480	0.575		0.056	0.852	-0.256
Friendly	0.235	-0.216	0.622	0.582	-0.366	-0.142	-0.511	-0.584	-0.379	0.056		-0.145	0.140
Formal	0.769	0.297	0.107	0.153	0.815	0.586	-0.212	0.419	0.575	0.852	-0.145		-0.312
Humorous	-0.184	-0.480	-0.330	0.525	-0.098	-0.533	0.005	0.223	-0.384	-0.256	0.140	-0.312	

Figure 5-19: Correlations between attributes

This method allows for rapid understanding of the ways in which these adjectives are related in the context of this experiment. **Pleasing** and **elegant** were strongly positively correlated, as were **formal** and **pleasing**. Masculinity was positively correlated with a label of **aggressive**, and a label of **mature**, while it was negatively correlated with a label of **humorous**. The descriptor of **classic** was negatively correlated with the descriptor of **exclusive** and with the descriptor of **futuristic** (as would be expected), but positively correlated with the descriptor of **friendly.** This is particularly interesting when placed in the context of the qualitative responses: when asked to select a die material for their grandparents, respondents frequently selected **classic** materials with the explanation that such materials would seem comforting and familiar to those afraid of change. Based on the correlations, this may also be because users subconsciously also find **classic** materials to be friendlier than newer (**futuristic**) ones.

As would similarly be expected, **friendly** and **cozy** were positively correlated, while **cozy** and **futuristic** were not. **Aggressive** was correlated positively with terms including **exclusive, formal, rugged,** and **elegant.** A label of **mature** was positively related to **rugged** and **formal,** but negatively correlated to **humorous** or **futuristic.** As follows from the analysis of **classic,** the **futuristic** labelling was negatively related to the **friendly** labelling, and, logically, a rating of **exclusive** was negatively correlated with a rating of **friendly. Exclusive** and **aggressive** were also positively correlated. Interestingly, the label of **humorous** had primarily negative correlations and no strong positive correlations.

These results indicate that a die that appears masculine to a user is likely to also appear aggressive, while a die that seems cozy is unlikely to seem futuristic. This has interesting implications when added to the understanding that more classic and cozy materials were selected for some groups of individuals (i.e. grandparents), while more novel and unique (futuristic) materials were indicated for others (i.e. best friends).

5.4.3 Pearson Correlations

Based on the pearson correlation coefficients, density and **aggression** appear to be strongly correlated. When I shared this story, a friend he stated that this made sense because "you can never hurt someone with a fluffy pillow," highlighting the intuitive nature of this result.

Masculine and thermal conductivity, **exclusive** and **aggression** and thermal conductivity are also correlated, which is interesting for two reasons: metals typically have high thermal conductivity, and we perceive those surfaces as cold. Thus, the next logical step is to assume that users would perceive metallic samples as more masculine, exclusive, and aggressive than others, which proved to be true in

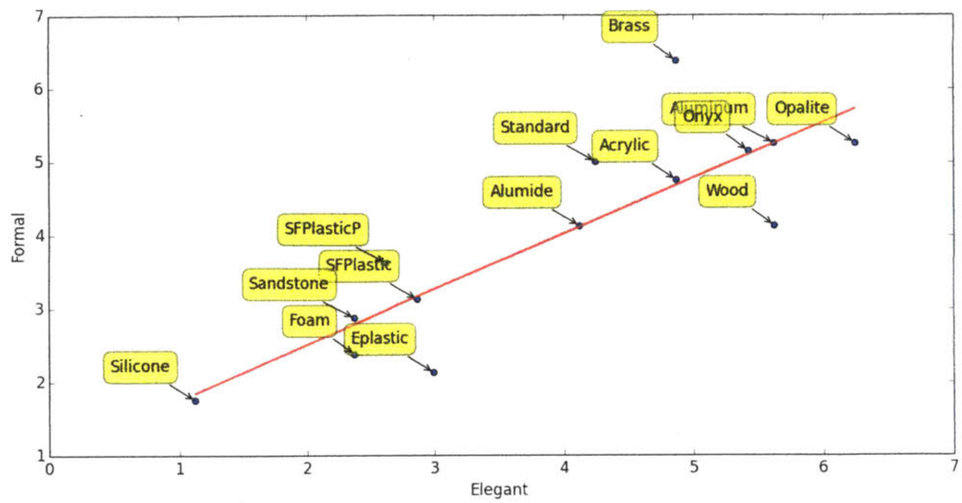


Figure 5-20: An example of strongly correlated attributes, this case 'Elegant and 'Formal'

	Attribute/Density	Attribute/ThermalCond	Attribute/Roughness	Attribute/Reflectance	Attribte/COR
Pleasing	0.387	0.416	-0.419	0.328	-0.459
Masc	0.323	**0.663**	-0.012	0.206	-0.306
Classic	-0.107	-0.320	-0.016	0.141	-0.280
Cozy	-0.020	-0.350	-0.300	0.057	0.029
Aggressive	**0.775**	**0.726**	-0.395	**0.602**	-0.533
Mature	0.171	0.165	**-0.427**	0.055	**-0.588**
Futuristic	-0.085	0.413	0.005	**-0.256**	0.439
Exlclusive	**0.607**	**0.565**	-0.133	0.384	-0.113
Rugged	0.317	0.489	**-0.502**	0.089	-0.287
Elegant	0.392	0.367	-0.416	0.294	-0.550
Friendly	-0.382	**-0.527**	-0.124	-0.146	0.084
Formal	**0.682**	0.482	-0.358	**0.593**	**-0.788**
Humorous	0.057	-0.431	0.061	0.151	0.350

Figure 5-21: Correlation coefficients of material properties with emotional attributes

this experiment. Exclusive individuals are often perceived as "cold," in alignment with this ideas that surfaces that feel colder to touch seem more exclusive. On the other hand, a label of **friendly** was negatively correlated with thermal conductivity, indicating that as materials feel warmer, they feel friendlier, which intuitively makes sense.

Roughness was negatively correlated with **mature**, and with **rugged**, where the second was contrary to intuition. It is important to note that aluminum was ranked as the most **rugged** sample, and it has a relatively moderate to low roughness value, and thus may have had a dramatic influence on the trend.

For reflectance, there was a strong positive correlation with **aggressive** and **formal**, and a negative correlation with **futuristic.** Here again, aluminum may have skewed the data; aluminum was ranked the most futuristic sample by far, but it a reasonably low reflectance value, thus significantly impacting the correlation.

Coefficient of restitution (COR) had a very strong negative correlation with the attribute of **formal.** COR was also strongly negatively correlated with mature. This metric for 'bounce' had some positive correlation with **humorous** as might be expected.

These trends provide a basis for fabrication guidelines that can be used to construct emotive objects. Ultimately, this indicates that we view bouncier materials to be more child-like and informal, colder materials to be more masculine, smoother samples to be more mature, and denser materials to be more aggressive. Warmer materials are perceived as friendlier, and materials with higher reflectance are seen as more formal. As such, this sheds interesting light on our perception of concepts such masculinity as a whole based on our association with specific physical sensations. Do we, indeed, perceive masculine individuals to be colder? Are child-like individuals seen to be more energy or seem bouncier?

As with each of these analysis methods, statistical results must be examined in conjunction with qualitative information from users. For instance, reflectance and futuristic are negatively correlated here, but that could potentially be attributed to the fact that aluminum, which was ranked as one of the most futuristic materials both numerically and in the terms subjects used to describe it, has a low reflectance value. It is immediately apparent that more data and a larger sample size are necessary to further understand the trends.

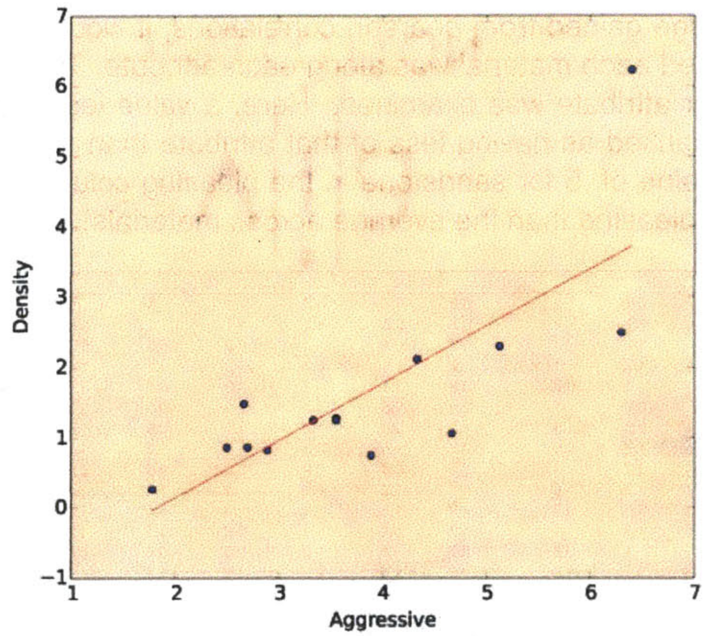


Figure 5-22: plot of the correlation between density and aggression

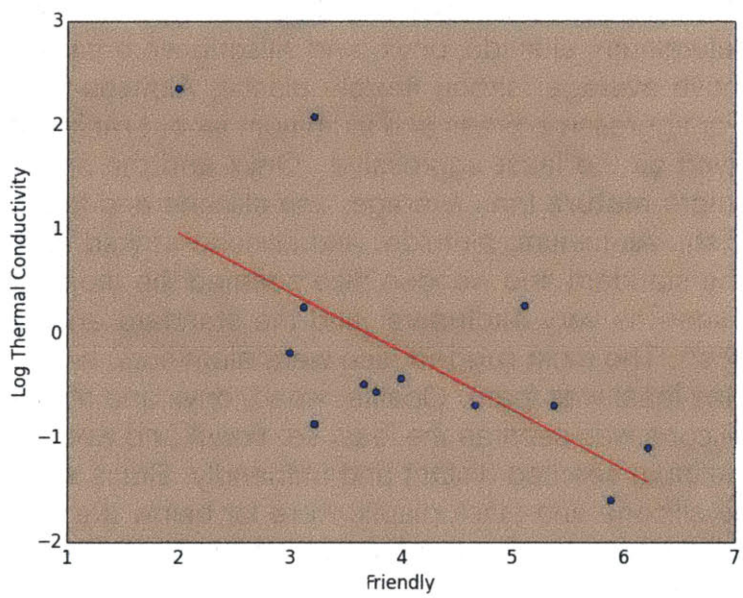


Figure 5-23: plot of the correlation between thermal conductivity and friendliness

5.4.4 Individual Material Deviation from the Mean

Using the knowledge gained from pearson correlations, it would be interesting to examine how loaded each material was along each attribute. To do this, deviation from the mean per attribute was examined. Here, a value less than one means the material was ranked as having less of that attribute than the average across materials (i.e. a value of .5 for sandstone in the pleasing column indicates that it was deemed less pleasing than the average across materials).

	Pleasing	Masculine	Classic	Cozy	Aggressive	Mature	Futuristic	Exclusive	Rugged	Elegant	Friendly	Formal	Humorous
Alumide	1	0.9	0.7	1	0.9	0.7	1.3	1	1	1	0.7	1	1.1
Eplastic	0.8	0.9	0.9	1	0.7	0.8	1.1	1.1	1	0.8	0.9	0.5	1.1
SFPlastic	0.7	1	1.1	0.7	0.7	1	1	0.9	0.9	0.7	0.8	0.8	0.8
Brass	1.3	1.3	1.2	1	1.7	1	0.7	1.3	1.1	1.2	0.8	1.6	1.1
SFPlasticP	0.7	0.9	1	0.8	0.8	1.1	1	0.9	0.9	0.7	0.8	0.9	0.8
Silicone	0.6	0.9	0.7	1	0.9	0.5	1.3	1	0.9	0.3	1	0.4	1.7
Opalite	1.4	0.5	0.8	1.3	1.1	0.8	1.2	1.2	0.8	1.6	1.3	1.3	1.2
Standard	1.1	1.1	1.7	0.9	0.9	1.4	0.5	0.5	1.2	1.1	1.3	1.3	0.5
Foam	0.8	0.9	1.2	1	0.5	0.6	0.9	0.6	0.5	0.6	1.5	0.6	1.2
Wood	1.6	1.3	1.2	1.6	1	1.2	0.6	1	1.1	1.4	1.5	1	0.9
Aluminum	1.4	1.5	0.6	0.7	1.6	1.2	1.6	1.4	1.4	1.4	0.5	1.3	0.4
Acrylic	1.1	0.9	1.3	1	1.2	1	1	0.8	1.1	1.2	1.2	1.2	0.9
Sandstone	0.5	0.9	1	0.7	0.7	1	0.9	0.8	0.9	0.6	0.9	0.7	0.8
Onyx	1.2	1	0.7	1.4	1.3	1.5	0.6	1.4	1.2	1.4	0.8	1.3	1.4

Figure 5-24: How Each Material Deviated from Mean Values

For the attribute of **pleasing**, the materials with the greatest deviation were wood, opalite, sandstone, and silicone, where wood and opalite were far more pleasing than average, and sandstone and silicone were far less pleasing than the average. For **masculine**, aluminum, wood, and brass were the farthest above average, and opalite was the farthest below. The standard dice was far above the average for **classic**, and aluminum, alumide, onyx, and silicone were far below. For **cozy**, wood was far above average, strong flexible plastic, Aluminum, and sandstone were far below. For aggressive, brass and aluminum far out-ranked the others, and foam was perceived as the least aggressive. Onyx and the standard resin dice were viewed as more **mature** than average, and silicone and foam were seen as much more childish. Aluminum, alumide, and silicone ranked above average as **futuristic**, and the standard and wooden dice seemed the most historic. Opalite and brass were seen as very **exclusive**, and the standard and foam dice were seen as the least so. The most **rugged** dice were aluminum, wood, and the standard dice, while the least was foam. Opalite, wood, onyx and aluminum projected **elegance**, and silicone was seen as the least so. Foam and wood were ranked as **friendly**, and aluminum seemed distant and unfriendly. Brass was viewed as the most **formal**, and silicone and elastoplastic were far below the mean for this. Finally, silicone and onyx were seen as **humorous** and aluminum and the standard dice were seen as the farthest from it.

Alumide, acrylic, and strong flexible polished plastic were the closest to average and thus the most "neutral."

5.4.5 Principal Component Analysis of Attributes

Principal component analysis was performed to reduce the attributes and ratings of materials down to underlying components. PCA can be used to determined meaningful elements that can be mapped onto certain material properties (i.e. if brass and aluminum have a high factor loading in one component, thermal conductivity may be a relevant dimension for that component). PCA would ideally allow the researcher to correlate the components with material characteristics. Using the PCA function, it was determined that 6 components accounted for 97% of the variance within the data.

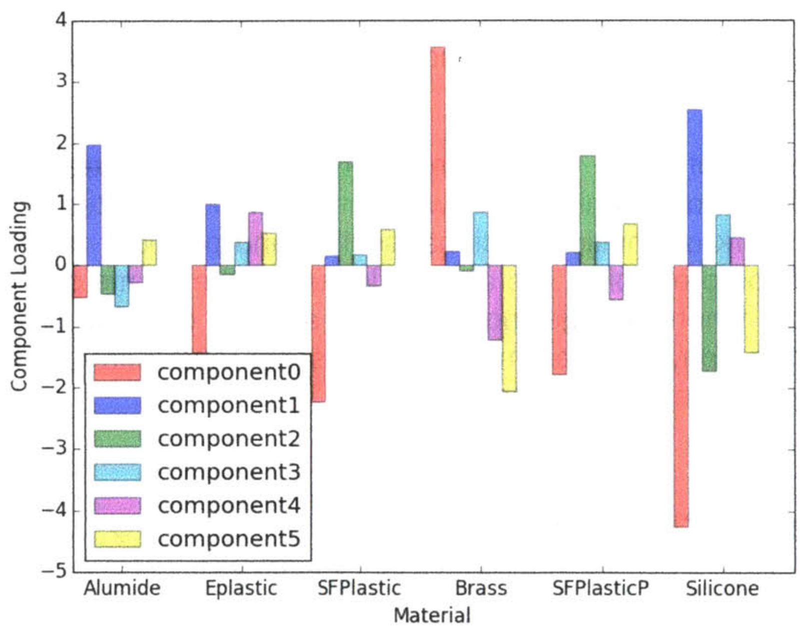


Figure 5-25: Principal Component Analysis (first half of plot)

In **component one**, brass, aluminum, and onyx have a strong positive loading, and foam and silicone have a strong negative. Elastoplastic, both of the strong flexible plastics, and sandstone had moderate negative loadings and wood, and opalite have moderate positive loadings. While brass, aluminum, and onyx are three of the densest samples (with opalite close behind), based on the materials with negative loadings, it is unclear that this is the contributor to this component.

In **component two**, Aluminum has a strong positive loading, followed by silicone, though less so. The standard and wooden dice have a strong negative loading. Foam has a moderate negative loading and alumide has a moderate positive loading Perhaps this component reflects some element of expected vs. unexpected materials in dice, or alludes to the tags of foreign or scary that users assigned to alumide and silicone.

In **component three**, opalite has a strong negative loading, and there are no materials with a strong positive loading. Strong flexible plastic, standard, and aluminum are moderately positive, and silicone and wood are moderately negative.

In **component four**, onyx has a strong positive representation, while no materials have a strong negative representation. Opalite and aluminum are moderately negative.

In **component five** wood has a moderately positive loading, and opalite and brass have a moderately negative loading.

Finally, in **component six**, opalite is moderately positive, and brass and silicone are moderately negative.

While the meaning of these components is not immediately apparent, this test can provide a basis for examining the ways in which these materials are related. In Bergmann's work on multidimensional scaling and physical measurements of roughness and compressibility, the authors looked at the norms of the vectors fitted in the space, where a larger norm implies a better ordering of the stimuli in the direction of the physical parameter it represents, and therefore that physical parameter is a more important factor [81].

5.4.6 K Means Clustering

K means clustering was used to cluster the material properties around the attribute designations. In this iteration of K means clustering, the materials were clustered based on the values that subjects assigned to each material for each adjective attribute (i.e. pleasing).

Elbow plots (as in Figure 5-27) are used to determined the number of clusters present in the data. Based on the elbow plot for this data set, either seven or four clusters seems appropriate. With seven clusters, the clusters are as follows:

1. silicone
2. brass and onyx
3. opalite

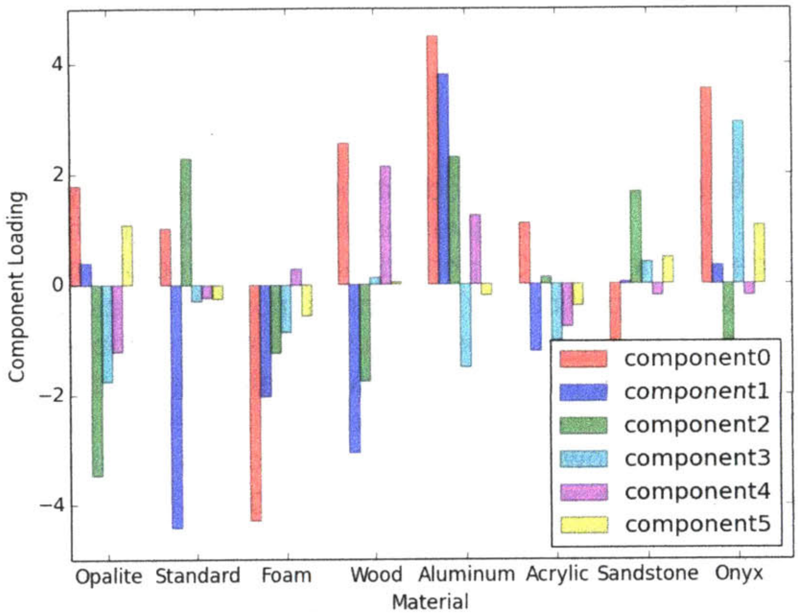


Figure 5-26: Principal Component Analysis (second half of plot)

4. alumide, elastoplastic, strong flexible plastic (both varieties), sandstone
5. acrylic, wood, standard
6. foam
7. aluminum

Here we see that all of the 3D printed dice from shapeways are grouped, indicating that their attribute rankings were similar. Brass and onyx were given similar associations; they were two of the heaviest samples, and both were associated with quality in the open-ended questions. In Figure 5-20, for instance, it is apparent that these samples fall close together on the trend line. Acrylic, wood, and standard dice were all described as being familiar to users, and participants were easily able to list contexts in which they had used these dice and these materials. Aluminum, foam, opalite, and silicone were all materials that surprised or confused users, though based on this clustering iteration, they were not surprising in the same ways, and instead were deemed to be unique.

For the four cluster version, which has less resolution:

1. alumide, elastoplastic, both of the strong flexible plastics, silicone, foam, sandstone

2. brass,opalite, onyx
3. standard, wood, acrylic
4. aluminum

In this more condensed iteration, wood, standard dice and acrylic dice are still clustered together, which is logical given users' familiarity with the materials and dice. Foam is added to the list of 3D printed materials, none of which were ranked as particularly pleasant or particularly extreme in most attributes. As indiciated by material deviation from the mean (subsection 5.4.4), many of these materials were ranked as being close to the mean, or neutral. Opalite, onyx, and brass are now grouped, indicating that their unique nature produced somewhat similar responses, while aluminum is still in its own cluster. This is logical as aluminum was far from the mean for many attributes, and thus elicited strong reactions.

K means clustering was used to cluster the samples based on material properties. The elbow plot was less clear for this iteration, so the three cluster and six cluster versions are shared here. For the three cluster version, which has less resolution:

1. alumide, flexible plastics, silicone, foam, sandstone, opalite, elastoplastic, standard, acrylic, wood, onyx
2. brass
3. aluminum

While this is an extremely course clustering, it does indicate that aluminum and brass act as outliers, which fits with the understanding gained from pearson correlations discussed above. The properties of these samples were so far removed from the other samples that they significantly impacted correlations.

With six clusters, the grouping is as follows:

1. elastoplastic, silicone, sandstone
2. aluminum
3. brass
4. standard, acrylic, opalite, strong flexible polished plastic
5. onyx

6. wood, foam, strong flexible unpolished plastic, alumide

Here again we see aluminum, onyx, an brass serving as outliers, which may explain or complement **component 1** of the PCA results. Standard and arcylic samples are still bunched together, and the rough, sticky elastoplastic, silicone, and sandstone samples are grouped.

When combined with the components from PCA, this can be one piece of a multi-element analysis to determine how the materials are related based on attribute rankings.

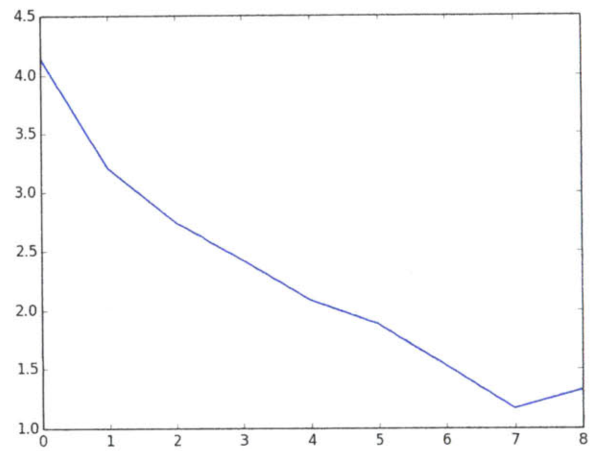


Figure 5-27: Elbow Plot used to determine number of clusters for Material Attributes

5.4.7 Analyzing Ranked Data

Based on the average values of each individual's ranking, the dice can be ranked in the following order of least to most likely to use: elastoplastic, silicone, polished strong flexible plastic, unpolished strong flexible plastic, alumide, sandstone, foam, onyx, brass, opalite, aluminum, standard, and finally wood.

Histograms were produced for all of the ranking questions completed, however due to the decision to have participants complete only two or three ranking questions each for the sake of time, there was not enough data to accurately analyze these results. It can be seen on a broad level, however, that user preferences were generally aligned with the hypotheses presented for this study. Brass and aluminum, with their very loud rolls and high density, were appreciated, but not the most likely to be used. Elastoplastic and silicone were in the regime of being too bouncy to be pleasant.

5.4.8 Qualitative Analysis of User Interviews

Extensive open-ended interviews were conducted with the subjects as part of this study. Since these interviews were designed to collect stories and look at the free-formed labels, associations, and classifications that participants generated, the first-pass method of analysis was to collect stories and key words. These interviews were then coded based on positive and negative descriptors, notable actions, approaches, and aspects of dice that were mentioned. Frequently used words were tallied and tagged based on demographics.

Some of the most fascinating insights can be drawn from the manner in which participants approached the topics and questions. As a general note, while the objects were dice, many participants actually did not roll them. One graduate student in an engineering field asked many questions about the thermal conditions and environmental properties that would impact the responses to ranking questions. Another engineer ranked the shininess of dice by pulling out the flashlight of their phone and examining each specimen. In contrast, one subject with a background in textiles evaluated warmth by touching the samples to their cheek and rubbed them against the back of their hands to test how soft they were. The same individual threw the dice in the air and judged the weight by how much pain (s)he experienced in the palm when the dice landed. One user specifically referred to an aunt who always dressed really well when evaluating the elegance of the dice.

Two participants approached the mapping task by writing out a list of emotions first and one astutely remarked that comforting is the combination of sleepy and happy. On average, those with a design background found it much easier to imagine if samples were in a different context or in figurative situations than those without such a background. One designer explained the levels of response and interpretation as they completed the mapping: "the first level is feeling-based, visceral reactions like pleasing. The second level is more cognitive or memory based." Though no participant explicitly stated this, it is apparent from their responses that the others also experienced these levels.

When explicitly asked what aspects of each die were important and impacted desirability, nine participants mentioned weight, nine mentioned feel, seven mentioned smoothness (two said texture more broadly), five mentioned clarity of number, three mentioned sound, two mentioned temperature, ten mentioned roll dynamics or direction, two mentioned entropy, and two mentioned bounce. Ten individuals brought up visuals and aesthetics, two mentioned material and color, two mentioned reliability, and two mentioned sturdiness. One individual discussed previous affection for the material, one mentioned familiarity, and one mentioned functionality. One participant explained that they "felt happier touching the dice that were the most like smooth marbles (cold, smooth, hard, hefty, or shiny)" and another said that they liked things that were "cold and heavy."

In describing the dice, a plethora of interesting terms were employed. Patterns of words often emerged. For **brass**, five people described the pieces as heavy, where two people specifically mentioned the term bludgeon or damage, and one person elaborated with the term harsh. Two people described the sample using the words bling or metallic, and one used the terms steampunk and disco. Three people described the dice in terms of legitimacy, status, solidity, and weight, with one person mentioning power, one mentioning luxury, and one mentioning the relation between weight and quality. When asked about what die would be given to a best friend, one participant specified that they would pick a heavy material to provide a substantial gift. Four participants described the brass as obnoxious, tacky, sleezy, or revolting. One subject mentioned this in relation an association with money, three mentioned Las Vegas and casinos, and one mentioned loud. Finally, two mentioned art or sculpture. Overall, twelve separate positive words were used, and twenty negative words were used.

For **foam**, five individuals mentioned kids and toys, with two people clarifying the description in terms of crafts or artists, one describing the dice as cute, and one describing the dice as funny. Four subjects described them as soft, squishy, or mushy; one compared them to kittens, one compared them to packing pellets, and two specified that they were fuzzy or fluffy. Two described the dice as light, and two mentioned feathers. Two associated the dice with safety. According to two participants, the dice exhibited unexpected properties, and five said the dice felt bad. One participant mentioned that they seemed poorly manufactured, one said they were intended for one-time use, one said they were not durable, and three described them as cheap and lame. Overall, sixteen positive terms were used, and eighteen negative terms were used.

With the **wooden** dice, five people used terms relating to classic, old school, historic, rustic to describe the samples. Three subjects referred to family, and four referred to nature or trees. Four individuals thought of games, and one explicitly stated that wood "makes [them] feel sharper when used, because of an association with strategic games." Four participants mentioned calm, peace, or comfort. Five instances of descriptions of home or furniture occurred, and one association with craftsmanship. One subject stated that they are very tactile, [(s)he] like[s] to touch wood, and [(s)he] like[s] old houses with wood. 31 positive terms were collected, and only one negative term.

Elastoplastic was compared to sugar by one person, wax, soap, or candles by four, bones and cartilage by two, and exfoliating cubes by one. Two people stated that the dice appeared edible. Four people said that the samples reminded them of erasers, and three said that they were flaky and seemed to disintegrate. Two commented on the bouncy and fun nature of the dice. Three participants found them to be foreign and unknown, two found them scary, and two found them unpredictable. Three described the dice as surprising and novel, and two described them as unpleasant. The images used for this set was by far the most vivid, and overall five positive terms were used and ten negative ones were used.

Opalite was received as pleasant, stylish, pretty, and unique by six individuals, with one mentioning decadence and luxury, and one comparing them to jewelry. One participant described the set as deceptive, fake, and cheap, one described them as a "snoozefest," and one described them as "new-agey." The dice seemed similar to rainbows, holography, and glass by one person each. One participant found them scary, but another considered them to be his/her favorite sample. In total, ten positive terms were used, and three negative ones.

The **strong flexible plastics** were compared to sugar by three individuals, sandpaper and scratching by two, chalk by three, and bones or teeth by two. Two participants mentioned that they seemed to disintegrate, two found them unpleasant, and two found them bland. Overall, no positive words were used, and seven negative words were used.

Aluminum was described as futuristic or similar to robots by three, with one individual stating that "its like robots are taking over, and machines are everywhere." Six participants mentioned factories, machine shops, or industrial references. Two found the aluminum to be unusual or unique, two found the dice to be cold, one described them as steampunk, one found them artsy, and one found them to be metallic. Aluminum and wood had the most cohesive descriptions, where people used very similar terms to describe the samples. Many of the words used to describe aluminum were not evidently charged as positive or negative (they were merely descriptive terms), but two were clearly positive and two were clearly negative.

Standard dice were reported to be conventional, classic, and standard by five and boring by two. Four people mentioned games, one mentioned family, and one mentioned casinos. Few descriptions were used, potentially because these dice are so common. Five positive terms were used, and three negative ones.

Acrylic was described as generic, normal, or classic by five individuals, and boring by two. One person found the set to be lame, one found the set gimmicky, one found the set to be tacky, and one considered this set to be their favorite. In the same sentence as describing the dice as gimmicky, one participant also described them as "girly" in comparison to the more masculine aluminum. Overall, four positive terms were used, and six negative ones.

Silicone was described as bouncy by four participants, unpredictable by four, and fun by two. One found them to be stupid, and two found them useless. One said that the set were squishy, and one found them to be interesting. Four people mentioned that the dice were reminiscent of kids, toys, or childhood, and five associated the set with crafts or prototypes. Two found them to be alien, foreign, and scary. Two described the surfaces as sticky. Five positive terms were used, and eight negative ones.

Sandstone was grouped similarly to many of the 3d printed samples: two people described them as looking like food and seeming edible. One compared them to sugar, and one to marshmallows. The sandstone was compared to soap, teeth, sand, chalk, and stone. Very few terms were clearly positive or negative.

Alumide was found to be sparkly, glittery, and paint-like by two, interesting by one, and similar to crafts by one. One individual found them to be peaceful, two people described them as weird or outliers, and two found them to be scary or foreign. One subject compared the dice to pebbles, and one stated that they looked like files for filing nails. Four positive terms were used, and three negative ones.

Onyx was received positively overall, with three individuals relating them to quality or fanciness. One person said that the dice would garner external validation, and one said that they seemed like they would endure. Two brought up crafts or sculpture, and one mentioned earthiness and geology. The dice were seen to be discovered, or personal by one, and tacky and "new agey" by another. Six positive terms were used, and two negative ones.

At the end of the interview, participants were asked what dice they would provide for their grandparents, and what dice they would give their best friend. In describing materials for grandparents, users employed much more abstract and similar terms than the nuanced answers given for best friends. Five people selected wood, one described the dice as soft, one specified luxury, one specified old-fashioned, and one said large. Three people stated that they should be easy to read, and one required big dots. Familiar, conventional, comfortable, safe, and classic were common descriptors. Five individuals selected "standard" dice. When asked why, one individual said "standard dice... dice are not really relevant to anyones life." Another specified that they would select "wood or standard or bakelite or hardened because I guess I dont know why." A third shared the fact that they selected standard because "old people are afraid of anything usual or any change." In contrast, when selecting qualities of dice for friends, they used terms such as best quality, more interesting, glittery, distinctive, contemporary, unique, and novel. In some cases, specific materials were selected based on material ("wood because shes an earthy and woodsy person"). There are interesting parallels between the dice selected for grandparents and best friends here, and the correlations between terms such as **cozy**, **friendly**, and **futuristic** mentioned based on pearson correlations, PCA, and K means testing.

5.4.9 Future Possible Analysis Methods

While the work outlined here delves into the richness of this data set, further analysis techniques could be conducted in the future to reveal deeper trends.

The maps created by users represent their interpretation of the similarities between samples and the categories present within the sample set. Qualitatively, these maps and clusters inform researchers on how subjects process information about the samples and derive meaning within the sample space. Quantitatively, these clusters could be analyzed mathematically, compared rigorously across the participant pool, and compared to structures such as K means analysis or PCA. In examining dice that are perceived as similar, researchers can gain insights into the context and broader significance of the samples. Multidimensional scaling could be employed to interpret the space of the sample set along specific dimensions. The ranked data could be assessed to understand how actual properties affect rankings, shedding more light on the relation between material properties and attributes. It would be helpful to create bins with which to analyze data, both from the ranking questions and with the qualitative answers, so that similar themes could be quantified and captured effectively in a way that is presently overlooked since the terms vary slightly. Standard deviations values and box and whisker plots could be produced to understand the variations in responses within the data set and evaluate how cohesive meaning was for each sample.

As was alluded to within this chapter, multivariate regressions should be conducted, both to account for the multifaceted nature of our perception of physical stimuli (warmth is not simply derived from one property, but the packaging of multiple aspects together) and to interpret how multiple properties come together. How do the variables and properties impact each other? Is brass aggressive because it is shiny and loud? Is wood friendly because it is has a high COR and low thermal conductivity? This type of analysis can be used to explore the contribution of demographic differences to perceptual responses, and the interaction between aspects such as sound and roll.

Finally, as mentioned in the introductory sections of this chapter, demographic analysis would be incredibly informative here- how did the individuals background, interests, job, or age impact results. One of the primary goals of such an approach is to identify the needs of members of different communities to determine whether people in different psychological states or environments respond differently to material stimuli and prefer certain ones over others. Essentially, this exploration would aim to produce material profiles of people, or a type of "Ashby chart" in which the x and y axes were material properties (i.e. soft and fuzzy) and the sections were types of individuals (i.e. women). To begin to chip away at the ambiguities presented by such a task, however, there are some fundamental questions that need to be answered. *How do we categorize people based on material property preferences and responses?* Ultimately, this would allow the exploration to reach a point at which parameters can no longer be separated as their whole contribution is much more significant than the individual components.

5.5 Conclusions

In the proposal for this experiment, the question was posed of the relevance of material differences on preference and whether these material differences would be perceptible to users. This study demonstrated clear evidence that within the same form, material differences were extremely relevant to user interpretation and perception - though size, shape, and color were held constant to the extent possible, human reaction to the samples varied immensely, and there were clear preferences. With many of the materials, there was significant agreement amongst participants in terms of vocabulary used to describe the sample, associations brought about by the sample, and attributes possessed by the sample. It is thus clear that material differences are perceptible and impactful - the sandstone dice was not met with the same reaction as the brass, which was not met with the same reaction as the wood.

It quickly became apparent that people approach materials differently, where engineers delve into the technical and struggle to answer the more abstract, and designers use completely different gestures and tactile interactions to evaluate, but these differences highlight the gap that makes such work so interesting. Despite this, some clear associations became apparent, especially with materials that were outliers in some dimension: samples what were overly bouncy were perceived almost universally as more immature than more predictable samples, weight was tied strongly to quality and value, and "soft", light samples were perceived to be safe. Aluminum was seen as industrial and futuristic, and wood was seen as homey, natural, and classic, and in both cases users exhibited significant cohesion in terminology. With samples that appeared to deviated from the mean less or appeal more "neutral," subjects were not able to differentiate or characterize them in a cohesive or meaningful manner, though ultimately the label of "boring" or "neutral" is telling in and of itself.

Also fascinating was the manner in which participants assigned and designated materials for others. People have abstract ideas about grandparents, but concrete ideas about best friends (dice for grandparents were repeatedly selected as standard, wood, or foam, whereas participants listed very creative and varying dice for best friend). This highlights interesting ways in which societal influences shape our assumptions, particularly around concepts such as aging.

Brass and aluminum, and to an extent onyx, served as outliers here, as is apparent in the K Means analysis, pearson correlations, and PCA. Many of the results that did not align with intuition may be attributable to how drastically brass varied from so many of the other samples, especially considering the fact that it brought about very strong associations and reactions and thus anchored the correlations (in a way that a neutral sample could not have done). Similarly, aluminum was far from the mean along many attributes, and far from the pack on many material properties. This indicates that more samples and more data points are necessary to create more robust guidelines, though the process and concept themselves are still potentially viable.

An aim of this study was also to identify and evaluate properties that contribute to the ideal dice, and this study made definite progress towards doing so. Reasonable weight (a trait repeatedly connected to quality), smooth finish, a predictable and somewhat linear roll, pleasing aesthetics, and avoidance of being too loud or damaging were all cited as contributing to positive evaluation of and experiences with the dice samples. This also answered the proposed question of whether certain properties may be more relevant, though further multivariate regression would be needed to understand the interplay between these properties.

The outcomes thus indicated some potential fabrication guidelines based on correlations that were established between material properties and descriptive emotional attributes, as shown in TABLE. While these properties will need to be manipulated intentionally and specifically to evaluate their impact in a controlled manner, these guidelines serve as a starting point from which to work.

The outcomes for this experiment demonstrated that this technique could be valid, and that concrete hypotheses in this space could be rigorously examined through experimentation to connect qualitative and quantitative metrics. Overall, the evaluation demonstrated that the intuition on concepts was broadly correct about how properties impacted likely use. This study inspires many follow-up opportunities, but demonstrates the viability of working to connect these aspects of user interaction with an object.

Through the process, a repeatable procedure for design and implementation of this scope of study was established. The same process was used to carry out the second experiment to build upon the findings of the dice study. The process also allowed for acquisition of skills and instrumentation needed to enable future experiments in this space.

5.6 Learnings for Future Tests

Many variations on this experiment could be made to uncover further information. One participant suggested providing users with both dice and material slabs (of the constituent materials) so that individuals could compare the two forms. Similar studies often provide participants with dimensions upon which to map samples, rather than leaving the prompt as open-ended as was the case here. Some of the questions could be altered to encourage more complex storytelling,such as asking participants to recount an instance when they felt comforted by a material. Furthermore, some simple formatting matters could be altered and improved: people may have preferred digital sliders in the survey rather than gradated rankings, and one participant stated that it would have been better to have the ability to snap digital images of dice into the spaces or rank them in order rather than physically writing out sample numbers. For some participants, pictures of their rankings and mappings were taken here to skip this step. Having more participants in the study would have allowed for more statistically significant results, and for examination of individual differences and the role of demographic, field, or interest differences. After completing the study, I became aware of the Behavioral Research lab at MIT. Using this resource could allow me to access a broader cross-section of the Cambridge/Boston area population and conduct larger studies.

One of the most apparent takeaways from this work, as made apparent in the Okamoto review, was that the results were severely limited by the selection of materials. Much more data would be needed to get more accurate results. According to Media Lab statisticians, for each variable, at least ten samples are usually required in order to get truly reliable results (meaning that for the six properties examined, sixty samples would have been necessary). In future experiments, it will be imperative to acquire much greater amounts of data using more material samples. It would, perhaps, be interesting to pick fifty samples and have users evaluate them along one property. By systematically doing this across properties, more robust conclusions could be drawn.

The biggest concluding question, however, was whether or not the takeaways would be the same if the object has been nonfunctional. Further experimentation should be conducted to approach this question.

While the primary goal of these experiments was to determine the importance of material properties in evaluation of dice, an interesting parallel exploration would return to the theme of storytelling. Dice have a rich cultural and social history, and as such they provide a fascinating opportunity to explore their use and meaning in a broader context. It would, perhaps, be interesting to observe their significance in casino settings and determine how material variability could alter the course of gambling. This concept is further discussed in chapter 8.

6 Exploring the Impact of Materials on Behavior

Phone Case Study

"When brand is built from the inside-out, elements of materiality and making matter most. Design plays the role of connecting materials to a bigger story."

– Mike Ashby and Kara Johnson, *Materials and Design* [9]

6.1 Approach

The first experiment of this thesis was an exploration into the methods and feasibility of assessing human emotional response to material samples. It provided a broad picture of the impacts of material properties on responses and connections to samples. For the second study, I aimed to focus on more targeted, rigorous hypothesis-based testing. With the initial dice samples, the novelty of the samples may have contributed significantly to user responses. To gain a more realistic understanding of the potential impact of tailored material properties on behavior and emotional response, in the second study, users were asked to interact with mobile phone cases for an extended period time. Over the course of the study, they participated in tasks that were natural to the phone environment: reading curated news articles, skimming through their email inbox, or making phone calls, in addition to their normal phone tasks.

Hypotheses for this study were based on existing literature on the impacts of physical stimuli, as outlined in section 2.2. For each of the three research questions examined, a specific material property was examined (density, thermal conductivity, or roughness). This study was implemented around a single case experiment design, where each individual served as their own baseline. To complement the longer-term interaction, a pre-test was conducted in which users were asked to complete all relevant study tasks for ten minutes and respond. Between these two approaches, the implications of the the case materials were explored on both a micro and macro level. This studied was designed with guidance from Roz Picard, Natasha Jaques, and Akane Sano from the Affective Computing group. As with the dice experiment, this work experiment was reviewed and cleared by the Internal Review Board (COUHES) under protocol number #1601348759. It was carried out with assistance from the MIT Behavioral Research Lab.

6.2 Using Phone Cases to Understand Individual Responses Over Time

6.2.1 Reasoning

Coming out of the first experiment, it was apparent that examining individual differences could yield extremely different and intriguing results. This second experiment was also an attempt to get around the novelty factor that impacted subjects' perception of the dice. Through this study, experimental materials were placed in a setting with which users constantly interact, without causing undue burden. The most interesting and practical option was thus iPhone cases- the average person is in almost constant contact with their phone, or at least knows its location at all times. By crafting cases out of various materials, we explored the ways in which individuals responded to different cases, and the ways in which their responses changed over time. For convenience, MIT students were the focus of this study. In determining the phone case model, a large sampling (over 50) students was polled to determined the most commonly owned iPhone, with the iPhone 6 ultimately proving to be the most prevalent.

The intention with this study was to zoom in on very specific research questions and alter as little as possible about participants' interaction with their phone in order to understand their response to the material. This informed the selection of tasks, all of which were thought to be very natural uses of the phone. One key benefit of building for the iPhone 6 was the guarantee that all produced objects were the same size. The cases were all made in the same color (black/grey) and were built off of the same base thing plastic case, eliminating color and style as variables.

This also ensured some minimum protection for the phones while maintaining the simplest form possible.

The process developed in the previous experiment was adapted as follows:

1. **Select object based on desired exploration:** In this case I wanted to understand our perception of materials through a narrow perspective over a longer time range materials, and if and how material interfaces impact our behavior.
2. **Select relevant technical properties to examine.** In this study, I used existing literature in haptic sensations and embodied cognition to determine properties that typically have a significant, measurable impact on behavior (weight, roughness, and temperature).
3. **Select the range of materials to be examined.** Selected fewer here to be more focused and cuz the previous study was very burdensome, especially in terms of analysis and material testing
4. **Select and acquire access to the tools needed to effectively measure these properties.** The same tools were used in this experiment as in the previous experiment.
5. **Measure the relevant properties.** Here, roughness values were collected on the DekTak, density was calculated using the scale, and thermal conductivity was pulled from manufacturer provided values.
6. **Design questions and activities to gauge the emotive aspects of the materials.** Adjectives and hypotheses were drawn from relevant literature.
7. **Conduct multiple rounds of testing:**
8. **Select analysis methods:** For single case user studies, rapid evaluation can be conducted through visual scanning of temporal data, and more in-depth statistical investigations can follow as needed.
9. **Analyze results.**
10. **Visualize results and use findings to select the next experiment.**

6.2.2 Single-User Case Design

In contrast to the previous study that used a traditional group testing model, for this experiment, a single-case experimental design was used (informally referred to as "n=1" testing). Group testing methods tend to paint a broad picture of subject responses, but lose the temporally dynamic features of behavior. In his work on Single Case Experimental Design, Dallery equates this to "underusing the resolving power of a microscope." [19] In single-case designs, the "treatment" or experimental condition is limited so that variation between subjects is minimized, and frequent monitoring of or interaction with the participants is needed to track the effects of experimental conditions. This method allows researchers to compare each subject to their own baseline, where changes from the baseline state are examined through replication within and across participants [19]. As such, this type of experiment allows researchers to systematically examine the impact of components by introducing and removing treatments at specific times. Variables are systematically manipulated to rule out alternative hypotheses to explain any changes. By combining a series of single-case experiments, small, meaningful changes can be examined [19].

Most single-case experiments begin with a period of observation during which a baseline is established from which behavior could be predicted [19]. This serves as a control condition in which the dependent variable is measured - the baseline period is complete when the dependent variable has stabilized to a point where future responses could be predicted [19]. In situations where the behavior or response begins to change at the end of the control period, it is difficult to interpret the results of the experimental condition.

Single-case design thus provides a method for comparing relative intervention success. Components can be examined by systematically introducing treatments or independent variables. Various methods can be used to achieve this, including drop-out analysis (where a baseline period is followed by introduction of the entire suite of treatment options and elements are dropped one by one), or add-in analysis (where components are either examined individually or added incrementally to reach the full option list) [19]. Often, adding elements individually or alternating treatments proves most effective. In all cases, the ordering of experimental conditions is important and should be tested and considered. Some experimenters intersperse periods of treatment with periods of time in which subjects are allowed to return to the baseline.

Another advantage of this method is the ease with which it can be analyzed visually. Since the data is usually presented in a time series, clinically significant changes should be visually apparent [19]. This reiterates the importance of allowing a stable baseline to form, a process that usually requires at least five data points [19]. More rigorous analysis can then be performed by extending regression lines from the baseline to predict what responses would have been with no intervention and then counting the data points that lie above or below the prediction line once the treatment is added [19]. Binomial formulas can be used to assess the significance of these results. In this experiment, the data points were daily responses (collected in both the morning and evening), and the experimental treatments were the various cases.

6.2.3 Limitations

Similarly to the dice experiment, there were some basic limitations to this experiment, made even more stringent by the fact that subjects were asked to carry the samples with them for two to three weeks. As such, while some samples were produced with the intention of producing a stress response, there was an upper limit to the discomfort the cases could cause while still posing a feasible option. The cases needed to be of a reasonable weight and thickness so they could be carried in a normal manner, and the material could not hinder usage of the phone in any significant way. Furthermore, by nature of being a case, the sample needed to provide some degree of protection. The case had to be robust enough to last seven days, while still being affordable to produce or buy. Most importantly, the materials had to be safe, nontoxic, and exclude common allergens.

6.2.4 Hypotheses

Research questions for this experiment were based off of existing literature (primarily discussed in Chapter 2, especially the work of Ackerman and team), and intuition developed from the first study. Initial hypotheses for this experiment were as follows:

1. Since weight has been associated with importance and seriousness, would denser cases make people perceive interactions/texts/news more seriously? Would it increase stress?

2. Numerous studies have demonstrated that warm stimuli can remedy feelings of exclusion and increase interpersonal warmth, so can materials with lower thermal conductivity make people feel less isolated or stress?

3. Since smooth surfaces have been shown to have a more calming effect on individuals than rough ones, does a smooth case make people feel more relaxed when using a phone to talk to family/friends? This question was posed by Thalma Lobel in her book, Sensations [47]. As stated by Wang in her work on the impacts of roughness on empathy, "roughness is more salient than form or size for touch: In fact, it is much more salient than other haptic attributes such as form or size (Klatzky, Lederman, & Reed, 1987) " [86]

6.2.5 Material Samples and Testing

Based on these hypotheses, materials were selected to highlight these properties. Having two cases exhibiting a specific material property for each research question allowed for more rigorous examination of the impacts, so cases were selected on opposite ends of the spectrum for contrast and to prove that any response that occurred was not just a stress response over receiving a new case. To examine the impact of density, a thick rubber traditionally used for carving was contrasted with balsa wood. The rubber is a blend of paraphinic plasticizer, calcium carbonate, titanium dioxide, styrene butadiene styrene synthetic rubber, white factis synthetic rubber, polysiloxane, magnesium stearate, calcium stearate. To test thermal conductivity, a thin sheet of aluminum casing was compared, again, to balsa wood. To test the impact of roughness, 600 grit waterproof sandpaper was contrasted with black vinyl. Cork, leather, birch, silicone, polycarbonate, polystyrene, and bamboo were all considered and eliminated due to confounding variations in size, color, or feel.

To hone in on one main parameter for each of these cases, the number of cases was limited to two per hypothesis.

6.2.6 Materials Testing Techniques

Testing for these samples was conducted in the same manner as testing for the samples for the dice experiment. The Dektak of the NanoStructures Laboratory cleanroom (under the Microsystems Technology Laboratories) was utilized, and manufacturer provided values of thermal conductivity were used.

Table 6.1: Material properties of phone cases used in study

Roughness (A)	**Thermal Conductivity (W/mK)**	**Density (g/cm3)**
Sandpaper	*Aluminum*	*Rubber*
43966.667	201.00	1.976
Vinyl	*Balsa Wood*	*Balsa Wood*
1534.100	.050	0.0733

6.3 Methods: Survey and Procedure

Though the main focus of this study was the single-case experiment design mentioned earlier, the complexity of our interactions with our phones implies that the

Figure 6-1: Examples of cases produced for the study)

material effect may get diluted, especially over the course of three weeks. In an effort to understand a more complete picture, the longer-term study was conducted in parallel with a 45-minute mini-test using randomized control testing. Both the three-week study and the briefer version involved the same baseline three tasks: skimming emails, placing a phone call, and reading a pre-selected article. As the content of the article could dramatically impact mood, trigger various emotions, or distract from the intended measurements, an online pre-test survey was conducted with a random sampling of college and graduate-school age individuals (not limited to MIT). A pre-selected collection of about thirty-five articles was sent out, and participants were asked to rate the pieces based on positivity to negativity of tone and content. To minimize unwanted variations in responses due to article content, only those ranked as "neutral" on average were selected.

As explained previously, this experiment is modelled off of single-case experiments typically used for health intervention. It is readily apparent that each day in an individual's life can differ dramatically, and two days cannot inherently be treated as equivalent. For instance, if an experimenter were to provide a participant with

Table 6.2: Considerations for task selection

Task	Place a phone call	Read emails	Read Standardized Articles
Pros	realistic interaction, natural	natural, easy to implement	can easily control across participants, can pre-test for expected positivity-negativity
Cons	irregularly time, hard to control, recipient may skew results, some users are averse to phone calls	unable to control type or tone of interaction, sender may skew results	content may skew results, content is limited

cases for two days at a time, the responses collected over a period including Friday and Saturday would probably vary dramatically from responses collected over a period including Monday and Tuesday. Thus, it was determined that to avoid the "day of the week" effect, a seven-day period for each participant should be examined for each case. Within this framework, there were many options for the study design:

- 1 week normal/no case, followed by one week treatment case (Half participants get one type, half another)
- 1 week baseline with normal case, then switch to treatment case (one per participant)
- 1 week baseline with normal case, then switch to treatment case (one per participant)
- 1 week treatment case A, 1 week baseline, 1 week treatment A (repeated intervention)
- 1 week baseline , 1 week treatment case A, 1 week baseline
- 1 week treatment A, 1 week baseline, 1 week treatment B
- 1 week baseline, 1 week treatment A, 1 week treatment B (randomize order of the two treatments)
- Staggered treatment duration per user

- 2.5 days of baseline, 2.5 days of each case, or keep switching after 2.5 days in a rotation

Initially, to collect information on a larger set of materials, the experiment was designed to provide users with seven cases. The case was to be swapped out on a daily basis in a pre-determined, random order, and each participant would receive all seven cases. This method proved to be overly complex, overly burdensome for the user, and would not allow for proper baseline development. Constantly changing the cases would also minimize the ability to understand how responses to the cases changed with time. Eventually, the model of establishing a baseline in the first week, and then providing the cases in a randomized order in subsequent weeks was adopted. For half of the participants, treatment a (case 1) was provided first, and for half of the participants treatment b (case 2) was provided first in order to mitigate ordering effects. This also provided the possibility for ending the study after two weeks if a significant effect had been demonstrated, thus saving time and cost related resources. For the first week, individuals were asked to complete the surveys and tasks while using their normal case (or no case if that was their standard practice). Furthermore, both for the sake of practicality and scheduling and to further avoid the impact of specific days and times, users were started in groups on different days spanning a five-day period. Thus, some users started and ended on Thursdays, while others started on subsequent days. Also users were surveyed during weekdays and weekends. To further understand the context of the individual's moods and responses, qualitative information about the events experienced that day were collected. Due to practical constraints, a desire to mimic natural situations, and a desire to minimize burden on the user, no constraints were placed on the phone call other than the estimated duration and the approximate window in which it should be placed. As will be discussed in the conclusion, this is a factor that may need to be altered in future experiments to further control variation.

The data was collected through self-report in a combination of in-person interviews (pre- and post- interviews, in addition to brief discussions and questioning during the case exchanges which were done in person) and online, daily survey forms. Two surveys were sent out, one in the morning (to be completed between the hours of 9-11 am), and one in the evening (to be completed between the hours of 8-10 pm). Thus, for the majority of participants, around 42 data points were collected for each parameter and measurement. Participants filled out the surveys around the same time each day. To be valid, most single user case experiments require at least five people, thus, for the three hypotheses, 15 total people (at least) were recruited. Participants in the longer-term study were paid $4 a day for completing two surveys and coming in to discuss the cases every seven days. Two subjects experienced scheduling issues that ended their participation after fourteen days (one experimental case and the baseline), and two dropped out entirely, leaving thirteen sets of data. The 31 participants (aimed for around 30, plus 5 control) in the 45-minute study were paid $15 for their time. The control group was asked to use their iPhone six without a case to do the same tasks.

In both the "micro" and "macro" versions of this experiment, questions were drawn from existing psychological metrics to promote validity in results. Questions were drawn from the Positive and Negative Affect Schedule developed my Watson and Tellegan to gauge general mood [79], from the Perceived Stress Scale of Cohen, Kamarck, and Mermelstein to measure stress [16], and the UCLA loneliness scale developed by Russell, Peplau, and Ferguson to examine isolation [70].

However, in the interest of time, especially since subjects were asked to complete this survey up fourty-two times, plus two times in person during case exchanges, the shortened versions of these tests were used. The 20 question version of PANAS, the three-item version of the UCLA loneliness test (validated in [30]), and the four-item version of the PSS (validated in [16])) were utilized.

Thus, the data collected was as follows:

Each morning:

- mood (PANAS)
- isolation (UCLA loneliness test)
- PSS
- read an article and ranked based on seriousness and positivity
- read emails and ranked based on seriousness, how quickly they need to respond, how connected they feel to the senders
- what they are going to do that day
- how they feel about today compared to yesterday
- how they feel about today

Each evening:

- mood (PANAS)
- isolation (UCLA loneliness test)

- make a phone call and talk about how they felt about phone call, how connected they feel to that person, how important the call was
- how they feel (scale of 1-7) about relationships, mental health, physical health, and work based on that day
- list memorable events
- predict tomorrows weather
- how often did they notice the case that day? How often do they touch the case?
- How relaxing will tomorrow be in comparison?

When they switched phone case:

- mood
- read email and responded to same questions
- open-ended questions about the case and their experiences

In addition, some qualitative questions were asked to contextualize the numbers and craft stories about the participants. As is well-known by the members of Affective Computing, asking indirect mood questions can provide interesting, more subconscious information about the subject. In studies related directly to monitoring emotions, researchers will ask about indirectly related concepts, such as how an individual feels about their phone that day. If the participant is in a pessimistic or foul mood, they will project that feeling in the manner that they describe their case. In these instances, the persons current mood directly impacts their response to generic questions on topics that the user does not often think about. Though here we are seeking to examine the reverse, a complicated process, so participants were asked to predict tomorrow's weather without checking, rank it on a Likert-style scale and describe what they expected to see. They were also asked to anticipate how relaxing tomorrow would be in comparison to the present day (see Appendix E for complete question list). In the brief ("micro") version of the study, subjects were given the overall mood assessment, asked to place the case on their phone, given the tasks in a randomized order, asked to take the mood assessment again, and then asked a series of open-ended questions that were very similar to those asked in the longer-term study.

6.4 Results

6.4.1 Procedure for Analysis

One of the appeals of the methodology employed here is that results can be interpreted visually. For each user, **plots were produced to track each parameter per day** over the course of the study, separated based on morning or evening (see Figure 6-2). These graphs provide a temporal snapshot of the users response, but must be combined with the qualitative responses about the events of the day in order to fully understand the situation. If deviations from the baseline do not consistently occur on the same day, it is more plausible that the response can be attributed to the material stimulus than if a user consistently exhibits a spike on the same day. As a first-pass analysis, all plots were generated for each user, and the experimenter visually examined alterations from the baseline. In some instances, this proved difficult if no clear baseline was established in the first seven days. As explained by Dallery, "The first and most important analysis of whether a technology based intervention affected a health related behavior is visual analysis of the time series data. Clinically significant change in patient behavior should be visible. Even a change in a slowly developing skill should be visible in the graphical display of the data. Visual analysis prioritizes clinically significant change in health related behavior as opposed to statistically significant change in group behavior. A statistically significant effect may be clinically meaningless" [19].

The plots for each individual can be found in Appendix D. In the following paragraphs, some of the more visible trends from the plots are highlighted in the cases where there is adequate variation between weeks. The **roughness hypothesis** was tested on users 982, 839, 321, and 32. User 982 received the sandpaper case on day 7 and ended the study on day 14, providing information for a baseline week and one experimental week. Based on the subject's responses to open-ended questions, the subject experienced a spike on day 12 as a result of planning a graduation reception that involved a lot of work. The participant's reported levels of excitement exhibited a downward trend during the baseline week and stabilized during the case week. The subjects report of feeling afraid in both the mornings and evenings were higher in week two after a week of a clear baseline. The user reported greater feelings of being ashamed in week two, in addition to experience a greater sense of difficulties piling up and feeling more distressed on average. The participant exhibited a greater sense of guilt in both the morning and evening, which was not attributed to anything in qualitative section of the survey. The same effect was seen for the report of hostility and nervousness in the mornings of week two. The user perceived articles as being more positive in week two, and also reported feeling more proud overall in week two, though this could be attributed to

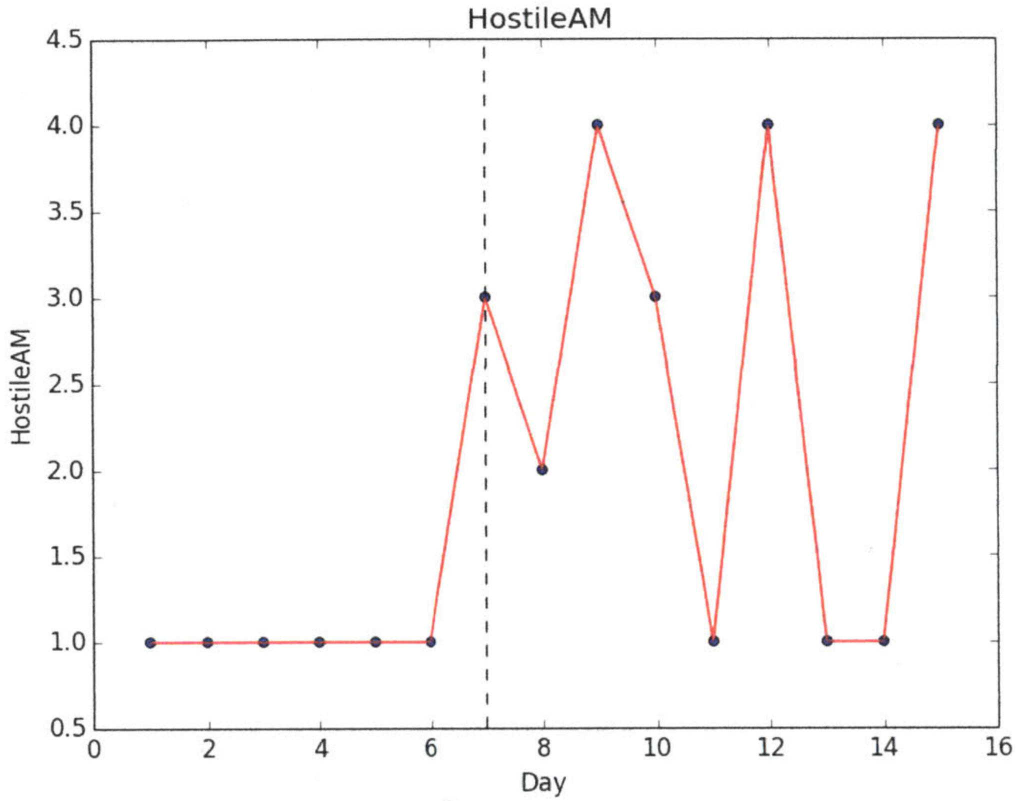


Figure 6-2: Example of a plot of a specific parameter (hostile) created to track individual response over the course of the study. In this instance, a relatively clear baseline is formed during the intial period before the case is introduced on the day marked by the dashed line

the fact that many of the subject's friends graduated towards the end of the week. In week two, the user reported feeling less good about relationships and also felt less relaxed, and more scared. Some of this fear may be attributed to the work that went into planning the graduate reception mentioned earlier. Overall, the subject exhibited higher sums of negative attributes in the morning and evening of week two in a manner that had no clear reason in the qualitative portion of the survey, thus indicating that the sandpaper case may have had an effect. 982 noticed the case much less over time, exhibited by a downward trend.

Participant 321 received the vinyl case on day 7 and the sandpaper case on day 14 (where week two thus indicates vinyl and week three indicates sandpaper). The participant experienced the lowest levels of alertness in the evening of week two out of the three weeks of evening responses, and the highest levels of alertness in the morning of week three out of the three weeks of morning responses. Participant 321 reported being less attentive in the mornings of week two. The subject reported higher levels of connection to the senders of the specific emails on which the participant spent the most time in week two than the others, and the lowest levels of connection to senders of emails on average in week three. 321 reported higher levels of determination in the morning and evening of week three, but also reported feeling the most left out in the mornings of week three. 321 also reported feeling the most inspired in the mornings of week three, and took emails on average least seriously in week three. The user reported being prouder in the evenings of week two, and more irritable in the same evenings. The user selected higher values of positivity for the articles in week two, and reported the biggest drop in expected pleasantness of the next day's weather in week three. 321 touched the cases less and less as the study progressed.

Participant 32 received the sandpaper case on day 7 and the vinyl case on day 14. The user reported having a stressful day on days 11 and 12, and had a stressful time at work on days 20 and 21, so analysis of plots was calibrated according to that qualitative information. The subject reported feeling the highest values of guilt in the evenings of week two, as well as feeling less confident about their abilities. The user reported the lowest feelings of difficulties piling up in week three. There was a downward trend in the users perception of future weather in week two, and an upward trend in how connected the user felt to senders of emails on which the most time was spent in week three. The user reported feeling more distressed in the evenings of week three and most irritated in the mornings of week two (when using the sandpaper case). 32 felt the least nervous and scared in the mornings of week two, and felt the best about the day in week three. 32 noticed both cases less over time.

Participant 839 received the sandpaper case on day 7, a vinyl one on day 13, and ended the study on day 19. This participant left a lot of questions blank, especially towards the beginning, mentioned feeling sad on day 14 upon watching many friends graduate and not doing so, and signed divorce papers on day 19. It was thus extremely difficult to distinguish between changes attributable to significant life effects and changes attributable to the physical stimulus. 839 exhibited a greater sense of fear in week three, and an upward trend in responses for alertness in week two, and a downward trend in the mornings of week three. 839 did not feel connected to the senders of emails on average in either week two or three, and felt least guilty in both the mornings and evenings of week two. The participant noted feeling less attentive in the evenings of week three, and had the lowest physical health during that time. 839 felt the proudest during the mornings of week two, and the strongest in the mornings and evenings of week two. The subject felt the worst about relationships in week three (which makes sense given the context of divorce), and the most upset in the evenings of week three. The user noticed the case less over the first three days, but then noticed the case a lot and touched the case a lot (the user reported using the sandpaper case to sand various surfaces and was thus very aware of the case).

The **density hypothesis** was tested on users 364, 414, 103, and 62. Participant 364 received the rubber case on day 8 and the balsa wood case on day 15. The subject reported higher values for distress in the mornings and evenings of week three, was the least upset in the mornings on week two, and the most upset in the evenings of week three. 364 felt the least guilty in the mornings of week three, and the least ashamed in the same mornings. The participants reported the highest levels of hostility in the evenings of week three, and reported higher values for "scared" on the day of the mass shooting in Orlando. 364 was the most attentive in the evenings of week three, and felt that events were out of their control in the mornings and evenings in week three. 364 felt things were going their way to the greatest extent in week two, and felt the best about work in week two. 364 found the articles to be the least relevant in week three, and presented responses on how serious the emails they spent the most time reading were with a downward trend in week two and an upward trend in week three.

Participant 414 received the rubber case on day 7 and the balsa case on day 14. 414 reported lower levels of isolation in weeks two and three. The participant felt the least alert in the evenings of week two, and felt the most inspired and interested in the mornings of week three. The subject felt guiltier in the mornings of week three, found articles to be the most positive in week three, and felt the worst about their relationships in week two. They predicted better weather during the days of week three. The participant noticed the case about the same amount over the course of week two, but decreasingly so in week three.

Participant 103 received the balsa case on day 9 and the rubber case on day 14. In the evenings of week three, 103 reported lower values for alertness, attentiveness, excitement, inspiration, and interest. The subject also reported being more irritated during this time. The participant reported perceiving their calls as more important in week three (which is in line with the hypothesis). Some data points are missing for the responses on how serious 103 perceived the articles to be in week three, but the existing trend indicates that the values were higher in this week. The subject felt the least upset during the mornings of week two, and the most upset in the evenings of week three out of all evenings surveyed. The participant touched the case less over time.

Participant 62 received the rubber case on day 8 and the balsa case on day 14. This subject had a birthday on day five, celebrated commencement on day 11, and moved on day 12, causing some fluctuations in the plots. The participant indicated feeling less ashamed in the mornings of week three, and reported lower values for frequency of feeling that things were out of their control in week three. 62 felt the most connected to senders of specific emails and of emails on average in week three, and ranked the articles as most positive during this time. The perception of performance at work has an upward trend across the three weeks, but 62 felt more distressed in the evenings of week two. 62 did perceive calls to be more important in week two, which is in line with the hypothesis. This subject touched the case less over the course of week three and noticed the case significantly less.

The **thermal conductivity hypothesis** was tested on users 90, 303, 122, 155, and 536 , but 122 did not provide enough consistent data to view any trends. User 90 received a metal case on day 7, and completed participation on day 15. Participant 90 graduated during this time, and many data points were missing so it was difficult to find reliable trends. Overall, 90 seemed less distressed and irritable in week two, and indicated lower sentiments that things were out of their control in week two. They reported lower values for hostility during the mornings of week two. They noticed and touched the case much less over time.

User 536 received a metal case on day 9 and a balsa case on day 16. Overall, reported values of being upset in the evening seemed to decrease over the course of the study. 536 indicated being less connected to the senders of specific and average emails after week one, and responses seemed slightly lower in week two (which would be in line with the hypothesis), but the difference between the second and third week is difficult to evaluate. This participant felt more afraid and more left out in the evenings of week two, and feelings about yesterday decreased slowly in week three. 536 felt the most isolated in the evenings of week two, and indicated the highest values for lacking companionship and feeling left out in week two, which is also in line with the hypothesis. The subject found articles to be more relevant in week two, and found calls to be more important towards the end of week three. 536 felt less determined in the mornings of week two, less distressed in the mornings of week two and three than the first week, and felt less inspired in the evenings of week two and guiltier in the evenings of week two. There was no obvious decrease or increase in how often the user touched or noticed their case after the first week.

User 303 received the metal case on day 7 and the balsa case on day 14. During week three, 303 experienced higher values of attentiveness and interest in the mornings, and inspiration in the mornings and evenings. The subject was less determined in the mornings of week two, and reported the highest values in the mornings and evenings of week three. 303 was the least proud and least excited in the mornings of week two, and the most proud in the evenings of week three. There was an upward trend in how often 303 touched the cases.

User 155 received a balsa case on day 7, and a metal case on day 15. During this study, 155 graduated on days 10 and 11 and spent much of that time with family. 155 also got accepted into an accelerator during this time. These events had a clear impact on the subjects responses. This subject was the least attentive in the evenings of week three, but was the most nervous in the mornings of that week. During week two, 155 perceived the articles as being more positive, felt more proud in both the morning and evening (possibly due to graduation), felt the best about yesterday and today, and felt the most excited in the mornings. During week two, the subject also reported lower values for difficulties piling up and distress, indicating lower stress overall. After the first two days of receiving the cases, 155 appeared to notice the cases less over time.

To gain further information about trends in a more global manner, **average values for each parameter across each week** were taken. This measure gives a rough idea of the individual response to the case along each parameter in a way that is sometimes difficult to gauge visually based on turbulent charts. Responses were then binned based on labels of "positive" or "negative" based on the PANAS score, and the **weekly average of positive and negative parameters** was calculated. This measure allows for rapid assessment of the potential for a case to produce a net negative or positive response, which can then be examined in the context of the qualitative information. These results are demonstrated in Figure 6-3 through Figure 6-8. All of the **positive and negative attributes were then summed(separately) and plotted per day** in a manner similar to the initial visual analysis. The plots are organized by hypothesis, where the top row represents the results of the morning survey and the bottom row represents the results of the evening survey.

For hypothesis 3 (regarding roughness), for the morning surveys, participants reported slightly lower values for positive attributes during the weeks in which they used the sandpaper case. Intuitively, it is logical that when presented with sandpaper first thing in the morning, users might report lower values of positive mood words. User 982 was viscerally impacted by the sandpaper case, stating that "its making me angry, not gonna lie" and "this ruined my day." In the evening, the difference in values between the sandpaper week and the vinyl week are less apparent, though the values for sandpaper are certainly lower than the values from the baseline week. For the negative attributes, in the morning three out of the four participants reported higher values for negative attributes when using the sandpaper case than the other two weeks. Participant 839 did not provide enough data for any clear conclusions to be drawn. In the evening, the same effect was seen.

For hypothesis 1 (regarding density), there was no obvious trend for the negative attributes reported in the morning, where half of the participants seemed to report higher values and half reported lower values. In the evening, three out of the four participants seem to indicate higher negative attributes when using the rubber case. It is possible that of course of the day, they case seems to get "heavier" as the user tires of carrying it. In the initial survey, when asked to react to the case,

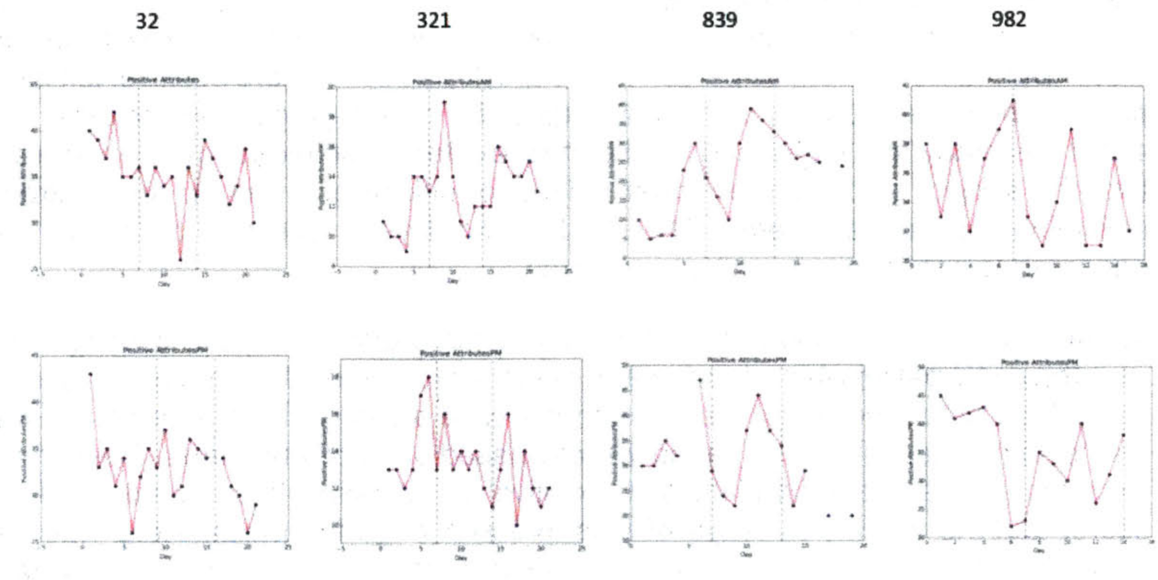


Figure 6-3: Plots of sum of Positive Attributes in the morning (top row) and evening (bottom row) for each participant receiving the rough and smooth cases (Hypothesis 3)

participant 364 stated explicitly that over the course of the 15 minute in-person interview, the case did seem to feel heavier in her hand. For the positive attributes, generally users reported lower positive values on all weeks with rubber, and in the evening three out of four participants experienced lower values of the positive attributes on weeks with the rubber case. Here, it is possible that while the case may not explicitly have made any event, article, or call seem more "important," it did make these occurrences weigh more heavily on the subjects mind.

For hypothesis 2 (regarding thermal conductivity), in the morning, three out of the five participants exhibited lower positive attribute on the weeks with metal cases (and higher positive attributes on the week with the balsa case which was universally well-liked), and three out of the five experienced lower positive attributes in the evening, though for one user there is not enough data to make a clear trend, and for one user positive attributes did increase during the week with the metal case. For negative attributes, two users reported higher values in the morning, two reported lower values, and one did not provide enough data for any clear conclusions, though values generally seemed to trend higher. In the evening, two participants displayed higher values, two users provided insufficient or unclear data, and one experienced lower values, though all demonstrated a significant difference from the baseline week. With the metal case, the sheet of aluminum was very thin,

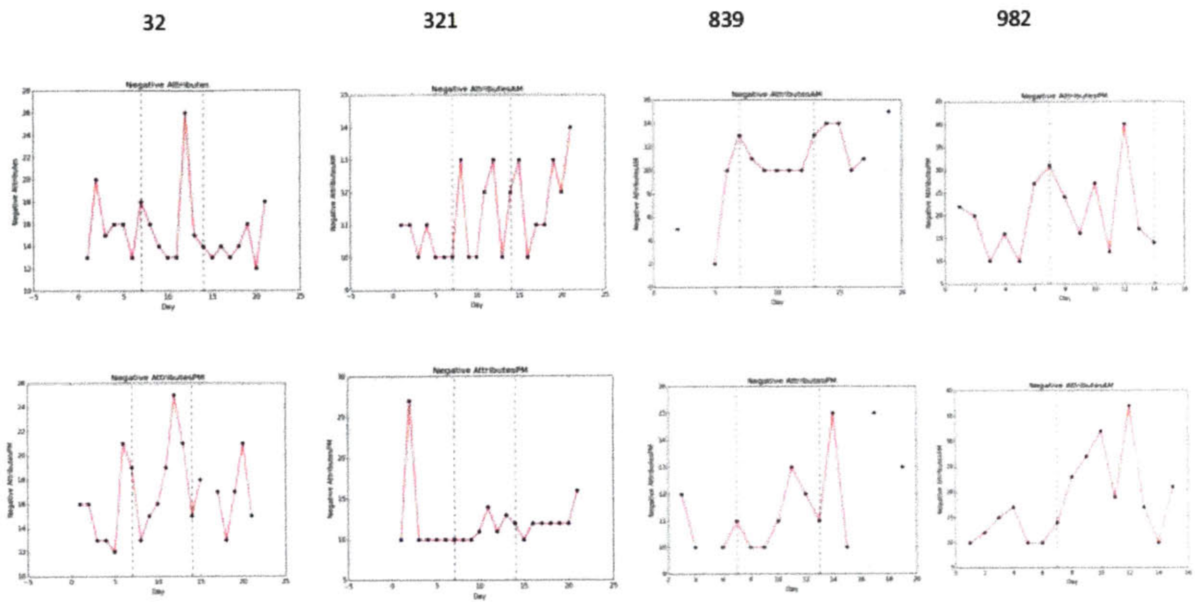


Figure 6-4: Plots of sum of Negative Attributes in the morning (top row) and evening (bottom row) for each participant receiving the rough and smooth cases (Hypothesis 3)

and if the phone was carried in a users pocket, it is conceivable that it would have felt much warmer at the end of the day than the beginning.

With all of the aggregate data, it is useful to remember that in the morning, the subject is most likely interacting with the case for the first time after hours of sleeping (and thus not being in contact with it). Results are potentially more similar to the initial reaction of experiencing the case for the first time than they are in the evening, when the user has adapted to the case.

Finally, the responses from the in-person questionnaires completed during sessions in which the case was exchanged were compiled and compared to the weekly average. This measure allowed the experimenter to compare the instantaneous reaction to the prolonged response.

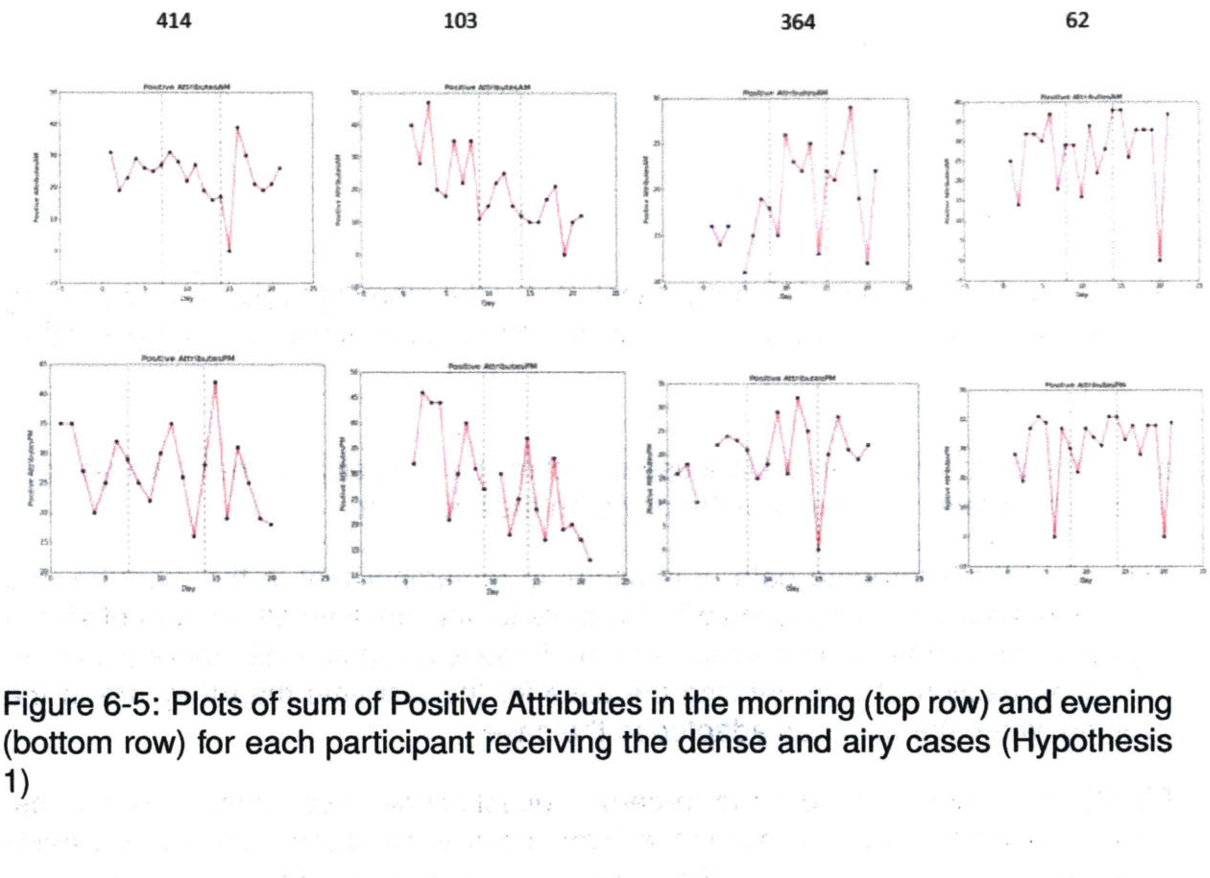


Figure 6-5: Plots of sum of Positive Attributes in the morning (top row) and evening (bottom row) for each participant receiving the dense and airy cases (Hypothesis 1)

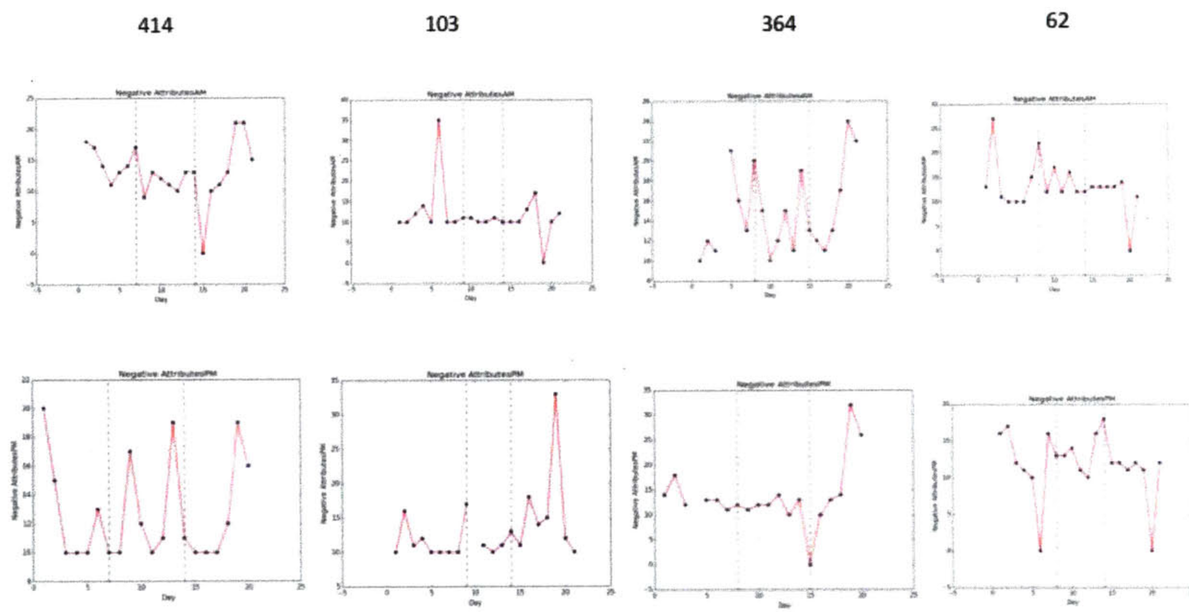


Figure 6-6: Plots of sum of Negative Attributes in the morning (top row) and evening (bottom row) for each participant receiving the dense and less dense cases (Hypothesis 1)

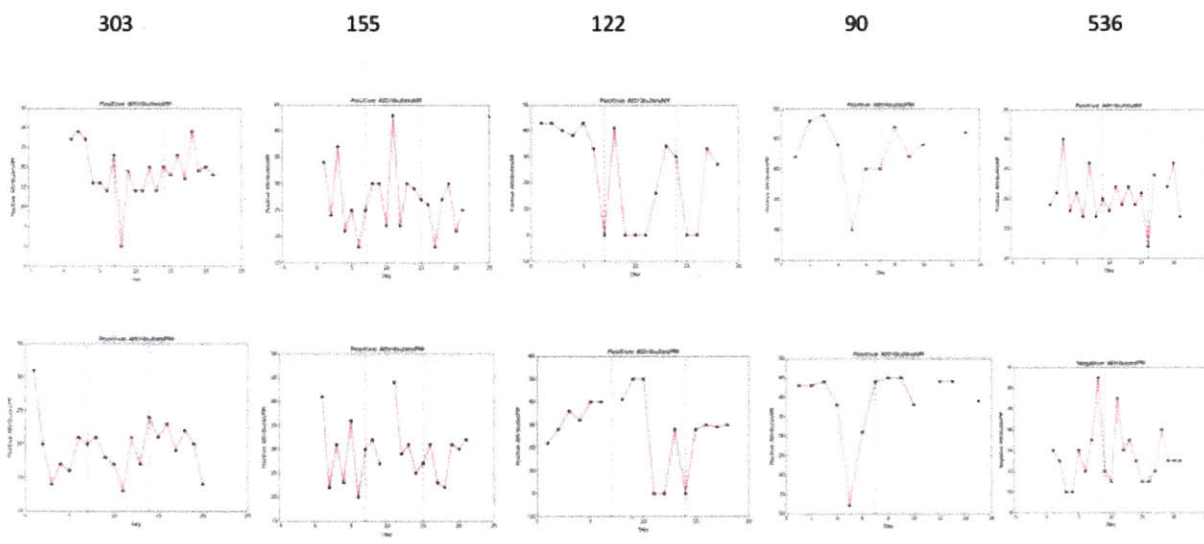


Figure 6-7: Plots of sum of Positive Attributes in the morning (top row) and evening (bottom row) for each participant receiving the high and low thermal conductivity cases (Hypothesis 2)

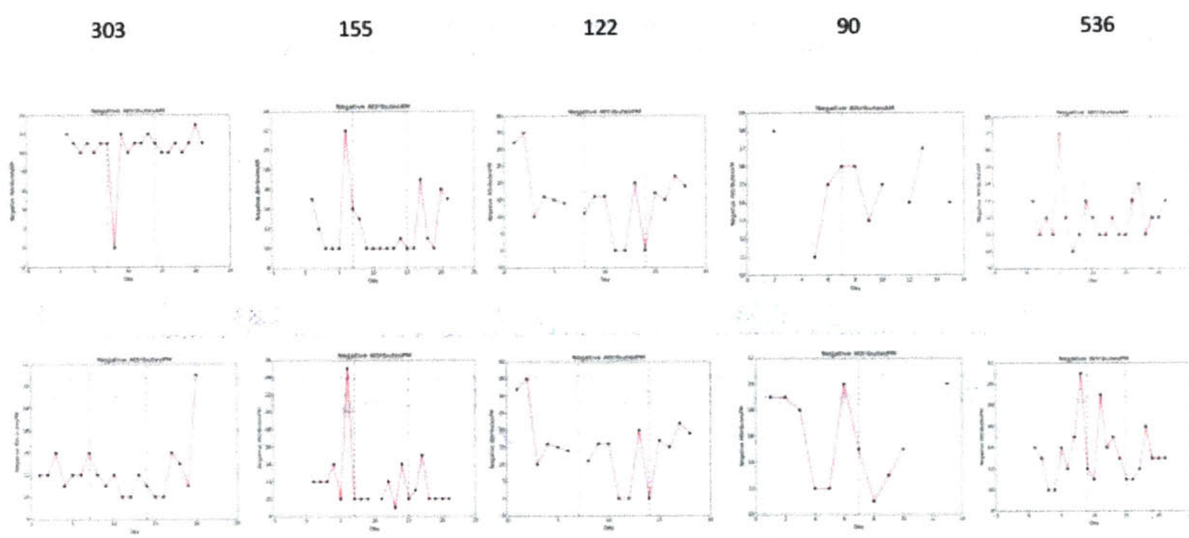


Figure 6-8: Plots of sum of Negative Attributes in the morning (top row) and evening (bottom row) for each participant receiving the high and low thermal conductivity cases (Hypothesis 2)

Figure 6-9: Average of positive or negative attributes for each participant, shown by case

Participant	Case A, Pos Before	Case A, Pos After	Case A, Neg Before	Case A, Neg After
36	1.3	1.8	2.2	1.4
397	2.6	3.1	4.2	4.2
219	1.9	1.4	1	1.1
199	3	3.6	2.1	2.1
59	2.5	2.6	2	1.3
932	2.6	2	1.6	1.8
AVG	**2.32**	**2.42**	**2.18**	**1.98**

Participant	Case B, Pos Before	Case B Pos After	Case B, Neg Before	Case B, Neg After
478	2.7	2.4	1.2	1.5
49	2.5	2.1	1	1
97	3	2.4	1.3	1.2
891	3.1	3.2	4.2	3.6
215	4.2	3.3	1.2	1
909	2.7	2.9	2.1	2.3
AVG	**3.03**	**2.72**	**1.83**	**1.77**

Participant	Case C, Pos Before	Case C Pos After	Case C, Neg Before	Case C, Neg After
394	2.6	2.6	1.2	1.3
854	2.2	2.4	1.1	1
512	2.8	3.4	1.1	1
8	3.2	3.3	1.7	1.7
213	3.2	3.4	1.4	1
44	4.1	4.6	1.4	1.5
102	2.3	2.3	2	1.9
33	2.2	2.1	1.3	1.1
709	3.2	3	2.5	2.9
AVG	**2.87**	**3.01**	**1.52**	**1.49**

Participant	Control, Pos Before	Control Pos After	Control, Neg Before	Control Neg After
5	4	3.7	1.5	1.4
635	3.8	3.4	1.9	1.7
537	2.7	3	1.3	1.1
439	3.6	3.4	1.2	1
994	3.2	3.3	1	1
71	2.6	3	2.2	1.5
16	2.4	2.5	2.8	2.9
28	2.4	2.8	1.3	1
AVG	**3.09**	**3.14**	**1.65**	**1.45**

6.4.2 Micro Survey Analysis

As with the 2-3 week study, the positive and negative attributes were binned. For each participant, the average of positive terms before the tasks, positive terms after the tasks, negative terms before the tasks, and negative terms after the tasks were all collected. The average of these averages was then calculated to get an idea of the overall impact on each experimental group, with the following results, and demonstrated in Figure D-6:

- For case A (aluminum), the mean of positive attributes before was 2.32, and afterwards was 2.42 (**an increase**). The mean of negative terms was 2.20 and became 1.98 (**a decrease**).
- For case B (sandpaper), the mean of positive attributes before was 3.03 before, and 2.72 after (**a decrease**). The mean of negative traits went from 1.83 to 1.76 after (**a decrease**). .
- With case C (dense rubber), the the mean for positive attributes was initially 2.86, and became 3.01(**an increase**). For negative attributes, it was 1.52 and became 1.45 (**a decrease**).
- For the control, the mean of positive attributes was initially 3.08 and became 3.14 (**an increase**),and for negative attributes, the mean changed from 1.65 to 1.45, (**a decrease**)

The average responses across participants was calculated for each task-related question, and then organized based on the case provided, as shown in Figure D-5. Based on this figure, it appears that participants given the control case or sandpaper case found the content of the call placed to be the most serious, while those with the metal case or the control case found it to be the most important. Those with the control case, followed by the rubber case, felt the best about the call. Those with the rubber or metal cases felt the most connected to the recipient of the call. Sandpaper users deemed the content of their emails (on average) to be the most important, while users of their own standard cases deemed the content of specific emails to be the most important. Those with control cases felt the least connected to the senders, while those with the sandpaper case felt the most connected. Those users given the rubber case felt that they should respond the most quickly to their emails. The individuals using either their own control cases or the sandpaper cases found the content of the article to be the most important, and the control users found the article to be the most relevant to their lives. People using sandpaper and rubber found the article to be the most positive. Overall, it is possible that sandpaper simply increased valence overall. Further testing is needed

Figure 6-10: Average responses per case treatment for the various tasks in the 45 minute study

	How "serious" was the content of this call?	How "important" was the content of this call?	How do you feel about this call?	How connected do you feel to the recipient of your call?	How "serious" or "important" was the content of these emails on average?	How "serious" was the content of the emails that you spent the most time on?
Average for A	2.33	3.00	3.67	4.50	1.80	2.20
Average for B	1.57	2.29	3.71	3.14	3.14	3.29
Average for C	2.00	2.33	3.83	4.17	2.38	2.75
Average for Control	2.33	2.83	4.00	3.50	2.43	3.43
	How connected do you feel to senders of these emails?	How connected do you feel to senders of these emails (specific)?	How quickly (on average) do you feel you should respond to these emails?	How "serious" or "important" was the content of this article?	How relevant do you feel this article is to you?	How does this article rank in terms of negativity to positivity?
Average for A	1.80	2.00	2.40	3.40	2.20	2.80
Average for B	3.00	3.14	2.29	4.29	2.43	3.14
Average for C	2.13	2.88	2.75	3.63	1.88	3.13
Average for Control	1.57	2.14	2.00	4.29	2.57	2.71

to evaluate this information and understand the variation, as these averages only provide a rough overview of the responses.

Figure 6-11: Changes in positive and negative values in the 45 minute study

Case A	Case B	Case C	Control
36 positive increased negative decreased	478 positive decreased negative increased	394 positive same negative increased	5 positive decreased negative decreased
397 positive decreased negative same	49 positive decreased negative same	854 positive increased negative slight decreased	635 positive decreased negative decreased
219 positive decreased negative increased	97 positive decreased negative slight decreased	512 positive increased negative slight decreased	537 positive increased negative decreased
199 positive increased negative same	891 positive slight decrease negative slight decrease	8 positive slight increase negative same	439 positive decreased negative slight decrease
39 positive slight increase negative decreased	215 positive decreased negative decreased	213 positive increased negative decreased	994 positive slight increase negative same
932 positive decreased negative increased		44 positive increased negative decreased	71 positive increased negative decreased
		709 positive decreased negative increased	16 positive increased negative increased
		102 positive same negative slight decrease	28 positive increased negative decreased
		33 positve slight increase negative decreased	

6.4.3 Further Possible Analyses:

As so much data was collected in both the brief and extended versions of the study, many more analysis procedures could be conducted. To begin with, a more thorough comparison between the qualitative answers and individual plots needs to be conducted and cross-referenced to examine differences. Analysis of variance (ANOVA) tests could be conducted to determine if the means of various case conditions are equivalent or not. If different cases resulted in different mean values, it is probable that the material impacted user behavior and responses. ANOVA tests on the values of change in mood parameters would similarly yield useful insights. Box and whisker plots could be produced to further understand the variation in data. Tighter boxes would indicate more similar impact, while a broader box would indicate more diversity in responses, meaning that the case did not have the same impact on all individuals. Thus, box and whisker plots would provide some idea of the standard deviation of the spread on mood or change in mood. Pairwise t-tests could be conducted on the change in positive or negative values to see which is more significant for each parameter. Finally, for the extended study, the weekly average could be compared to the reported values collected immediately after the cases were switched.

6.5 Conclusions

It seems that a thicker metal layer was needed for thermal properties to matter the sheet was so thin that any effects dissipated quickly. Furthermore, after keeping their phone in pants pockets all day, participants are likely to have warmed their phones. Due to material sample differences, the phones varied in thickness, which was definitely noticeable to participants. In future iterations, all cases should be precisely the same thickness. Numerous subjects remarked on the quality of construction and the obviously hand-crafted nature of the phone, indicating that more attention should be paid to fabrication in the future.

The abbreviated versions of the various psychological tests may have been too short some users commented that the limited number of choices reduced the resolution of their responses, and it is possible that some subtle changes were lost as a result.

The majority of participants reported noticing the case less and less overtime, demonstrating our ability to adapt with relative ease even in contexts where we interact with interfaces that we initially deem to be extremely distracting.

While further analysis is needed to determine whether or not the case had the predicted effect on the perception of specific tasks of reading emails, placing a phone call, or reading an article, there is some initial evidence that the cases may have had an overall positive or negative impact (where the rough case had a negative impact on average, and the denser case may have had a negative impact over the course of the day).

Initial analysis indicates that the balsa wood samples had a calming and pleasant effect on participants, where articles were deemed as more positive, users felt less distracted, and positive attribute reports increased. Overall, the wood was universally well-liked and some participants even reported that they would now purchase wooden cases in the future. It also seems plausible that the sandpaper cases increased valence in all directions, simply heightening user awareness on the whole.

We need to delve farther into qualitative answers to see if there is a coherent narrative between participants as there was for certain dice samples. For many subjects, having the cases resulted in decreased phone usage: one participant summarized their perception of the study as follows: yeah, its interesting because I definitely havent thought about how things like weight would make a difference, or cause behavioral changes to how people use their phone, but I definitely used my phone less with one case. Another commented that "its actually quite clever to hack how you use your phone - if you really dont want to use your phone, make it out of a crappy material, but make it pretty or hilarious."

Overall, the single user study design should help address the argument about cultural differences and personality differences, as responses are true to that individual user. Different people are affected by stimuli differently, which is part of the appeal of this method. Ultimately, further experimentation in this direction could be used for personalized recommendations for each person. For instance, with the sandpaper case, in incidental interaction with the samples, one individual really enjoyed the sample as it reminded him/her of designer bags, one remarked that it made the case grippier (which was deemed to be a positive effect), and one associated the material with the end of the woodworking process, and thus found it therapeutic [1]. In contrast, many of the study participants found the sandpaper to be irritating, infuriating, or uncomfortable. This technique is a worthwhile starting point for further testing.

6.6 Learnings for Future Experiments

If this study were run again, it would be beneficial allow participants to use their own case and the sample cases for a longer period of time to provide a greater opportunity for a stable response, something that was not frequently achieved here. A greater sample size of participants, especially for the brief study version, would have yielded more accurate results. More active monitoring of user responses

[1] Personal Communication, June 2016

would hopefully help alleviate the amount of responses that were missing in the end data. Rather than trying one material of a specific property followed by a sample on the opposite end of the spectrum, it might be more fruitful to examine three to four cases of same material property. As with the dice, a broader range of materials could allow for the examination of further hypotheses. It could be revealing to examine aspects such as specular reflectance, hardness, flexibility, and pliability that also impact perception of cases. For greater control over variables, instead of comparing similar materials, it might be worth comparing different processing conditions for the same material (i.e. sandblasted acrylic versus smooth acrylic).

The tasks chosen for this study also biased user responses. By nature of the fact that respondents were asked to make a phone call to the person or organization of their choice, participants often felt more connected during the time of the survey than they may otherwise have done. If, instead, users were assigned a number to call, results may be less biased. An even more effective method might be to have them respond to a scripted phone call to guarantee that content remained the same across each user and maintained the same general affect across the week for each user. Having a means for monitoring their cognitive responses in real-time right after or during the phone call, as was done with the 45-minute test, might provide more accurate results than asking respondents to rate the call hours later. Though the day of the week affected was accounted for in experimental design, the timing of the study meant that numerous users were experiencing life events such as commencement which severely skewed their responses in a way that was not representative of the material response. Selecting a time period could have significantly improved the results. With samples such as the aluminum case, it would have been interesting to monitor the change in temperature of the case over time and carefully monitor the environmental conditions that impacted it.

In future experiments, having subjects use a series of cases for an extended period of time in an assigned order before being asked to select cases based on their mood in the morning for the last period of the study would reveal useful and fascinating insights. It would be useful to more rigorously compare initial cases to the cases that participants were given. Material testing of the initial cases would allow for a better understanding of participant baselines. Future experiments could be based off of different interfaces that we regularly and subtly interact with, such as keyboard covers or laptop key materials.

An interesting question to explore out of this experiment is whether there are specific personality traits that make an individual more susceptible to being affected by the material of the phone case.

7 Conclusion

Building a Foundation

7.1 Identification of Key Properties

The processes for exploration developed in this thesis revealed a valuable methodology for identifying key parameters for emotive objects. Based on experiment one, we can say that 'people tend to feel X when confronted with die of material Y in context Z. Based on experiment two, we understand how responses to material X in context Y can change over time. The results of this study support the conclusion that material properties could be manipulated to elicit a desired response.

As specified based on experiment one, reflectance has potential implications of formality and aggression, roughness may imply immaturity, thermal conductivity is related to aggression, masculinity, exclusivity, and unfriendliness, and density relates to aggression.

On a broader level, bounciness was associated with energy, weight was repeatedly used as a metric of quality, and temperature and friendliness were linked. Some materials were met with very cohesive descriptions: wood was universally liked throughout both experiments, aluminum was described as futuristic by a plurality of subjects, and rubber was reminiscent of childhood erasers.

The experimental process and design outlined in both experiments could be employed in a variety of contexts to uncover more key parameters and establish usable and robust design and fabrication guidelines. To truly develop complex and realistic fabrication tools, it will be necessary to examine multivariate analyses and the various interactions that occur when these properties come together- when a dice is forged out of materials of different stiffnesses and takes on an entirely different bounce profile and personality, or when a phone case conforms to touch in certain areas and maintains a rigid protective layer in others.

7.2 Contributions

In this thesis, the following contributions were presented:

1. Established a paradigm for natural user testing regarding emotion-related materials. This thesis presents a series of experiments and studies that were conducted within a realistic, easily reproducible time-frame, scale, and budget. User studies examining this range and scope of properties (from technical through sensorial to cognitive and emotional) had not effectively been presented prior to this work. Literature reviews and personal interviews were combined to develop effective questions and the vocabulary needed to explore this space.

2. Developed an example for examining responses to material samples over time. In addition to exploring the immediate, controlled cognitive response that subjects exhibited when presented with experimental samples, this thesis presents a viable attempt at capturing user responses in their natural environment over time. A relatively new experimental design was employed, again applying this approach to questions that had previously been unexplored in this manner.

3. Examined the impact of materials on behavior change. Through this examination of user responses over time, this work began to question to potential of material samples to subtly nudge human behavior through physical cues. While many more iterations are needed to pose meaningful conclusions, the questions raised here are crucial to examining emotive materials and expanding the impact of physical design.

4. Established usable experimental techniques for testing hypotheses about emotion impacts and behavior change. In addition to assembling relevant vocabulary and questions for in-depth interviewing on these topics, this thesis presents a method through which clear hypotheses were examined and evaluated. This involved steps ranging from material selection, selection of testing method, determination of salient material properties, technical evaluation of samples, and presentation and analysis of collected information.

5. Selected and characterized materials to use in a standardized assay. As each experiment was designed, a materials library of usable samples was collected, and relevant instrumentation and characterization techniques were applied. As mentioned earlier, the process of testing materials is time intensive and can be difficult. Understanding and gaining competence on necessary equipment significantly eases the process of developing future experiments.

6. Gained IRB approval and performed two detailed user studies of different contexts. The studies designed were proven to fall within reasonable ethical guidelines for human subjects research and were carried out in a safe and practical manner that could easily be reproduced. It is important to note that all studies were carried out by a single researcher, and thus studies executed by a team could prove even more effective.

7. Identified the current gaps in a burgeoning field which is relevant for designers, engineers, and scientists. Through interviews, literature review, and experimentation, this work reveals challenges and uncovers promising future experiments to build off of the concepts presented here.

8. Developed standard measurements for characterization that are critical to material evaluation for product design. In identifying salient material properties, a set of promising material-attribute relations were discussed, and their relevance to user perception was demonstrated. We also evaluated and eliminated measurements that did not bear relevance on human perception.

9. Collected a repertoire of statistical techniques from various fields to frame, analyze, and interpret studies. Having the tools with which to analyze study results is crucial to understanding the impact of these experiments. Techniques were drawn in from various other fields and applied in new ways to questions relevant to this work.

10. Collected relevant measures and metrics from psychological tests, anthropological examinations, ethnographic interviews, and design work. Through the literature review, practical exploration, and personal communication conducted for this project, an effective vocabulary and arsenal of questions was assembled and tested. Numerous techniques were applied to examine the most effective, both in terms of statistical significance and in terms of practicality for actual users.

In doing so, this project has established a foundation and methodology that we, and other researchers can use, and we intend to use it as a basis for future work in this area at the Media Lab. Ultimately, we hope this exploration can help lay the foundation to allow other scientists, designers, and researchers to contribute to this area of research. Once the connection between material properties and perceived properties has been established, the design guidelines could be tested. We could build an object using these constraints and ask individuals compare it with other objects fabricated in a more traditional manner. The guidelines would then be deemed useful if using them results in an object with the intended perceived properties. Using these contributions, future studies can explore the complex interactions between properties.

7.3 Identifying Areas for Future Work

As an initial foray into this new field, this thesis also served to identify some key obstacles and challenges with the study of emotive materials. While the user studies yielded complex results that were somewhat difficult to parse, this process revealed important considerations in experimental design. Numerous unsolved issues were revealed; how, for instance, would designers go about measuring relevant material parameters once they are well-versed in relevant material properties? How can further information about material samples and uses be collected from a broad and varied user base? Access to instrumentation and knowledge of characterization methods are nontrivial barriers to entry, and collecting information is a difficult process. Thus, this work has sparked numerous other potential projects to build upon this foundation and further explore this area. These potential developments are discussed in-depth in chapter 8. In this thesis we have identified relevant challenges, future explorations, and methods for rigorously building on this work.

In summary, this thesis justifies further research in this field by providing a new framing for material science. Placing materials science and material selection in an emotive context is worthy of further exploration. This approach has many advantages to designers hoping to elicit a particular emotion from their products. Ideally, this work will lower the barriers for individuals working in both engineering and design. As Ashby posits, "Materials are not simply numbers on a datasheet." [75]. This work takes the first, necessary steps, towards understanding the space of relevant parameters, allowing for future work that may be less reductive and richer in scope and allowing for the design of experiences instead of objects.

8

Future Work and Impact

Further Understanding Materials In Context

"Materials are not simply numbers on a datasheet. And design is not a meaningless exercise in styling and it is not an isolated exploration of technology. What matters is the process of finding solutions that are meaningful to people, that enable new experiences and inspire and create positive impact in society and in our own daily lives."

– Mike Ashby and Kara Johnson, *Materials and Design (Pg 3)*

This thesis serves to explore the viability and potential of the field of emotive materials. In chapters 1-3 we discussed the current state of materials design, identified gaps, and motivated this research as part of a broader effort. In chapters 5 and 6, we reported on two studies that employ a different style of thinking around materials in the design process, explore the emotional implications of materials (the touchy-feely aspects), and presented and used a replicable experimental design process that combines techniques from many constituent fields. In chapter 7, we outlined the impact and contributions of this work. The hope is that this work is an initial foray into more research in the area of sentiment-based fabrication and material use to connect scientists and designers, providing a process from which future researchers can start. As explained in previous chapters, the conclusions drawn from these studies indicate that material properties have a measurable impact on emotive responses, which leads to the conclusion that these properties could be controlled and manipulated to foster a desired outcome.

Despite this progress, there is significant untapped potential in this area. In future investigations, we would like to examine materials more in terms of interfaces which respond to user interaction, so that the material changes the human in parallel to how the human changed the material. We would like to explore how actual patterns of behavior and emotion can be defined in future work. To enable such work, new methods of data collection will need to be combined with more in-depth monitoring of human responses. There is a readily apparent need for more information in order to be able to effectively draw trends and produce guidelines.

Through this thesis, we have gained insight into how crucial and beneficial it is to develop methods, tools, and forums for researchers and designers to gain insights in a quicker, broader manner without losing (or at least as a complement to) the richness of in-depth user studies.

8.1 Fabrication of Emotive Objects

As an immediate next step for this work, I plan to pull out specific design guidelines. To effectively implement the fabrication guidelines developed through the process outlined in the previous chapters, objects should be created to test the resulting emotive response. Evaluation would be conducted through extensive user testing. There are two main modes of evaluation based on the outputs for this work. The first involves evaluating the objects produced to see if they evoked the intended response. In order the to do this, I would conduct in-depth, interview-based user testing. Based on the process and questions developed by designers in their investigations of the sensorial aspects of materials. In this context, success can be evaluated by testing consensus between two parties at various points, with the ultimate goal of approaching consensus, or, as with experiment two, monitoring each individual against a baseline state. multidimensional scaling can be applied to see where the samples fall in the perceptual space based on the cues that were initially used to create them, and the accompanying statistical analysis can be conducted. Some of the testing will involve rapid collection of lots of information to understand quantitative trends, using tools such as the Design Data machine created by Pip Mothersill. The tool attempts to answer the need for rapid A/B testing of physical prototypes by providing an automated "slot-machine" style physical interface that allows users to examine and evaluate design samples in response to a word or other stimulus. In the cases where there is little to no literature or background on this perceptual information, I will mainly be seeking consensus and consistent trends as there is presently no metric in this field. I will examine consistency among people and return to multidimensional scaling as a means of determining where my samples lie on the intended dimensions.

One example of such an object would build upon the existing concept of stressballs, but perhaps be more appropriately labelled empathy spheres/sentiment spheres.

This would account for one specific form to remove some context concerns. It is a shape that is graspable both physically and cognitively, and begins to address the question of functionality and affordance. By taking a somewhat organic form, it would allow me to introduce novel materials in a less intimidating way than traditional means and removes the edges and foreign feel of rectangular slabs. By altering the surface properties, optical properties, composition, layers, mechanical properties, and internal composition of these objects, I could build on a familiar concept (of the interaction with stressballs) to evoke a range of emotions. Alternatively, this thesis now provides a set of guidelines pertaining to dice and phones: we now understand what makes dice desirable and what causes phone cases to be irritating. Using this knowledge, we could, perhaps, build the friendliest dice.

As a secondary means of evaluation, I would examine the methodology and fabrication guidelines based on my initial premise of creating a shared foundation for designers and engineers, which will be explained in an upcoming section.

Based upon this experience of fabricating objects, the process of creating everyday objects could also be altered. For instance, chairs could be built using a materials-first, emotion-centric process to enhance the daily lives of workers who spend the majority of their time seated and support them over the course of stressful day-to-day interactions. In this manner, a new form of design with emotive materials could be undertaken.

In this process, it is important to examine the relation between salient perceptible properties across scales. The process of evaluating and manipulating properties becomes more complex (and more interesting) when properties are combined and mixed, prioritizing one over the other (with dice, for instance, Neri brought up the example of implementing soft corners with an overall stiff material, which introduces a spring). These matrix combinations would allow us to design for experiences, rather than simply designing objects.

8.2 Holistic Material Database for Selection and Discussion

To address the initial problem of connecting the disparate communities of engineering and design, a final outcome of this work would be to integrate and develop the quantitative design language data into applications that can help people understand, choose and create more communicative materials to use in the objects they design.The knowledge collected through the methodology outlined in this thesis could be used to develop digital resources for a broader material selection process based on the ability to draw connections between physical parameters and human responses. An example would be an interactive database of materials filtered via emotional output, where conclusions drawn in this thesis could guide users towards appropriate material choices. Through the utilization of such tools, users could engage in previously unexplored fabrication techniques and adapt a truly materials-centric and emotion-centric approach. Considering design decisions in this manner would allow for the creation of objects with a consistent emotional and aesthetic meaning.

Some broader questions arose through this work about the role of form and context. As articulated by research scientist James Weaver who served as a reader for this thesis:

> "One thing to keep in mind, however, is that people often have a hard time separating the emotions elicited from the material that an object is constructed from the functionality of the object itself. For the dice example, one should consider how much emphasis is placed on the functionality of the object, rather than it's composition. For example, while fuzzy dice are very warm and cuddly, they are completely impractical for game play, so in this context, they could elicit a completely opposite emotion than what was intended. A classic example of this comes from my own experience. Some friends of mine who were finishing culinary school were very fond of Asian cuisine, so as a gift one year, I gave them each a beautiful set of stainless steel chopsticks. The surface finish was stunning and they exuded class and sophistication. A perfect gift, or so I thought. I later learned that none of them shared my same feelings of excitement regarding these utensils as they were impractical for general use by inexperienced dinner guests who would get very frustrated with their slippery surfaces. The lesson here is that perhaps these different materials would be better viewed in a context where the functionality is secondary. A good example might be kitchen cabinet doors. Assuming that cleanability and maintenance were similar, it would be very interesting to understand what emotions people feel when seeing wood doors with different stains or paints, which could vary dramatically depending on whether the kitchen was intended to function as a social gathering point in the house of as a site for simply preparing food."

As this work was intended for both engineers and designers, working with practicing designers will be central to the viability of this concept. Through spending extended time building and learning with designers, I could better understand the questions that they grapple with. It would be extremely valuable to work with practicing individuals from both fields to design a process for collaboration between engineers and designers, and to understand how much room there is in the existing design process to incorporate novel materials science or engineering techniques. Is it feasible to make materials more central to the design process, and if so, what would that look like?

Eastman Innovation Labs attempted to implement a similar solution through the development of Formity, an open platform for designers, engineers, brand managers and business strategists to connect and converse over Eastmans new material developments. While Formity is no longer active, continuing in this vein through a website to crowd-source knowledge about materials would be beneficial to individuals involved in any aspect of material development or consumer product design. Such a platform would also allow for the acquisition of broader amounts of data, especially if it were paired with physical libraries that enable the experiential interaction with materials.

I would examine the methodology and fabrication guidelines based on my initial premise of creating a shared foundation for designers and engineers. The work could eventually feed into a database, particularly in conjunction with some of the crowd-sourcing initiatives that local materials libraries (specifically those as the Harvard Graduate School of Design and at the Rhode Island School of Design) are attempting to implement. Here, the success would be determined

8.3 Workshops and Material Libraries

I have connected with engineers, designers, and materials librarians over the course of this project to collect their stories and understand existing problems. Over the course of my PhD, I plan to see if they can use my proposed system, and see if they could utilize the guidelines. It would be particularly rewarding to use this information to build upon materials libraries by expanding the range of their technical information and figuring out how to display these technical factors.

I plan to build tools to facilitate design with emotive properties of materials in mind and create new material systems from unique building blocks. Along the way, I plan to further materials education by applying my findings to community-based workshops or tools. I began the process of connecting with scientists at MIT and Harvard to further test my ideas and gain more insights into the potential setbacks involved in my process. Workshops would not only allow me to test the process proposed in this thesis, but also help individuals on both ends understand the potential for collaboration and the motivation for doing so. Through these interactions, I also hope to open up a general discussion about the connections between engineering and design, and the path towards a collaborative design process.

I hope that this body of work is a step towards improving general education of both materials science and design. Understanding and quantifying the meaning of materials can benefit both novices and experts across these fields. By connecting with members of relevant disciplines in the Boston area, I could both evaluate the potential impact of this work and contribute something more meaningful to the science and design communities. Adding an emotive dimension to the scaffolding of existing lab classes could enrich the education of future scientists and engineers. Through such workshops, I hope this work can be implemented.

8.4 Deeper Ethnographic Research

A complimentary approach to the methodology assumed in this thesis would be to examine the interaction between society and the materials in the selected forms to further understand the contextual aspects of design. In particular, with dice, it would enrich the study to follow the arc of dice throughout human history. By spending some time observing the use of dice within actual contexts where dice hold importance (i.e. in casinos), more could be gleaned about the way that dice embody and enable stories and experiences. Researching the historical, social, and economic impact of dice would provide a new and meaningful perspective. In some ways, dice are able to reach an almost mythical status, and there are fascinating stories to be crafted around the concept of dice (and therefore the materials from which they are made) impacting destiny. Material changes impact how the dice falls and how it feels, and as such they alter the way we connect with the games and stories we use the dice to tell. Understanding these stories would strengthen the work started here.

8.5 Addressing Culture and Personality

One of the greatest challenges with this work was grappling with the idea of universal truths, as was alluded to in the discussion of extrinsic versus intrinsic properties of materials. It is immediately apparent that context is incredibly important in design and interpretation, and drawing generalizations across humans is an oversimplification. Some work was done to account for individual differences and demographics in these studies, but in future work, it would be nice to incorporate personality as a central component of analysis.

My main goal with this work was not to produce any "answers" in the sense of "this material = this emotion," but rather to open up a dialogue and provide a more understandable language that people can use to discuss materials. Ultimately, oversimplified standard two axis visualizations are probably not the best deliverable to communicate the desired information. Researchers have proven that there are some cross-cultural associations (warmer materials are generally seen as more pleasant, and materials like wood have produced relatively standard reactions (Zuo, van Kesteren, Karana), but this does not translate across all materials in all situations. There are so many contextual cues that matter, including the personality of the individual experiencing the object or material itself. While using a single-user case study design in experiment two was an attempt to address this, much more can be done. In part, I hope to address this issue by working closely with designers in the field to understand how they address personality and cultural differences. I also hope to expand upon the work started in this thesis to explore the possibility of mapping personality profiles or demographics to material preferences (i.e. do people less urban environments feel more comfortable with natural materials and less comfortable with artificial ones than those from urban environments? Do elderly individuals prefer materials from their youth?) and understanding if demographic or occupational differences can be used to account for any differences in preference. If so, this further opens up an opportunity for tailoring design and allowing individuals to experience more personalized objects and environments.

8.6 Machine Learning/Artificial Intelligence

Clearly, personal preferences and reactions vary widely - emotional reactions stem from prior experience, memory, cultural association, personality, learning style, and context. As such, creating a general set of guidelines would not be as insightful as personalized recommendations, and therefore, less useful than a more carefully crafted model, which could be achieved via machine learning. Instead, as part of this exploration, individuals would be asked to respond to a training set of stimuli used to normalize results to each respondent. Thus, initial conditions could be determined from which a baseline could be established to reveal patterns to determine relevant material parameters needed to elicit specific emotions.

My initial goal was to create a set of rules to interpret how individuals will emotionally connect to materials and to create materials databases that incorporate emotive properties of materials (a sort of Ashby chart for emotion). While for the purpose of my thesis I focused on approaching this from a broad perspective, in the future I hope to be able to examine individual preferences in addition. My present work has focused on identifying a baseline of salient and universal physical properties, but if instead I could develop a standard set of stimuli to work as a training set to understand initial conditions and train data on user preferences that expose a baseline, I could potentially use machine learning to uncover individual guidelines and patterns. The input would be individual preferences, and using an algorithm of property relations classified based on the person, the output could be emotional categories of objects and combinations of objects. This could result in a system for personalized recommendations.

Using these metrics, parallels could be drawn across material space. Using a baseline of salient and universal physical properties, emotional responses could be predicted. These guidelines could be used to craft environments that evoke very specific feelings more effectively than is currently possible for most novice designers, thus enabling a new model of design and new materials inquiries.

8.7 Understanding Behavior Change

8.7.1 Measuring Human Physical Reactions

In this thesis, all emotions and sentiments were evaluated and recorded through cognitive appraisal and self-report. In future experiments, it would add depth to these studies if responses were recorded through the monitoring of brain signals and physicals responses (through recording responses such as electroencephalogram and electrodermal activity). Exploring our physical signals would also allow researchers to uncover any interesting divergence between our understanding of our responses and our actual, involuntary responses. Recognizing the real-time, genuine responses of individuals to different material stimuli would allow us to design for specific reactions. We can then use such knowledge to subtly influence behavior and emotional responses, or guide someone towards a positive psychological state. This information could paint a much richer picture than mere cognitive responses alone.

8.7.2 Longer Term Behaviors and Emotions

The second study in this work attempted to unpack the ways that materials impact us over time. Users were asked to interact with mobile phone cases for an extended period time. The outcomes of this exploration were intended to rigorously demonstrate the potential use of subtle environmental cues to nudge individuals towards a more positive mindset, which could be employed for behavior change. For instance, if, in returning from a stressful meeting, I were met with desk that responded to my needs by gently nudging me towards a calmer state using a smooth, warm surface. What if it cooled as I felt drowsy to keep me alert? Could such an interface then be used to reduce stress over time? In future work in this area, researchers should focus on exploring the potential of materials to provide support over time, especially in traditionally stressful environments such as offices. These findings would also be extremely relevant to providing therapy and care: materials have been explored in the context of wellbeing of humans in long-term space missions, in providing care for individuals with Alzheimer's, and in calming children on the Autism spectrum. Having a rigorous methodology for understanding the implications of materials could allow us to push work in these areas farther, and even support preventative measures as objects and rooms could be designed in a manner that is personalized and calming for the user.

8.7.3 Second Order Reactions

In this thesis, we have discussed numerous means through which physical stimuli have influenced emotion, mood, or temporary states. For the most part, these influences were direct: sandpaper makes us experience discomfort, which makes us feel sour. But what happens as a result of *that* feeling? What are the "second order" emotional reactions? Wang and colleagues began to answer this question in examination of the role of roughness on empathic behaviors. (cite). The researchers used charitable donations as a quantifiable metric for engagement in empathy, and provided participants with rough or smooth stimuli to examine the difference in response. Rough surfaces increased user awareness of discomfort, which in turn primed people to pay increased attention to those experiencing misfortune (cite). Participants demonstrably acted upon this attention by donating. By causing slight discomfort, experimenters caused other discomfort to become more apparent. In this case, the "first order" reaction was awareness of discomfort due to the rough stimuli, and the "second order" reaction was the increase in empathy that such roughness inspired.

Wang's findings reemphasize the power of subtle contextual cues on shaping important behaviors (cite). The results can be attributed to an "interconceptual mechanism" by which a physical sensation activates mental concepts that are reminiscent of the experience. Based on the spreading activation model, recall of these concepts will then spread to semantically similar ideas (Collins and Loftus, 1975, Higgins et al., 1985 and Wyer and Carlston, 1979). So, for instance, when carrying weight, similar concepts such as heavy seem more salient. Through this mechanism, other concepts are activated as being important, which can then influence the perceived importance of an unrelated item. (Ackerman et al., 2010; Zhang Li, 2012).Wang's findings regarding the impact of spreading activation theory on behavior imply that further research into these "second order" reactions would prove fruitful. Similar examinations into the deeper behavioral impacts of specific material properties would be beneficial for a broad variety of applications ranging from mental health to marketing.

By increasing a person's attention and awareness of a specific sensation, researchers could then direct attention towards desired environmental cues. If findings from spreading activation theory could be combined with further knowledge of the chemical and biological bases of behavior, we could understand the bases of emotions in relation to perception. An interesting future application of such knowledge, as posited by Neri, would be to then attempt to alter perception that occurs as a result of physical stimuli. If, in this manner, materials were seen to act as interfaces that respond to the user, they could evoke unexpected responses for individuals. As suggested by Neri, one ideal outcome of fabrication would be a perception kit that alters or "fixes" perception based on material properties combined effectively. The underlying principle is that if we can, for instance, better understand why engaging with a squishy material (such a stressball or silly putty) is pleasant, we can build materials intended to alter mood. There is inevitably an entire layer of emotion below the immediate cognitive response examined in this thesis, as was alluded to by one participant in the dice study (show image of his mapping).

8.8 Responsive Materials and Environments

Advances in science and engineering are bringing us closer and closer to systems that are able to respond to human stimuli in real-time. Shape-changing materials already operate effectively based on gradients in temperature, composition, chemical exposure, light exposure, and other external inputs. The Tangible Media Group has created shape-changing displays that mimic the feel of materials, 3d printed hair that serves to sense and actuate, and programmable pneumatic systems. It is therefore interesting to consider the possibility of materials that could respond to mood through alteration of such external inputs. What if the soles of my shoes could become more elastic on days when I needed a bit more of a spring in my step? Having a language and mapping of the properties that can evoke specific reactions would allow designers to enable these kinds of interactions with responsive materials.

8.8.1 Building on Haptics

As stated in the introduction, there is a strong link between work undertaken in the field of haptics and robotics and the methods used in this thesis. While current work has focused primarily on learning how to respond to and identify different stimuli, once robots are able to replicate the psychophysical dimensions of human perception, next steps could include exploring the impact of robotics in therapy, restorative care, and wellbeing. Allowing machines to artificially understand the complexity of human response to material stimuli has far-reaching implications. Furthermore, carefully considering the materials that are used to design robots could also be used to improve their reception and make them more familiar and comforting to users (building on the work done to produce Huggable, a robot intended to provide comfort to children in hospitals, in Personal Robots, for instance).

In Kuchenbecker's work at Penn, the robot learns the meaning of haptic adjectives. What if we could add another step and teach robots the emotive meaning as well? What if we could build upon the idea of robots providing comfort to those in hospitals and have them deliver comforting objects to people in other hostile, scary, or uncomfortable environments? Robots presently learn words using physical experiences, but there is room to draw from how children learn emotive meanings through play and exploration. In their studies, the researchers at Penn attempted to produce generalizable physical knowledge by teaching a robot to understand how objects feel, but what if we could actually teach robots how objects make *us* feel? Robots are getting closer and closer to mimicking human action and human ability to differentiate between objects- what if they could also predict and understand the emotional implications?

8.8.2 Virtual and Augmented Reality

In a more immediate application, much of the work I have done with Object-Based Media has been focused on developing technology for holographic video display technology, and we frequently explore and expand the range of user experiences with three-dimensional imaging interfaces. As I continue to develop an understanding of the ability of specific material properties to evoke reactions and create compelling emotional environments, I hope to be able to use this knowledge to reproduce these physical experiences in virtual and augmented environments. Object-Based Media is currently working to incorporate haptic feedback with holographic visual displays, and I anticipate incorporating my findings as this work evolves. Such an endeavor could be completed in an even more compelling manner if I were to further understand methods used by designers to influence and measure behavior change, as I mentioned above. Being able to quantify and identify the factors that make a material feel real and compelling to us would allow us recreate the emotional sense of an environment, thus allowing us to produce more engaging experiences.

8.9 Designing for Wellbeing

This work has implications for many potential applications, but one of the most intriguing lies with design and wellbeing- creating products with specific emotional intentions can be used to promote positive wellbeing and mental health, and to generally create positive user experiences. What if, for instance, knowing the material properties that can cause someone to feel alert or comforted would allow us to build desks that could help keep you awake as the afternoon drags on or calm you down after a stressful meeting?

Understanding the emotive power of materials can also allow us to mitigate unpleasant experiences. For instance, understanding the fundamental properties that evoke comfort could allow designers to create less clinical experiences for patients receiving hospital care. There is an extensive history of materials having value for therapy (team at the Institute of Making is working on understanding materials to communicate emotions in therapy settings, and specific materials are often used to help calm children with autism). Helping everyone be more conversant with the emotive implications of materials could expand the potential for the use of tailored materials in the space of wellbeing.

8.10 Exploring Novel Systems and Metamaterials

In the opening of this thesis, I framed the work in the context of novel materials. Having a means for evaluating the impact of material properties on human emotion would promote more accessible design with new materials. Traditionally, the general public is not initially privy to advancements in science. In some cases, vague notions about the impact of new technology are spread through science fiction. One example is the depiction of nanotechnology in it, where Michael Crichton tells a story of nanorobots preying on humans [34]. In 2003, Prince Charles explicitly articulated fears that nanotechnology would destroy life on earth [34]. People are often uncomfortable with or feel threatened by upcoming technology that they are not given the opportunity to fully understand, or by emerging concepts that are presented to them out of context. As such, designers have an opportunity to introduce individuals to previously mysterious materials in a less fatalistic manner.

The most intriguing future application of this work is the idea of tailoring materials to emotions and building structures that have not yet been explored in this manner. A material system of particular interest to my research group is metamaterials. Metamaterials are artificial media structured on a size scale smaller than the wavelength of external stimuli. Whereas conventional materials derive their characteristics from properties of atoms and molecules, metamaterials enable us to design our own atoms or structural units and thus access new functionalities, which can be carefully tailored. Due to the high degree of control we can have over their functionality, they afford an interesting opportunity to evoke specific reactions. Metamaterials would allow us to push the boundaries of physics by exploring beyond the traditional research into optical, acoustic, and mechanical interactions. For these new systems, there hardly exists a technical taxonomy, let alone a means for interpreting their emotional and sensorial implications. Thus, any work towards this would be entirely new. As nanoscale fabrication techniques and novel material combinations become more commonly used in the design of materials and objects, knowledge on the emotive properties of such systems will be crucial. As stated earlier, designers are often the gatekeepers of interpretation, and thus will have a unique opportunity to introduce the world to metamaterials. As mentioned by Miodownik,

> The sensual experience many materials libraries advocate does not exclude vision, but rather encourages a synaesthesic and processual approach through experimentation and play. There is a sense that with some new materials, this kind of experimental engagement is necessary, since we cannot see what they do by just looking at them or touching them. For example, a meta-material is invisible to the naked eye. We cannot manipulate it to get a feel for it nor smell it like we would molten metal. We are sensually disconnected from it. Even with something like a magnetic liquid, you cant just see what it does with your eyes or your hands. You have to actually have some equipmentif you take a magnet to it, it turns into a solid [90].

What if we could understand the very structural essences of materials that can evoke a certain emotive reaction and develop metamaterials that could generate evocative perceptual qualities that no naturally-occurring material could?

What if we understood the tactile, optical and acoustic properties that would be perceived as conveying a positive emotion such as joy as opposed to a negative emotion such as disgust? How can we use scientific knowledge in this field to generate new properties that enhance the materials that we would choose for certain applications? And could these new techniques be used to create emotionally enhanced versions of traditional materials, for example meta-wood or meta-leather? Here again the concept of combining salient properties to create something more profound than the individual constituents comes into play. By working towards a shared language of the meaning of materials, we hope to can make this vision a reality.

A
Coefficient of Restitution Calculations

The following process was used to determine the coefficient of restitution of the dice used in experiment one. The video analysis method is adapted with the help of Nicholas M. Schneider, based upon the work described in "Automated analysis of evolving interfaces during in situ electron microscopy" [74].

A.1 Experimental Setup:

As stated in chapter 5, coefficient of restitution (COR) is defined as the ratio of the post-impact velocity of an object to the pre-impact velocity [27]. Typical simple experiments to determine COR use the impact of a spherical ball with a thick surface. According to the ASTM, this value is often calculated from a normal drop test via collision with a rigid plane of wood or metal. In this adaptation, the individual dice samples were used, and the wooden slab that participants had been provided as a roll surface was used as the planar surface. In traditional experiments, a ball-throwing device (often involving the use of a vacuum to hold the sample to the nozzle) was used to ensure consistency and replicable velocity of impact. For these experiments, a household vacuum hose was covered, held at a fixed distance, and used as the means of repeating consistent drops. In [27], images were post-processed and analyzed in Adobe Illustrator to determine the necessary parameters for calculation. In this version, images were analyzed using Mathematica. Speeds and behavior were determined by tracing the displacement five frames before and after impact.

A.1.1 Procedure:

An iPhone 6s was used to record videos of each drop in slow-motion mode (1080 dp at 120 fps check this). 40 drops were recorded for each dice to ensure adequate data was collected for accurate measurements. Consistent lighting and backdrops were used.

A.2 Analysis:

Videos were manually edited to determine the point of transition between incoming and outgoing velocity (first bounce), as demonstrated by the red dotted line in the graphs shown in chapter 5. The videos were imported into Mathematica, and clipped to relevant frames. The background was removed by subtracting the first frame (before the appearance of the dice) from other frames. The videos were binarized, and the motion of the centroid of the dice was tracked (see red dot in videos). The height (y position) was recorded as a function of frame (here representing time), and plotted accordingly. Using this plot, the transition point was observed. A line of best fit on either side was calculated, providing the velocity in both directions. The ratio of these velocities represented the COR. The average values of the velocities in 40 drops was used to calculate the COR for each of the 14 samples.

B

Dice User Study Questions

B.1 Part I

This part will be conversational and informal.
1. Can you think of an object that you feel particularly attached to? Please describe that object.
2. Can you describe an environment, setting, or room that you have an affinity for?

B.2 Part II

1. Rank these samples based on the loudness of the sound produced when you roll them (soft to loud). Place the sample number in the appropriate box.

2. Rank these samples based on how warm they feel (cold to warm).

3. Rank these samples based on how hard they seem (soft to hard).

4. Rank these samples based on how rough they are (smooth to rough).

5. Rank these samples based on how shiny they are (dull to shiny).

6. Rank these samples based on how heavy they feel (light to heavy).

7. Rank these samples based on how likely you would be to use them (least to most).

8. In considering the dice that you found the most pleasing and the dice which you found the least pleasing, which of these factors was most important to your overall evaluation of the dice?

B.3 Part III

1. Think about what emotional feeling you associate with the different samples and rate them for similarity, keeping in mind that you are rating based on similarity of feelings, not the pieces themselves. You may arrange them however you like (and turn the page sideways if you like). Please use the sample labels as you rate them.

B.4 Part I continued

3. If we were to describe the concept of dice, what properties would you consider desirable, and why?

4. (after part II) What were your initial reactions to the sample you considered most desirable? How about the least desirable? Did you have any initial reactions to the others?

5. (after part II) Did any of the dice remind you of anything? Have you seen any of them before?

6. In thinking of the material of the pieces that you found most and least desirable, what context might you see the material in? Are any particularly obvious? Can you imagine seeing them anywhere?

7. Does the material evoke any meaning?

8. What would a dice for your grandparents look like? How about your best friend?

B.5 Part III continued

- Please rate the dice based on how pleasing you find them. (each one)

- Rank these samples based on how masculine they are (feminine to masculine).
- Trendy to classic
- Cozy to Clinical
- Historic to Futuristic
- Common to Exclusive
- Delicate to Rugged
- Clumsy to Elegant
- Frightening to Friendly
- Serious to Humorous
- Youthful to Mature
- Passive to Aggressive

C

Dice Demographic Data

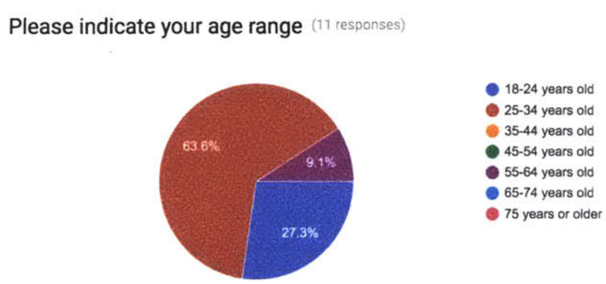


Figure C-1: Ages represented in the sample population

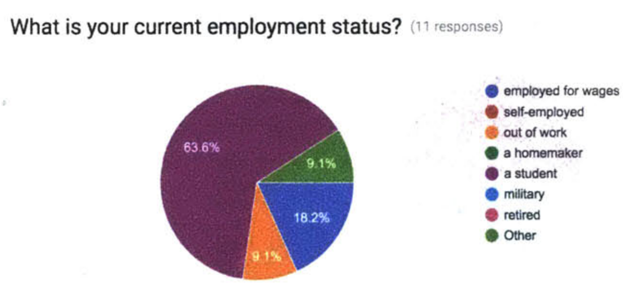


Figure C-2: Employment status of the sample population

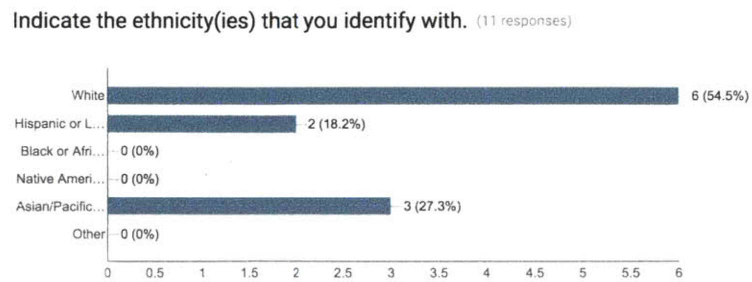


Figure C-3: Ethnicities represented amongst the sample population

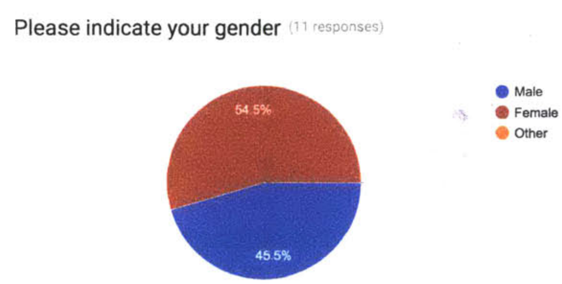


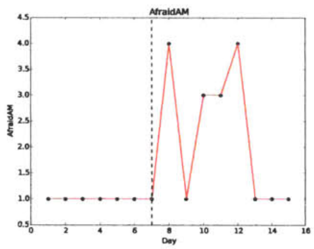
Figure C-4: Gender affiliations reported amongst the sample population

D

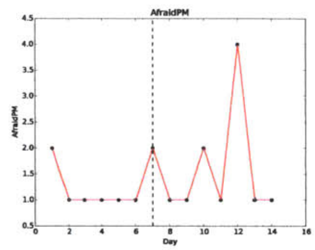
Phone Case Data

D.1 2-3 week study

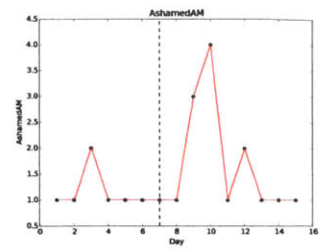
The plots for individual users per parameter are shown here:



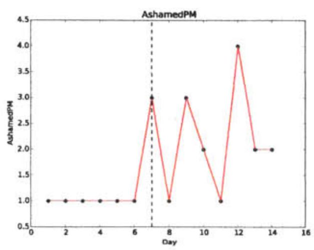
(a) AfraidAM



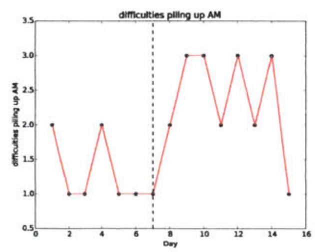
(b) AfraidPM



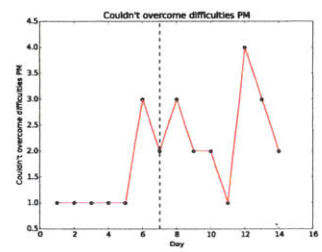
(c) AshamedAM



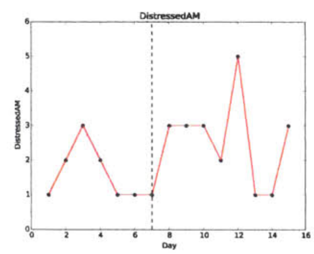
(d) AshamedPM



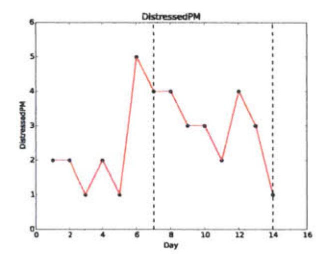
(e) Difficulties Piling Up AM



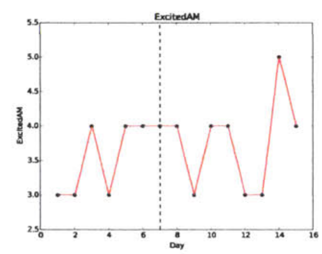
(f) Difficulties Piling Up PM



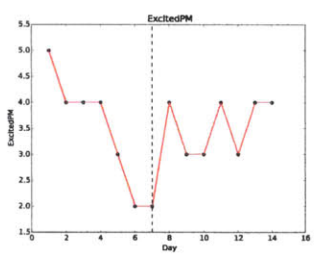
(g) DistressedAM



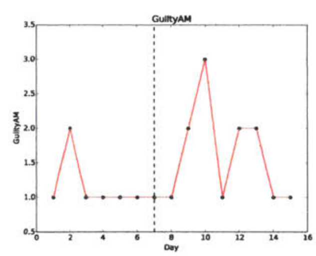
(h) DistressedPM



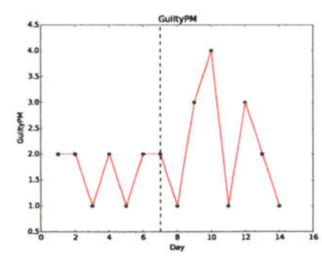
(i) Excited AM



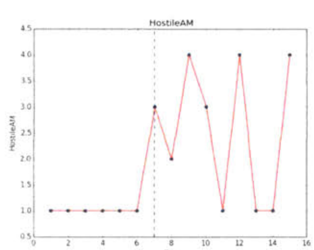
(j) ExcitedPM



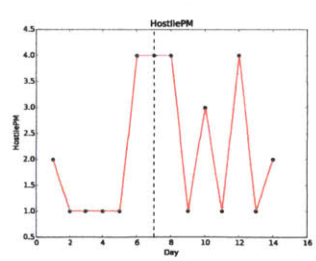
(k) GuiltyAm



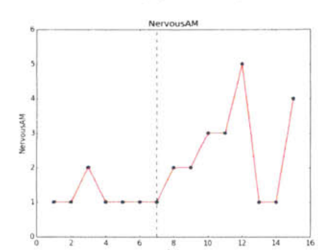
(l) GuiltyPM



(m) HostileAm

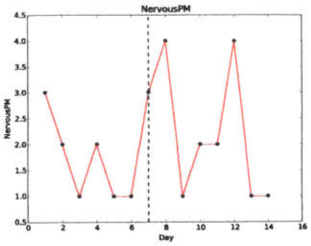


(n) HostilePm



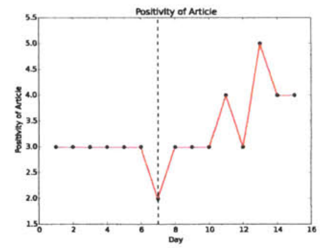
(o) NervousAM

Figure D-1: Relevant plots for user 982

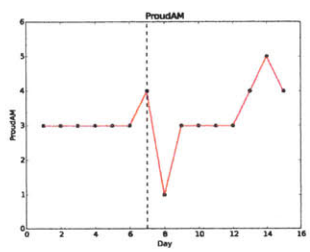


(a) NervousPM

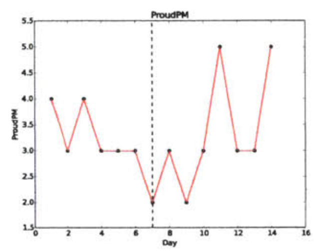
(b) Notice Case



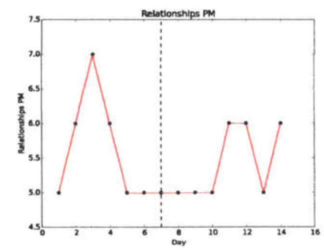
(c) Article positivity



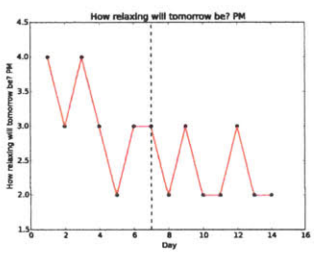
(d) ProudAM



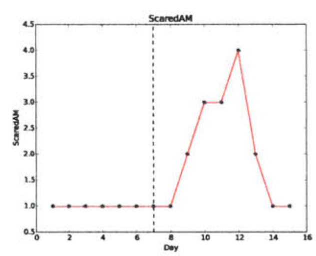
(e) ProudPM



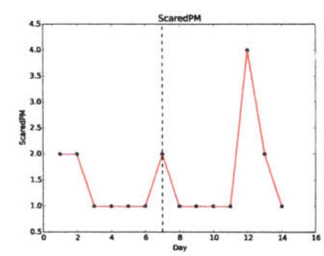
(f) Perception of relationships



(g) How relaxing will tomorrow be?

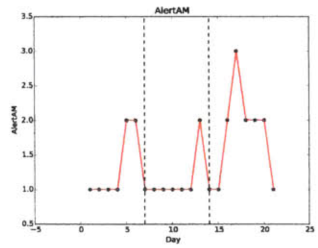


(h) ScaredAM

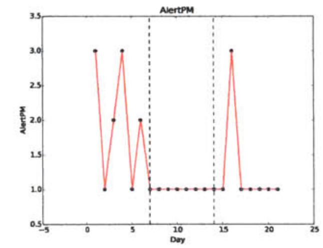


(i) ScaredPM

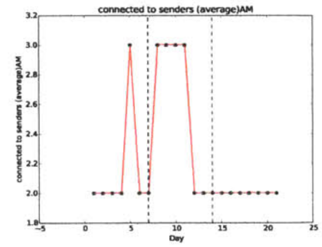
Figure D-2: Relevant plots for user 982



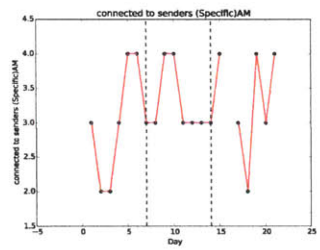
(a) AlertAM



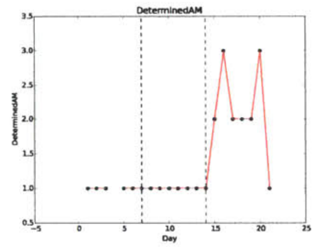
(b) AlertPM



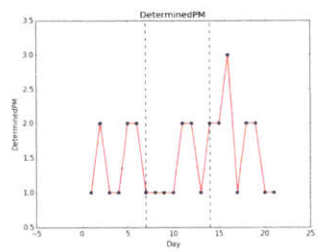
(c) Connected to senders



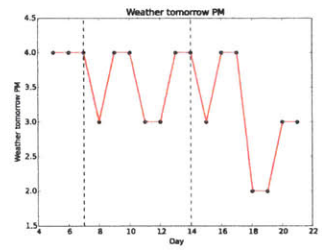
(d) Connected to senders (specific)



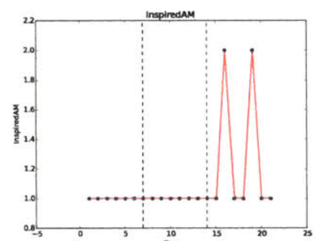
(e) DeterminedAM



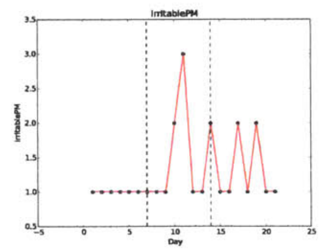
(f) DeterminedPM



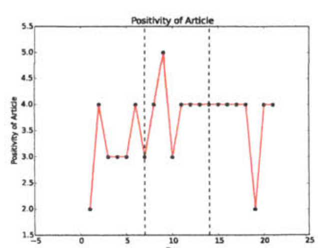
(g) Perception of future weather



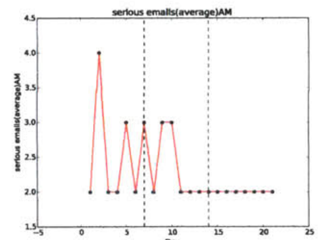
(h) InspiredAM



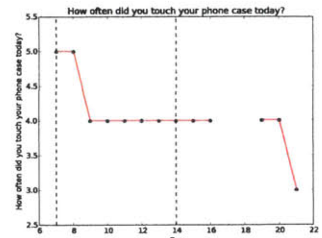
(i) IrritatedPM



(j) Article positivity

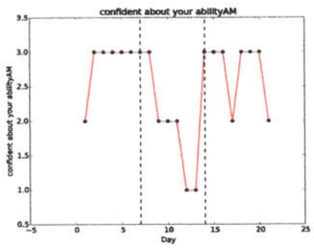


(k) Perceived seriousness of emails

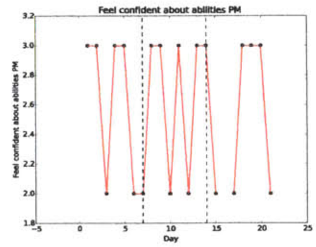


(l) How often case was touched

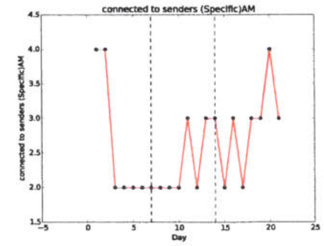
Figure D-3: Relevant plots for user 321



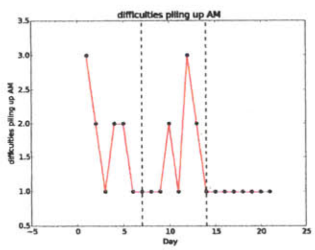
(a) ConfidentAM



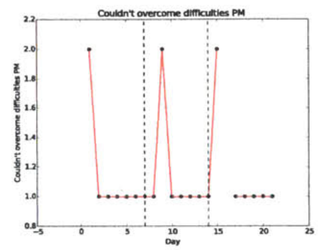
(b) ConfidentPM



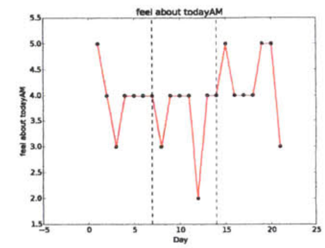
(c) Connected to senders



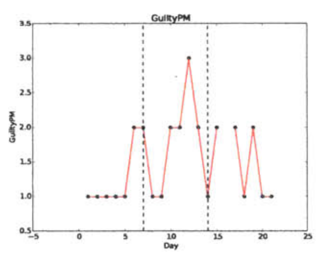
(d) Difficulties piling upAM



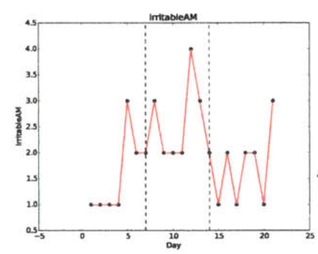
(e) Difficulties piling upPM



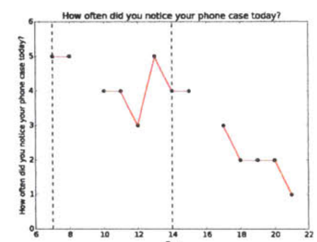
(f) Perception of the day



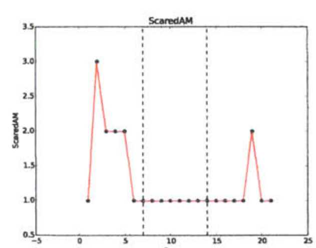
(g) GuiltyPM



(h) IrritatedAM



(i) How often did you notice the case



(j) ScaredAM

Figure D-4: Relevant plots for user 32

D.2 Brief study

Figure D-5: Average responses per case treatment for the various tasks in the 45 minute study

	How "serious" was the content of this call?	How "important" was the content of this call?	How do you feel about this call?	How connected do you feel to the recipient of your call?	How “serious” or “important” was the content of these emails on average?	How “serious” was the content of the emails that you spent the most time on?
Average for A	2.33	3.00	3.67	4.50	1.80	2.20
Average for B	1.57	2.29	3.71	3.14	3.14	3.29
Average for C	2.00	2.33	3.83	4.17	2.38	2.75
Average for Control	2.33	2.83	4.00	3.50	2.43	3.43
	How connected do you feel to senders of these emails?	How connected do you feel to senders of these emails (specific)?	How quickly (on average) do you feel you should respond to these emails?	How “serious” or “important” was the content of this article?	How relevant do you feel this article is to you?	How does this article rank in terms of negativity to positivity?
Average for A	1.80	2.00	2.40	3.40	2.20	2.80
Average for B	3.00	3.14	2.29	4.29	2.43	3.14
Average for C	2.13	2.88	2.75	3.63	1.88	3.13
Average for Control	1.57	2.14	2.00	4.29	2.57	2.71

Figure D-6: Average of positive or negative attributes for each participant, shown by case

Participant	Case A, Pos Before	Case A, Pos After	Case A, Neg Before	Case A, Neg After
36	1.3	1.8	2.2	1.4
397	2.6	3.1	4.2	4.2
219	1.9	1.4	1	1.1
199	3	3.6	2.1	2.1
59	2.5	2.6	2	1.3
932	2.6	2	1.6	1.8
AVG	**2.32**	**2.42**	**2.18**	**1.98**

Participant	Case B, Pos Before	Case B Pos After	Case B, Neg Before	Case B, Neg After
478	2.7	2.4	1.2	1.5
49	2.5	2.1	1	1
97	3	2.4	1.3	1.2
891	3.1	3.2	4.2	3.6
215	4.2	3.3	1.2	1
909	2.7	2.9	2.1	2.3
AVG	**3.03**	**2.72**	**1.83**	**1.77**

Participant	Case C, Pos Before	Case C Pos After	Case C, Neg Before	Case C, Neg After
394	2.6	2.6	1.2	1.3
854	2.2	2.4	1.1	1
512	2.8	3.4	1.1	1
8	3.2	3.3	1.7	1.7
213	3.2	3.4	1.4	1
44	4.1	4.6	1.4	1.5
102	2.3	2.3	2	1.9
33	2.2	2.1	1.3	1.1
709	3.2	3	2.5	2.9
AVG	**2.87**	**3.01**	**1.52**	**1.49**

Participant	Control, Pos Before	Control Pos After	Control, Neg Before	Control Neg After
5	4	3.7	1.5	1.4
635	3.8	3.4	1.9	1.7
537	2.7	3	1.3	1.1
439	3.6	3.4	1.2	1
994	3.2	3.3	1	1
71	2.6	3	2.2	1.5
16	2.4	2.5	2.8	2.9
28	2.4	2.8	1.3	1
AVG	**3.09**	**3.14**	**1.65**	**1.45**

E Phone Case Study Questions

E.1 AM

In the morning, participants were asked to respond to the following questions:

1. Read each item and then mark the appropriate answer in the space next to that word. Indicate to what extent you have felt like this in the past few hours. Use the following scale to record your answers. 1 = very slightly, 2 = a little, 3 = moderately, 4 = quite a bit, 5 = extremely. The terms provided were: Nervous Active Scared Upset Excited Guilty Jittery Ashamed Distressed Hostile Afraid Alert Interested Determined Irritable Inspired Proud Enthusiastic Strong Attentive

2. Indicate how often in the past few hours you have felt the way described in each of the following statements. 1 = hardly ever, 2 = some of the time, 3 = often How often do you feel isolated from others? How often do you feel left out? How often do you feel that you lack companionship?

3.The questions in this scale ask you about your feelings and thoughts during the last few hours. In each case, please indicate how often you felt or thought a certain way. 0 = never, 1 = almost never, 2 = sometimes, 3 = fairly often, 4 = very often

How often have you felt that you were unable to control the important things in your life? How often have you felt confident about your ability to handle your personal problems? How often have you felt difficulties were piling up so high that you could not overcome them? How often have you felt that things were going your way?

4. Each day participants were presented with a new article, and asked the following questions: How "serious" or "important" was the content of this article? (1-5) How

relevant is this article to you? (1-5) How does this article rank in terms of negativity to positivity?(1-5)

5. Please check your email for the next 5-10 minutes. Please dedicate this time just to scanning or reading emails. Do not respond to them during this time (unless it is URGENT). How serious or important" was the content of these emails on average? How connected do you feel to senders of these emails (on average) How serious or important" was the content of the emails that you spent the most time on? How connected do you feel to senders of these emails (that you spent the most time on)? How quickly (on average) do you feel you should respond to these emails?

6. Briefly list your major plans for the day (1-5 items)

7. How do you feel (overall) about the events that occurred yesterday?

8. How do you feel (overall) about the events that you anticipate for today?

E.2 PM

In the evening, participants were asked to respond to the following questions:

1. Please take 5-10 minutes to place a phone call(unless you have done so in the past 4-5 hours). How "serious" was the content of this call?

2. Who did you call?

3.How "important" was the content of this call?

4.How do you feel about this call?

5.How connected do you feel to the recipient of your call?

6.How often did you notice your phone case today?

7.How often did you touch your phone case today?

8. What do you think of this case so far? How do you like it? What do you notice about it?

9.The mood, loneliness, and stress questions posed in the morning were repeated here.

10. Please rank how you feel about your relationships based on today's events.

11. Please rank how you feel about your work based on today's events.

12. Please rank how you feel about your mental health based on today's events.

13.Please rank how you feel about your physical health based on today's events.

14.Please list memorable events that happened today. Were any of them stressful?Were any of them relaxing?

15. How relaxing do you anticipate tomorrow being in comparison to today?

16. What do you think the weather will be like tomorrow (please do not check the actual weather report)?

17. Please describe the weather you expect to see.

E.3 Case Exchange

When the cases were exchanged, users completed the mood assessment, loneliness evaluation, and stress scale, as well as the task questions related to emails. They were asked qualitative questions about the new and old cases (listed in the section below).

E.4 45 minute test

For the 45 minute study, users began by completing the same opening survey as participants in the longer study had, and were asked the same task questions as the participants in the longer study. Both participants in the longer and shorter study were asked the following questions: How do you typically use your phone? (rank the most to least common)
Do you currently use a phone case?
If so, how did you pick your phone case?
How long have you had your case for?
Why do you have a case?
How aware are you of the case on a regular basis?
How often do you use your phone?
Do you normally keep your phone in your pocket? Backpack? etc?

When you make phone calls do you normally use headphones? Hold your phone? Etc.

After using the trial case: What did you think of this case?
Would you use it?
What did you notice about it
Does this material remind you of anything?
Do you associate it with anything?
If you were to describe this case in one word, what would it be?
Did you feel like it changed as you held it in any way?
How pleasant did you find the case? Relaxing? Stressful? Warm?
What would you change about this case?
What would your ideal case be made of?
Do you think this case impacted how you view your phone? your mood?
What properties do you consider desirable in a phone case?
Any other comments about the case?

F

Making Casein

In my quest to examine fascinating materials, my advisor informed me that we absolutely had to try casein. Derived from milk protein, casein (also known as galalith), was once used for pen handles. As a result of its constituent ingredients, casein is said to have an incredibly unique, warm, smooth feel to it that could have provided an excellent counterbalance to the cold, shiny aluminum case. While it is difficult to purchase sheets of casein, the plastic is regularly produced in science classes as the ingredient list is simply milk, vinegar, and dye.

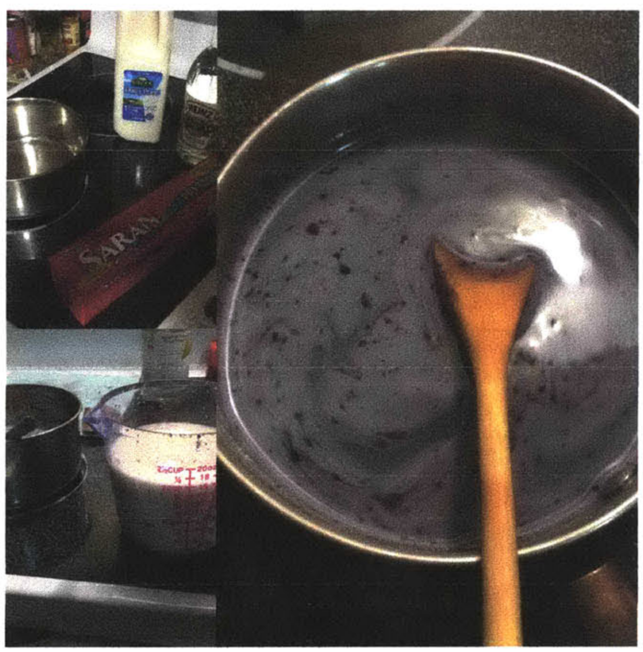


Figure F-1: The making process

Basic casein can be produced by bringing one cup of milk to simmer, and adding between 1-4 tsps of vinegar. A polymerization reaction will begin as the pot is removed from heat, and solid chunks will begin to form. The mixture should then be strained, and the solids are then dried and placed in a mold. Alterations in the temperature and amount of vinegar can have a dramatic impact on the result.

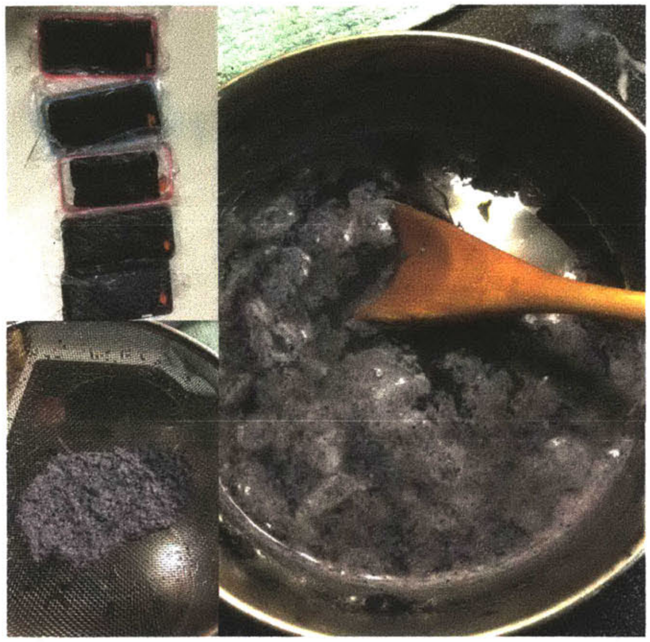


Figure F-2: Coagulating and straining

Unfortunately, the initial conditions tested here were unsuccessful: the end product shrank, warped, and became oily, though a plastic did form!

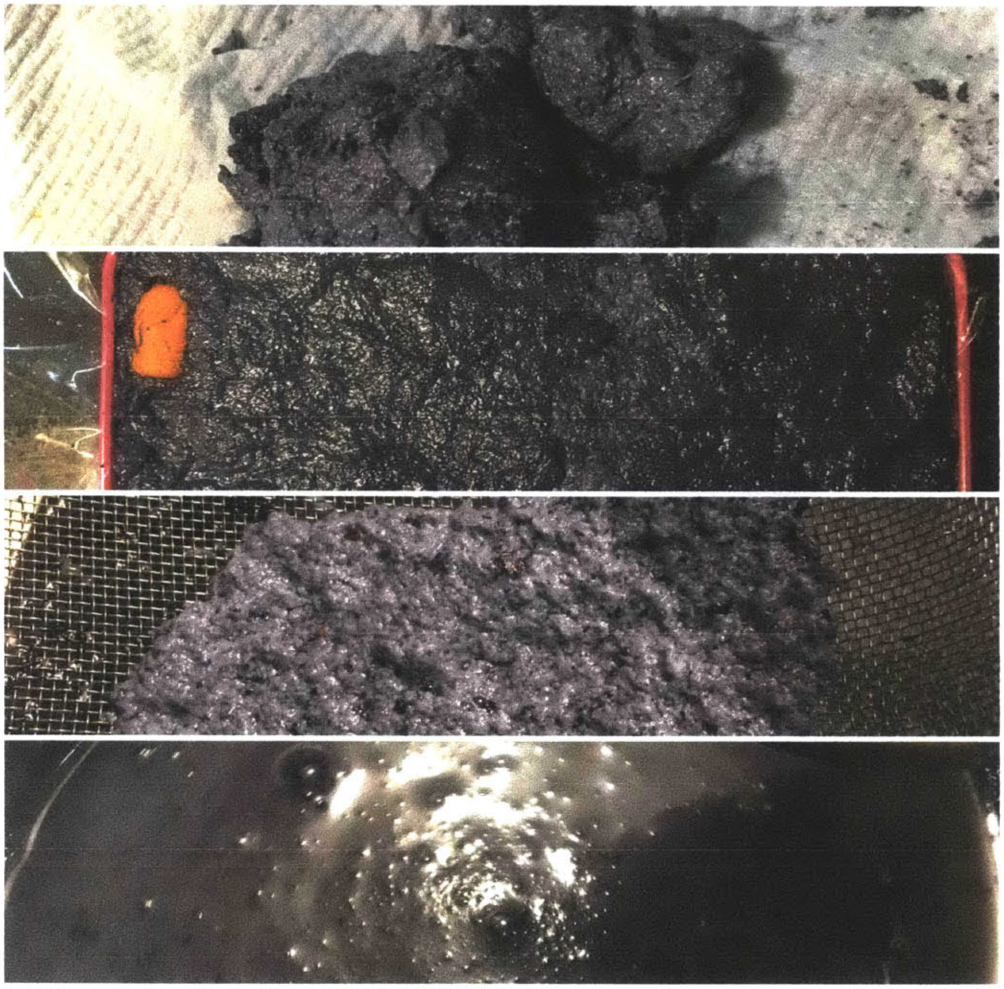


Figure F-3: The various stages of casein: drying, molded, strained, and liquid

Bibliography

[1] Harvard frances loeb library: Materials collection. http://www.gsd.harvard.edu//loeblibrary/collections/materials-collection/.

[2] Design implementation of baseball bats: Reinforced bats—a case study. *JOM*, 64(3):359–363, 2012.

[3] Lycurgus cup, 4th century. The British Museum, Gilded silver and glass.

[4] Iridescent butterfly wing properties to lead to better thermal imaging cameras, February 27, 2012.

[5] Granta's ces edupack. *Granta Material Intelligence*, Granta Design Limited 2007.

[6] Joshua M Ackerman, Christopher C Nocera, and John A Bargh. Incidental haptic sensations influence social judgments and decisions. *Science*, 328(5986):1712–1715, 2010.

[7] Chinese Fortune Angel. *The Personality and Five Elements in Chinese Astrology.* Available at `http:///www.chinesefortunecalendar.com/pc/Angel/5EPersonality.htm`, Accessed on June 1, 2016.

[8] H Aoki, T Suzuki, and Y Matsuoka. Study on correspondence between sensory and physical properties of materials (ii)–comparison of natural and substitute leather for hand. *Bulletin of JSSD*, 53:43–48, 1985.

[9] Johnson Kara Ashby, Mike. *Materials and Design - The Art and Science of Material Selection in Product Design (2nd Edition).* Elsevier, 2010.

[10] Philip Ball. *Made to measure: New materials for the 21st century*. Princeton University Press, 1999.

[11] Bernd Bickel, Moritz Bächer, Miguel A Otaduy, Hyunho Richard Lee, Hanspeter Pfister, Markus Gross, and Wojciech Matusik. Design and fabrication of materials with desired deformation behavior. In *ACM Transactions on Graphics (TOG)*, volume 29, page 63. ACM, 2010.

[12] HGTV Design blog. *Classy Trash Cans*. Available at `http://blog.hgtv.com/design/2014/03/13/classy-trash-cans/`, Accessed on April 24, 2016.

[13] Erik Cambria, Andrew Livingstone, and Amir Hussain. *The Hourglass of Emotions*, pages 144–157. Springer Berlin Heidelberg, Berlin, Heidelberg, 2012.

[14] Walter B. Cannon. The james-lange theory of emotions: A critical examination and an alternative theory. *The American Journal of Psychology*, 39(1/4):106–124, 1927.

[15] Vivian Chu, Ian McMahon, Lorenzo Riano, Craig G McDonald, Qin He, Jorge Martinez Perez-Tejada, Michael Arrigo, Naomi Fitter, John C Nappo, Trevor Darrell, et al. Using robotic exploratory procedures to learn the meaning of haptic adjectives. In *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, pages 3048–3055. IEEE, 2013.

[16] Sheldon Cohen, Tom Kamarck, and Robin Mermelstein. A global measure of perceived stress. *Journal of health and social behavior*, pages 385–396, 1983.

[17] Geoffrey L. Collier. Affective synesthesia: Extracting emotion space from simple perceptual stimuli. *Motivation and Emotion*, 20(1):1–32, 1996.

[18] Heather Culbertson, Juliette Unwin, and Katherine J Kuchenbecker. Modeling and rendering realistic textures from unconstrained tool-surface interactions. *IEEE transactions on haptics*, 7(3):381–393, 2014.

[19] Jesse Dallery, N. Rachel Cassidy, and R. Bethany Raiff. Single-case experimental designs to evaluate novel technology-based health interventions. *J Med Internet Res*, 15(2):e22, Feb 2013.

[20] Charles Darwin, Paul Ekman, and Phillip Prodger. *The expression of the emotions in man and animals*. Oxford University Press, USA, 1998.

[21] Pieter Desmet and Paul Hekkert. Framework of product experience. *International journal of design*, 1(1), 2007.

[22] Pieter MA Desmet and P Hekkert. The basis of product emotions. *Pleasure with products, beyond usability*, pages 60–68, 2002.

[23] Andrew Duffy and Ali Loewy. Physics lecture demonstrations at Boston University, 1998.

[24] Paul Ekman. An argument for basic emotions. *Cognition & emotion*, 6(3-4):169–200, 1992.

[25] Waka Fujisaki, Midori Tokita, and Kenji Kariya. Perception of the material properties of wood based on vision, audition, and touch. *Vision Research*, 109, Part B:185 – 200, 2015. Perception of Material Properties (Part I).

[26] Robert M Haralick, Karthikeyan Shanmugam, et al. Textural features for image classification. *IEEE Transactions on systems, man, and cybernetics*, (6):610–621, 1973.

[27] Adli Haron and K A Ismail. Coefficient of restitution of sports balls: A normal drop test. *IOP Conference Series: Materials Science and Engineering*, 36(1):012038, 2012.

[28] Manfred Hegger, Volker Auch-Schwelk, Matthias Fuchs, and Thorsten Rosenkranz. *Construction materials manual.* Walter de Gruyter, 2006.

[29] Mark Holliins, Richard Faldowski, Suman Rao, and Forrest Young. Perceptual dimensions of tactile surface texture: A multidimensional scaling analysis. *Perception & psychophysics*, 54(6):697–705, 1993.

[30] ME Hughs, LJ Waite, LC Hawkley, and JT Cacioppo. A short scale for measuring loneliness in large surveys. *Research on Aging*, 26(6):655–672, 2004.

[31] John Hunt, Jonah Gollub, Tom Driscoll, Guy Lipworth, Alex Mrozack, Matthew S. Reynolds, David J. Brady, and David R. Smith. Metamaterial microwave holographic imaging system. *J. Opt. Soc. Am. A*, 31(10):2109–2119, Oct 2014.

[32] Hans IJzerman and Gün R Semin. The thermometer of social relations mapping social proximity on temperature. *Psychological science*, 20(10):1214–1220, 2009.

[33] Anubhav Jain, Shyue Ping Ong, Geoffroy Hautier, Wei Chen, William Davidson Richards, Stephen Dacek, Shreyas Cholia, Dan Gunter, David Skinner, Gerbrand Ceder, and Kristin a. Persson. The Materials Project: A materials genome approach to accelerating materials innovation. *APL Materials*, 1(1):011002, 2013.

[34] Mikael Johansson. plenty of room at the bottom: Towards an anthropology of nanoscience. *Anthropology Today*, 19(6):3–6, 2003.

[35] Kara W Johnson, Torben Lenau, Mike F Ashby, et al. The aesthetic and perceived attributes of products. In *DS 31: Proceedings of ICED 03, the 14th International Conference on Engineering Design, Stockholm*, 2003.

[36] Nils B Jostmann, Daniël Lakens, and Thomas W Schubert. Weight as an embodiment of importance. *Psychological science*, 20(9):1169–1174, 2009.

[37] V Jousmki and R Hari. Parchment-skin illusion: sound-biased touch. *Current Biology*, 8(6):R190 – R191, 1998.

[38] Yoona Kang, Lawrence E Williams, Margaret S Clark, Jeremy R Gray, and John A Bargh. Physical temperature effects on trust behavior: the role of insula. *Social Cognitive and Affective Neuroscience*, page nsq077, 2010.

[39] B. Barati V. Rognoli A. Zeeuw van der Laan Karana, Elvin. Material driven design (mdd): A method to design for material experiences. *International Journal of Design*, 9(2):35–54, 2015.

[40] Elvin Karana. *Meanings of materials*. PhD thesis, TU Delft, Delft University of Technology, 2009.

[41] Elvin Karana, Paul Hekkert, and Prabhu Kandachar. A tool for meaning driven materials selection. *Materials & Design*, 31(6):2932–2941, 2010.

[42] Elvin Karana, Owain Pedgley, and Valentina Rognoli. *Materials Experience: fundamentals of materials and design*. Butterworth-Heinemann, 2013.

[43] David Kirsh. Embodied cognition and the magical future of interaction design. *ACM Trans. Comput.-Hum. Interact.*, 20(1):3:1–3:30, April 2013.

[44] Carl Georg Lange and William James. *The emotions*, volume 1. Williams & Wilkins, 1922.

[45] Ann-Sophie Lehmann. How materials make meaning. *Netherlands Yearbook for History of Art/Nederlands Kunsthistorisch Jaarboek Online*, 62(1):6–27, 2012.

[46] X Liu, Z Yue, Z Cai, D G Chetwynd, and S T Smith. Quantifying touch-feel perception: tribological aspects. *Measurement Science and Technology*, 19(8):084007, 2008.

[47] Thalma Lobel. *Sensation: the new science of physical intelligence*. Simon and Schuster, 2016.

[48] Neil MacGregor. "put-that-there": Voice and gesture at the graphics interface. *SIGGRAPH Comput. Graph.*, 14(3):262–270, 1980.

[49] Elicia Maine, David Probert, and Mike Ashby. Investing in new materials: a tool for technology managers. *Technovation*, 25(1):15–23, 2005.

[50] Ezio Manzini and Pasquale Cau. *The material of invention*. Mit Press, 1989.

[51] Roman Mars. "99% sound and feel", 2010. 99% Invisible, Podcast audio, Radiotopia. http://99percentinvisible.org/episode/episode-10-99-sound-and-feel/.

[52] David Matsumoto, Dacher Keltner, Michelle N Shiota, MAUREEN OSullivan, and Mark Frank. Facial expressions of emotion. *Handbook of emotions*, 3:211–234, 2008.

[53] Samuel McNerney. A brief guide to embodied cognition: why you are not your brain. *Scientific American*, 2011.

[54] Mark Miodownik. *"Stuff Matters: Exploring the Marvelous Materials that Shape our Man-Made World"*. Houghton Mifflin Harcourt, New York, New York, 2013.

[55] Mark A Miodownik. Toward designing new sensoaesthetic materials. *Pure and Applied Chemistry*, 79(10):1635–1641, 2007.

[56] Philippa Mothersill. The Form of Emotive Design. Master's thesis, Massachusetts Institute of Technology, Cambridge, MA, 2014.

[57] Paula M Niedenthal. Embodying emotion. *Science*, 316(5827):1002–1005, 2007.

[58] Donald A Norman. *The design of everyday things: Revised and expanded edition*. Basic books, 2013.

[59] Stanford University Institute of Design. Virtual crash course in design thinking, June 2016.

[60] S. Okamoto, H. Nagano, and Y. Yamada. Psychophysical dimensions of tactile perception of textures. *IEEE Transactions on Haptics*, 6(1):81–93, First 2013.

[61] Andrew Ortony and Terence J Turner. What's basic about basic emotions? *Psychological review*, 97(3):315, 1990.

[62] Juhani Pallasmaa. *The eyes of the skin: architecture and the senses*. John Wiley & Sons, 2012.

[63] John B Pendry, David Schurig, and David R Smith. Controlling electromagnetic fields. *science*, 312(5781):1780–1782, 2006.

[64] Bruna Petreca, Sharon Baurley, and Nadia Bianchi-Berthouze. How do designers feel textiles? In *Affective Computing and Intelligent Interaction (ACII), 2015 International Conference on*, pages 982–987. IEEE, 2015.

[65] Robert Plutchik. *The emotions*. University Press of America, 1991.

[66] Jonathan Posner, James A Russell, and Bradley S Peterson. The circumplex model of affect: An integrative approach to affective neuroscience, cognitive development, and psychopathology. *Development and psychopathology*, 17(03):715–734, 2005.

[67] Martin Reimann, Wilko Feye, Alan J Malter, Joshua M Ackerman, Raquel Castano, Nitika Garg, Robert Kreuzbauer, Aparna A Labroo, Angela Y Lee, Maureen Morrin, et al. Embodiment in judgment and choice. *Journal of Neuroscience, Psychology, and Economics*, 5(2):104, 2012.

[68] Travis Rich, Andy Lippman Kevin Hu, Basheer Tome, and Cesar Hidalgo. *Mapping the Emotional Language of gifs*. Available at `http://www.gif.gf/about`, Accessed on July 1, 2016.

[69] Valentina Rognoli. The aesthetical and sensorial characterization of design materials. In *1 st International Meeting of Science and technology of Design, Senses and Sensibility in Technology, IADE, Lisboa*, 2003.

[70] Daniel W Russell. Ucla loneliness scale (version 3): Reliability, validity, and factor structure. *Journal of personality assessment*, 66(1):20–40, 1996.

[71] Stanley Schachter and Jerome Singer. Cognitive, social, and physiological determinants of emotional state. *Psychological review*, 69(5):379, 1962.

[72] Hendrik N.J. Schifferstein and Lisa Wastiels. Chapter 2 - sensing materials: Exploring the building blocks for experiential design. In Elvin Karana, Owain Pedgley, and Valentina Rognoli, editors, *Materials Experience*, pages 15 – 26. Butterworth-Heinemann, Boston, 2014.

[73] Robert Schittny, Muamer Kadic, Sebastien Guenneau, and Martin Wegener. Experiments on transformation thermodynamics: Molding the flow of heat. *Phys. Rev. Lett.*, 110:195901, May 2013.

[74] Nicholas M. Schneider, Jeung Hun Park, Michael M. Norton, Frances M. Ross, and Haim H. Bau. Automated analysis of evolving interfaces during in situ electron microscopy. *Advanced Structural and Chemical Imaging*, 2(1):1–11, 2016.

[75] Daniel L Schodek, Paulo Ferreira, and Michael F Ashby. *Nanomaterials, nanotechnologies and design: an introduction for engineers and architects*. Butterworth-Heinemann, 2009.

[76] Christian Schumacher, Bernd Bickel, Jan Rys, Steve Marschner, Chiara Daraio, and Markus Gross. Microstructures to control elasticity in 3d printing. *ACM Transactions on Graphics (TOG)*, 34(4):136, 2015.

[77] Michael L Slepian, EJ Masicampo, Negin R Toosi, and Nalini Ambady. The physical burdens of secrecy. *Journal of Experimental Psychology: General*, 141(4):619, 2012.

[78] Craig A Smith and Richard S Lazarus. Appraisal components, core relational themes, and the emotions. *Cognition & Emotion*, 7(3-4):233–269, 1993.

[79] Auke Tellegen, David Watson, and Lee Anna Clark. On the dimensional and hierarchical structure of affect. *Psychological Science*, 10(4):297–303, 1999.

[80] Wouter M Bergmann Tiest. Tactual perception of material properties. *Vision research*, 50(24):2775–2782, 2010.

[81] Wouter M. Bergmann Tiest and Astrid M.L. Kappers. Analysis of haptic perception of materials by multidimensional scaling and physical measurements of roughness and compressibility. *Acta Psychologica*, 121(1):1 – 20, 2006.

[82] Wouter M Bergmann Tiest and Astrid ML Kappers. Haptic and visual perception of roughness. *Acta psychologica*, 124(2):177–189, 2007.

[83] Silvan S Tomkins. Affect theory. *Approaches to emotion*, 163:195, 1984.

[84] George Torrens and Diane E Gyi. Towards the integrated measurement of hand and object interaction. 1999.

[85] IEH Van Kesteren, Pieter Jan Stappers, and JCM De Bruijn. Materials in products selection: tools for including user-interaction in materials selection. *International journ al of sedign, 1 (3) 2007*, 2007.

[86] Chen Wang, Rui Juliet Zhu, and Todd C Handy. Experiencing haptic roughness promotes empathy. *Journal of Consumer Psychology*, 2015.

[87] Lisa Wastiels and Ine Wouters. Material considerations in architectural design: a study of the aspects identified by architects for selecting materials. 2009.

[88] David Watson, Lee A Clark, and Auke Tellegen. Development and validation of brief measures of positive and negative affect: the panas scales. *Journal of personality and social psychology*, 54(6):1063, 1988.

[89] Howard M Weiss and Russell Cropanzano. Affective events theory: A theoretical discussion of the structure, causes and consequences of affective experiences at work. 1996.

[90] Sarah Wilkes. Materials matter: An anthropological study of materials libraries. *Unpublished MA Dissertation, University College London*, 2008.

[91] Sarah Wilkes, Supinya Wongsriruksa, Philip Howes, Richard Gamester, Harry Witchel, Martin Conreen, Zoe Laughlin, and Mark Miodownik. Design tools for interdisciplinary translation of material experiences. *Materials & Design*, 90:1228–1237, 2016.

[92] Sarah Elizabeth Wilkes. Materials libraries as vehicles for knowledge transfer. *Anthropology Matters*, 13(1), 2011.

[93] Lawrence E Williams and John A Bargh. Experiencing physical warmth promotes interpersonal warmth. *Science*, 322(5901):606–607, 2008.

[94] Lawrence E Williams, Julie Y Huang, and John A Bargh. The scaffolded mind: Higher mental processes are grounded in early experience of the physical world. *European Journal of Social Psychology*, 39(7):1257, 2009.

[95] Supinya Wongsriruksa, Philip Howes, Martin Conreen, and Mark Miodownik. The use of physical property data to predict the touch perception of materials. *Materials & Design*, 42:238–244, 2012.

[96] Wilhelm Max Wundt. *Outlines of psychology*. W. Engelmann, 1907.

[97] Hengfeng Zuo. The selection of materials to match human sensory adaptation and aesthetic expectation in industrial design/insan duyumuna uyabilecek malzeme secimini yapmak ve endustriyel tasarimda estetik beklenti. *METU Journal of the Faculty of Architecture*, 27(2):301–320, 2010.

[98] Hengfeng Zuo, Tony Hope, Paul Castle, and Mark Jones. An investigation into the sensory properties of materials. *Psychology*, 2001.

[99] Hengfeng Zuo, Tony Hope, and Mark Jones. Chapter 3 - tactile aesthetics of materials and design. In Elvin Karana, Owain Pedgley, and Valentina Rognoli, editors, *Materials Experience*, pages 27 – 37. Butterworth-Heinemann, Boston, 2014.