THE THESIS COMMITTEE FOR TREVOR HOGAN CERTIFIES THAT THIS IS THE APPROVED VERSION OF THE FOLLOWING THESIS:

DATA AND DASEIN

- A Phenomenology of Human-Data Relations -

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DECLARATION

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text. I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Weimar, April 2016

Trevor Hogan

Aim for the sky and you will reach the top of the mountains.

— (Terry Hogan—on many occasions 1975-present)

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As I write these words I find myself reflecting on my PhD journey, from the first email exchange with my supervisor, over many fond memories travelling across the world attending conferences, to the endless pages of transcripts and finally to the last few words that I type here. It's been fun, exciting, inspirational, exhausting, intriguing, confusing, satisfying but most of all endlessly rewarding, an assortment of emotions all wrapped up in one bundle of fulfilment. But the words I wrote would not have been possible without the help and support of so many people. Firstly, I would like to thank my family, especially my Mam & Dad who have supported me, not only during this chapter, but on every page of my life.

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Eva Hornecker in friendship and admiration

ABSTRACT

In contemporary society, data representation is an important and essential part of many aspects of our daily lives. This thesis aims to contribute to our understanding on how people experience data and what role representational modality plays in the process of perception and interpretation. This research is grounded in phenomenology - I align my theoretical exploration to ideas and concepts from philosophical phenomenology, while also respecting the essence of a phenomenological approach in the choice and application of methods. Alongside offering a rich description of people's experience of data representation, the key contributions I claim transcend four areas: theory, methods, design, and empirical findings. From a theoretical perspective, besides describing a phenomenology of human-data relations, I define, for the first time, multisensory data representation and establish a design space for the study of this class of representation. In relation to methodologies, I describe and deploy two methods to investigate different aspects of data experience. I blend the Repertory Grid technique with a focus group session and show how this adaption can be used to elicit rich design relevant insight. I also introduce the Elicitation Interview technique as a method for gathering detailed and precise accounts of human experience. Furthermore, I describe for the first time, how this technique can be used to elicit accounts of experience with data. My contribution to design relates to the creation of a series of bespoke data-driven artefacts, as well as describing an approach to design that I call Design Probes, which allows researchers to focus their enquiry on specific design features. To answer the research questions I set out in this thesis, I report on a series of empirical studies that used the aforementioned methods. The findings of these studies show, for instance, how certain representational modalities cause us to have heightened awareness of our body, some are more difficult to interpret than others, some rely heavily on instinct and each of them solicit us to reference external events during the process of interpretation. I conclude that a phenomenology of human-data relations show how representational modality affects the way we experience data, it also shows how this experience unfolds and it offers insight into particular moments such as the formation of meaning.

ZUSAMMENFASSUNG

In der heutigen Gesellschaft sind Datenrepräsentationen ein wichtiger und wesentlicher Bestandteil vieler Aspekte unseres täglichen Lebens. Diese Doktorarbeit zielt darauf ab, zu unserem Verständnis beizutragen, wie Menschen Daten erleben und welche Rolle die Modalität der Repräsentation im Prozess der Wahrnehmung und Interpretation spielt. Diese Forschung basiert auf der Phänomenologie – meine theoretische Erforschung ist ausgerichtet durch Ideen und Konzepte der philosophischen Phänomenologie, und berücksichtigt zudem die Essenz eines phänomenologischen Vorgehens bei der Selektion und Anwendung von Forschungsmethoden. Zusätzlich zu einer detaillierten Beschreibung der menschlichen Erfahrung von Datenrepräsentationen sind die wichtigsten Beiträge meiner Arbeit die folgenden: Theorie, Methoden, Design und empirische Resultate. Auf theoretischer Ebene beschreibe ich die Phänomenologie der Daten-Mensch Beziehung, definiere erstmals den Begriff der multisensoriellen Datenrepräsentation und stelle den Designraum zur Untersuchung dieser Art von Darstellung auf. Um verschiedene Aspekte der Datenerfahrung zu untersuchen, wende ich zwei Methoden an, welche ich ausführlich beschreibe. Ich verknüpfe das ‚Repertory Grid' Verfahren mit Fokusgruppen-Sessions und zeige, wie diese Adaption angewendet werden kann um reiche design-relevante Einsichten zu gewähren. Zusätzlich wende ich die Elicitation-Interview-Technique an, um detailliert und präzise menschliche Erfahrung zu erfassen. Weiterhin beschreibe ich erstmals, wie diese Methode genutzt werden kann, um genaue Berichte der Erfahrung von Daten zu erhalten. Mein Beitrag zum Design besteht in der Schaffung einer Reihe eigens angefertigter Artefakte sowie der Beschreibung eines Ansatzes, den ich Design Probes nenne, welche es Forschern erlaubt, ihre Untersuchung auf spezifische Designmerkmale zu konzentrieren. Um die Forschungsfragen zu beantworten, die dieser Arbeit zugrunde liegen, berichte ich über eine Reihe von empirischen Studien, welche die oben genannten Methoden nutzen. Die Ergebnisse dieser Studien zeigen zum Beispiel an, wie bestimmte Repräsenationsmodalitäten ein erhöhtes Bewusstsein für den eigenen Körper bewirken. Einige Modalitäten sind schwieriger zu interpretieren als andere, manche werden eher instinktiv interpretiert, und alle fordern uns dazu auf, während des Interpretationsprozesses auf externe Ereignisse zu verweisen. Meine Schlussfolgerung ist, dass eine Phänomenologie der Daten-Mensch Beziehung zeigt, wie die Er-

fahrung von Daten durch die Repräsentationsmodalität beeinflusst wird, wie diese Erfahrungen sich temporal entfalten und entwickeln, sowie Einsichten ermöglicht in spezifische Momente, wie die Entstehung von Bedeutung.

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1 INTRODUCTION

In contemporary society, data representation is an important and essential part of many aspects of our daily lives. Representations in the form of demographic statistics, financial reports, environmental data, economic trends and others are being widely distributed by the media, which compete for people's attention and comprehension. The recent proliferation of data representations can be traced back to two key moments that breathe new life into this field of study – the publications by the eminent scholar and pamphleteer Edward Tufte, and the heralding of the era of personal computers. When Tufte's book The Visual Display of Quantitative Information was first published in 1983, it revitalised interest in the representation of data using visual elements and also revived interest in the eighteenth-century pioneers in this field [287]. Around the same time as Tufte's work was becoming noticed, the personal computer was becoming commonplace at work and in our homes. This technological advancement offered new opportunities for lay people to engage with new and novel ways of representing data. This was further enhanced later with the release of the World Wide Web and more recently with the easy access to data sets via APIs.

The 1990's also heralded a period of dramatic change for data representation; these technology developments paved the way for the formation of new fields of research, most notable Information Visualisation (InfoVis), which specifically focused on the study of interactive digital data representations. Shortly after its conception, InfoVis was defined as "the use of computer-supported, interactive, visual representations of abstract data to amplify cognition" [34, p.8]. As the practice and study of data representation broadened, so did the audience and target group that these tools were aimed at. No longer was it just aimed at experts and data analysts, but soon everyday people were confronted with data representations on a daily basis on websites, on television, at the museum, the library or other public spaces. While many aspects of data representation evolved during this period of time, one aspect remained unaltered - the vast majority of representation relied exclusively on the visual modality when representing data, requiring the audience to interpret and gain meaning from the data using only their visual sense. While using the visual modality to represent data is still the norm for the majority of data representations we see today, the emergence of research fields, such as: *Information Aesthetics* [154], *Artistic Visualization* [300], *Data Art* [172] and *Casual Visualization* [233] have sought to broaden the use of representation modality (cf. [196] [325]), widen the target audience (cf. [265] [233], and expose alternative data insight (cf. [207] [38]).

My research is inspired by these fields of study, and the lines of enquiry that have emerged from them. It is based on the belief that new insight and meaning can be achieved by representing data beyond the visual modality, which can be touched, felt, heard, held, or even possessed. Consequently, these data-driven artefacts act as the embodiment of the data source and capture the imagination and engage the interpretative and perceptive power of its audience through both their experiential, tactile or artistic qualities. An aim of my research is to represent data in a manner that exposes insight, which may be difficult to uncover when using traditional methods such as one-dimensional static graphs and charts. I contend that the use of modalities such as haptic, tactile, auditory - or any combination of these - to represent data can facilitate an experience that is significantly different from when only the visual modality is used.

In validating this, I strive to expose and explore the type of experience people have with data. I also seek to compare the experience of one representational modality against another, observing how this experience unfolds over time as well as looking at particular episodes of this experience, such as moments of insight. The approach I take to investigating these experiences is strongly motivated by literature that emphasizes the felt experience of interaction [180], the postulation of use qualities [165], discourse on hedonics (cf. [93]), affect (cf. [323]), empathy [320], enchantment [181], as well as the re-emergence of phenomenology within the HCI community, as an approach to better understand people's experience of technology [278].

This thesis aims to leverage the theoretical and practical aspects of this work to contribute to our understanding on how people experience data and what role representational modality plays in the process of perception and interpretation. Experience, in this context, relates to personal responses to a data representation, which goes beyond interaction and usability aspects to focus on capturing hedonistic, emotional, and sensory reactions to the representation as well as personal interpretations, meaning, and opinions that it may trigger.

1.1 RESEARCH QUESTION

When I started my primary research the question that I had in mind to answer was somewhat simply – How do people experience data? Following an initial review of the literature, as well as conducting some early design exercises, this question evolved and extended to three connected questions, which remained to be the focus of my research from then on, these questions are:

- *How do people experience data?*
- *What influence does representation modality have on this experience?*
- *How does it affect the way meaning is formed by the audience?*

The first question includes aspects, such as, the unfolding of this experience overtime and episodes of insight. The second part should not be read as being focused on one modality, instead I sought to compare the affect different modalities have on our experience of data. Whereas the third part involves, not only shedding light on the meaning that it formed from our experience with data, but also the cognitive activities used during this process. While seeking answers to these questions two other pertinent questions emerged:

- *How do you study people's experience of data?*
- *Which methods allow for the capture of precise accounts of experience?*

These methodologically focused questions necessitated the formulation of a coherent research approach, and prioritised the search for methods that would provide me with the tools to answer the three aforementioned questions. In the following I describe this research approach.

1.2 RESEARCH APPROACH

I divide the discussion on my approach into the three pillars of my research: Theory, Methods and Design. I return again to these pillars in the final chapter of this thesis when describing the key contributions of my work, the majority of which emanated from these areas.

1.2.1 *Theory*

While I situate this work in the tradition of HCI, I draw heavily on phenomenological theoretical perspectives on how to study human-data relations. Phenomenology is concerned with people's lived experience of phenomena or as Don Ihde eloquently describes it as an investigation into "*the conditions of what makes things appear as such*" [117, p.133]. In the context of my research, I leverage theories developed in philosophical phenomenology to explore people's relationship with data and to help understand the processes that are involved, such as, perception, action, and interpretation. In particular I use ideas and concepts developed by Edmund Husserl, Martin Heidegger, Maurice Merleau-Ponty and Don Ihde.

Commonly cited as the father of modern phenomenology, Husserl's reframing of *intentionality* describes the structure of an experience as both *actional* and *referential* in nature, while Heidegger's concepts helps to make sense of *temporality* and how we use equipment (in my case data representations). The work of Merleau-Ponty also focuses on our use of tools but he is better known for dealing directly with the nature of the human body and of perception, and finally Ihde's theory of human-technology relations is widely cited as a way to account for the various ways technology mediates people's experience of the world. Phenomenology has a long tradition in HCI and has shaped influential work (cf. [52] [152] [277] [111] [60].

I consider my approach to be similar to many phenomenological oriented approaches in HCI, in so much as I leverage theories from phenomenology but bracket all pre-suppositions when studying the phenomenon, which in my case is data.

1.2.2 *Methods*

While phenomenology, from a philosophical perspective, is concerned with the way phenomenon appears to use in our everyday lives, from a methodological perspective, phenomenology demands a process that emphasizes the unique subjective experiences of people and tries to uncover and describe the internal meaning structures of lived experience. Working within a phenomenological tradition, studying people's experience of data requires empirical grounding in actual lived experience. However, capturing direct human lived experience is notoriously difficult and calls for setting up situations where the essence of an experience can be grasped or understood by studying episodes as they are encountered. The two methods that would typically support the capture of lived experiences are observational studies and interviews; however, these methods have some limitations, such as, for instance, the introduction of post-hoc rationalisation. To overcome this and other issues, I combined two methodologies that would allow me to capture accounts on how people construe their experience of objects, people or events (the Repertory Grid technique) and gather detailed and precise accounts of human experience (the Elicitation Interview technique).

The Repertory Grid technique has been used widely in HCI since the 1980's, however, in this thesis I present an adaptation that allows for the capture of rich data in a group setting. On the other hand, the Elicitation Interview technique has rarely been used in empirical studies and on only two occasions in the context of HCI, I therefore describe the key characteristics of this interview technique and exemplify how it can be applied in an empirical setting to show what types of insights this technique can bring to the fore.

1.2.3 *Design*

The final pillar of my research approach that I describe relates to design. While the theoretical and methodological approach I followed remained stable since the outset, my design approach evolved over time. As I have a background in product and interaction design, I commenced with a series of design exercises that followed a traditional approach, which incorporated iterative phases such as analysis, concept development and synthesis. Following the first design and evaluation experiment, I recognized that creating complex artefacts impeded me from focusing on specific aspects that maybe affecting people's experience of data (such as representational modality). As my research prioritised the examination of representational modality, and I was more interested in how people experience data rather than how they used data-driven artefacts, my design approach evolved to address these specific concerns. What emerged is a design approach that I call *Design Probes*. While this is similar to *Research Through Design* (RTD) [326], it is unique in so much as it doesn't involve an iterative process, which is integral to RTD. I also consider it to be close in intent to *Technology Probes* [115], however, instead of studying the use of one artefact (which is the procedure followed with technology probes), I design multiple artefacts that possess similar design features but differ in one aspect (e.g. representational modality). This approach allows me to focus the subsequent evaluation precisely on this design feature.

1.3 THESIS STRUCTURE

This thesis is divided into three parts: (1) *Theory and Design*, (2) *Methodologies and Experiments*, and (3) *Reflection*. In Part One (*Theory and Design*), I discuss the theoretical and design foundations of my research. I start Chapter 2 by presenting the philosophical and methodological foundation of my research approach. I also provide a brief overview of the foundations of philosophical phenomenology, before focusing on the work of four important thinkers: Edmund Husserl, Martin Heidegger, Maurice Merleau-Ponty and Don Ihde, whose ideas provide an important theoretical backdrop to the critique and study of data experience. I conclude this chapter by discussing the role phenomenology has played in the field of HCI.

In Chapter 3 (*Data Representation and Evaluation*), I present and describe current approaches, techniques, tools, technologies and methods used in the creation and evaluation of data representations. I first address issues related to representational modality before highlighting the different domains that are actively engaged in topics related to the study and practice data representation. I then move on to aspects of evaluation and discuss current research that relates to the type of questions I am attempting to answer. I conclude by presenting commonly used approaches and methodologies that allow for the capture of people's experience of data representation.

In Chapter 4 (*Data, Design and Dasein*), I present a design exercise and user-study that produced and examined two prototypes that represent scientific data to a casual audience. I also describe how these prototypes were deployed in a public Space Observatory, where I conducted a series of user studies. I present an analysis of the prototypes through the prism of philosophical thought by Edmund Husserl, Martin Heidegger, Maurice Merleau-Ponty and Don Ihde, where I apply phenomenological theories and ideas to the exploration of people's experience of tangible data representation.

In Chapter 5 (*A Design Space for Multisensory Data Representations*), I present a systematic analysis of the state-of-the-art in data representations over the last 150-years. In particular, I focus on representations that require more than one sensory channel to fully interpret and understand the data. Drawing on techniques and theories adapted from Thematic Analysis and Prototype Theory, I analyse 154 examples of multisensory data representations to establish a design space along three axes: *Use of modalities*, *Representation intent* and *Human-data relations*. Following a discussion on the design space, I present key research challenges that emerged and point out future research topics. This chapter concludes the theoretical part of my thesis.

In Part Two (*Methodologies and Experiments*), I introduce two methods that are used to elicit accounts of experience and present three studies that exemplifies the use of these methods - in the context of understanding how people experience data representation. The aim of Chapter 6 (*Adapting the Repertory Grid Technique*) is threefold; I first introduce the Repertory Grid technique as method of collecting data on how people construe their experience of objects, people or events. I then present my adaptation of the technique, which involves blending it with a focus group session to allow for the capture of first-hand accounts of experience during the study. Finally, I describe an experiment that was designed to validate and confirm this adaptation by comparing two side-by-side Repertory Grid studies (traditional verses adapted).

Chapter 7 (*From Phenomenology to Psycho-Phenomenology*) is dedicated to introducing the Elicitation Interview technique as a method for gathering detailed and precise accounts of human experience. I show how it can be applied in the context studying data representation, to help understand how people experience and interpret representations as part of exploration and data analysis processes. This chapter also presents a description of the key characteristics of this interview technique and exemplifies how it can be applied to evaluate static data representations. This study illustrates what types of insights this technique can bring to the fore, and presents general evaluation scenarios where the Elicitation Interview technique may be beneficial and specify what needs to be considered when applying it.

Chapter 8 (*Delving Below the Surface*) is divided into three phases, a design phase and two evaluation studies. The two studies described in this chapter incorporate different methodologies (The Repertory Grid Technique and The Elicitation Interview Technique), and were conducted consecutively. The rationale for employing this approach was to conduct a series of experiments that allows for the elicitation of accounts of experience at finer levels of granularity. While I will discuss the findings of each of the studies separately, I conclude this chapter by collating the findings of both studies. This chapter concludes the methodologies and experiments part of this thesis.

In the final part and chapter of this thesis I reflect upon the work conducted over the course of my PhD and I revisit the major points and research questions in this thesis. I summarise what I have learned and what does this mean for the study and design of future data representations - in the context of HCI and neighbouring fields. I also draw together the key findings from the experiments presented in earlier chapters and reveal patterns that appear across these studies.

1.4 DISSEMINATION OF RESEARCH AND LIST OF PUBLICATIONS

Much of the content of this thesis has been disseminated in various ways, which has made some of the findings available to a larger audience than the readers of the thesis. Additionally, almost every part of this thesis has been presented and discussed at public talks, seminars and doctorial consortiums. I believe that my work has benefited from this dissemination through valuable suggestions and revisions from my supervisor, colleagues, anonymous reviewers, and co-authorship. While every publication that I list below was co-authored with my supervisor Professor Dr. Eva Hornecker, the work described in Chapter Seven was also carried out in collaboration with Dr. Uta Hinrichs, who helped me gain an overview of the state-of-the-art in the field of InfoVis. In the introduction of each chapter in this thesis I highlight the parts that have already been published, I also briefly describe the adaptions that appear in this thesis. In the following I present a list of these publications:

LIST OF PUBLICATIONS

- Hogan, T., and Hornecker, E. (2016) Feel it! See it! Hear it! Probing Tangible Interaction and Data Representational Modality. In Proceedings of the 50th Design Research Society conference (DRS'16), (Accepted February 2016).
- Hogan, T., Hinrichs, U., and Hornecker, E. (2016) The Elicitation Interview Technique: Capturing People's Experiences of Data Representations. IEEE Transactions on Visualization and Computer Graphics (Accepted December 2015).
- Hogan, T., Goveas, D., Noonan, R., and Twomey, L. 2015. TaraScope: Controlling Remote Telescopes Through Tangible Interaction. In Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15). ACM, New York, NY, USA, 281-284
- Hogan, T., and Hornecker, E. (2013) Blending the repertory grid technique with focus groups to reveal rich design relevant insight. Proc. of DPPI'13, Designing Pleasurable Products and Interfaces, ACM 2013, 116-125.
- Hogan, T., and Hornecker, E. (2013) The Personal Construction of Representation Modality. In Proceedings of the 6th Irish Human-Computer Interaction conference (iHCI'13), ACM, 107-111.
- Hogan, T., and Hornecker, E. (2013) In Touch with Space: Embodying Live Data For Tangible Interaction. Proc. of TEI'13, ACM, 275-278.

- Hogan, T., and Hornecker, E. (2012) How Does Representation Modality Affect User- Experience of Data Artifacts? In Proc. of HAID'12. Lund, Sweden. Springer. 141-151.
- Hogan, T., and Hornecker, E. (2012) Beyond Data Visualisations. In Beyond Data. Baltan Laboratories & Kitchen Budapest. 131–136.
- Hogan, T., and Hornecker, E. (2012) Data Modality and the Repertory Grid Technique. Poster at DIS 2012, June 2012, Newcastle, ACM.
- Hogan, T., and Hornecker, E. (2011) Human Data Relations and the Lifeworld. Poster at IHCI 2011 (Irish Human Computer Interaction Conference), September 2011, Cork, Ireland CIT Press.

IN REVIEW

- Hogan, T., and Hornecker, E. (2016) Towards a Design Space for Multisensory Data Representation. In Review with: Interacting with Computers. Oxford Press (Accepted with minor revisions January 2016).

DOCTORIAL CONSORTIUMS This research has also been accepted by and presented at DIS 2012 and TEI 2015 Doctoral consortiums.

- Hogan, T. 2015. Tangible Data, a Phenomenology of Human-Data Relations. In Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15).
- Hogan, T. (2012) Toward a Phenomenology of Human-Data Relations. Doctoral Consortium DIS 2012.

WORKSHOPS I also was the lead organiser of a workshop at TEI'15 and I am part of the organising team of a workshop at DRS'16. The topic of these workshops developed specifically from the research I present in this thesis.

- Hogan, T., Hornecker, E., Stusak, S., Jansen, Y., Alexander, J., Vande Moere, A., Hinrichs, U., and Nolan, K. (2016) Tangible Data, explorations in data physicalization. Workshop at the Tenth International Conference on Tangible, Embedded, and Embodied Interaction, Eindhoven (TEI '16). 2016. ACM.

- Jansen, Y., Gourlet, P., Huron, S., Hinrichs, U., and Hogan, T. (2016) Let's Get Physical, Exploring the Design Process of Data Physicalization. Workshop at the fiftieth Design Research Society Conference, Brighton, UK. (DRS '16).

Part I

THEORY AND DESIGN

In this part of my thesis I discuss the theoretical and design foundations of my research. I present these across four chapters. In Chapter 2, I introduce Phenomenology as the basis of the philosophical and methodological approach of my research. I follow this in Chapter 3 by discussing two other central aspects of my thesis: *data representation* and *evaluation*. Here I present a historical overview of these aspects and describe current approaches, techniques, tools, technologies and methods used in the creation and evaluation of data representations. In Chapter 4, I bridge the gap between theory and design by describing a design exercise, which produced two bespoke data driven artefacts that represent scientific data for casual users. I also present an analysis of these designs that is framed around the philosophical concepts that I introduce in Chapter 2. In the final chapter of this part, I present a survey of the state-of-the-art in data representation over the course of 150-years. In particular I focus on examples that require more than one modality to fully interpret the representation. Using a database of 154 example, which I collected over the course of my PhD, I define and establish a design space for multisensory data representation, to help system designers reason about decisions on data representation and to assist researchers better understand the study of data representation through and beyond the visual modality.

2 THE PHENOMENOLOGICAL LANDSCAPE

With this we meet a science, of whose extraordinary extent our contemporaries have as yet no concept; a science; is true, of consciousness that is none the less not psychology, a phenomenology of consciousness as opposed to a natural science of consciousness.

— (Edmund Husserl, 1965)

2.1 INTRODUCTION

In this chapter, I present the philosophical and methodological foundation of my research approach. I first provide a brief overview of the foundations of philosophical phenomenology, before focusing on the work of four thinkers: Edmund Husserl, Martin Heidegger, Maurice Merleau-Ponty and Don Ihde, whose ideas provide an important theoretical backdrop to the critique and study of experiencing data representation. I conclude this chapter by discussing the role phenomenology has played in the field of HCI.

2.2 HUSSERL AND THE BEGINNINGS OF PHILOSOPHICAL PHENOMENOLOGY

The term phenomenology appears in more than one context, it first entered the lexicon of philosophical writings during the Age of Enlightenment when Immanuel Kant and G. W. F. Hegel began using it. However, phenomenology in its modern philosophical sense began with the work of the German philosopher Edmund Husserl (1859-1938), who established Phenomenology as an important tradition within 20th century European Philosophy, alongside others such as Structuralism or Existentialism. Phenomenology can also be seen as a research approach and is the study of "what comes to light" or the study of phenomenon. Etymologically, it is a fusion of the Greek *phainómenon* (that which appears) and logos (study, words and reasons). Essentially, taking a phenomenology approach involves trying to provide an account of how things appear to our awareness and ultimately how the world appears to us - in terms of our subjective experience. In other words, phenomenology is about reflecting upon our everyday experience to gain some sense of its underlying order, structure and coherence. It is descriptive rather that explanatory, it focuses on describing the experience that we have. So instead of trying to explain "why" we have a certain experience, we bracket that, and focus purely on describing the experience.

The origin of this philosophical movement rests with Husserl recognising that science and mathematics were increasingly conducted on an abstract plane and were disconnected from human experience and understanding. He sought to redress this imbalance by envisioning a science that was firmly grounded on the phenomena of experience, which in turn meant developing the philosophy of experience as a rigorous science [114]. One of phenomenology's fundamental building blocks, which Husserl's framework is built upon, is a reaction to the idea of the *Natural attitude*, where we proceed through our lives with a common natural belief, we see things around us, such as physical objects, other people, and even ideas, as simply real and we don't question their existence: we view them as *facts*. In contrast to the *natural attitude*, Husserl advocated adopting a *phenomenological attitude*, wherein, we suspend or bracket our belief in the *natural attitude* by recognizing that it is merely a belief. This act of *bracketing*, which is also known as the *epoché*, allows us to turn our attention to the on-going activity of consciousness to which our experience of reality is ultimately constituted. Husserl termed the overall act of using the *epoché* as a phenomenological reduction. By adopting a phenomenological reduction we in turn assume a phenomenological attitude toward our experience. To explain this, let me use the example of how we experience time. From the perspective of the natural attitude, an hour of time is simply an hour no matter where or how we spend it. Whereas, if we employ a phenomenological attitude, an hour of time depends on how we experience it. For instance an hour may pass slowly if we are bored or very quickly if we are excited, so the meaning of time can vary significantly depending upon whether we are viewing it from the perspective of a natural attitude or from that of a phenomenological attitude. The same is true for other facets of our lives, including how we experience data. From the perspective of the natural attitude, data may be seen as, for instance, simply discrete numerical points, however, if we view data through the lens of a phenomenological attitude our experience maybe altered depending on variables such as the representational modality, past personal experience or even the mood we are in at the time of experiencing the data.

Another important aspect of phenomenology that Husserl developed is the idea that consciousness or human experience, is, by its very nature, intentional. Based on earlier work by Franz Brentano, whom Husserl studied under, the theory of *intentionality* describes the way experiences are both actional and referential in nature, in that they involve an activity and always refer to something external. For example, the kind of experience we have when reading a data representation involves the activity of interpretation, this is the action-oriented aspect of data experience, which in phenomenological parlance is known as a "Noesis". At the same time, data experience is referential – which may be a specific data set and the representational format, which is known as a "Noema". Husserl suggested phenomenology as a research approach to uncover the relationship between the objects of experience (*Noema*) and our mental experiences of those objects (*Noesis*). The results of adopting such as approach would provide an account of how *Noesis* and *Noema* cohere and unfold over time. In respect to data experience, a *phenomenology of data experience* would aim at exploring how that specifically happens.

Exploring human experience - in this way - occupied Husserl for several decades. However, toward the end of his life he recast his vision of phenomenology in terms of exploring what he called the "lifeworld" (*lebenswelt*). Basically the *lifeworld* is the total assemblage of the entire world, as we know it, including the inter-subjective, social spheres of everyday experiences. This shift in emphasis heralded the beginning of existential phenomenology, whose notably exponents include Martin Heidegger.

2.3 MARTIN HEIDEGGER

While Husserl conceived phenomenology as a purely descriptive process - collecting information about people's experience of the world and letting others reflect on its meaning - Martin Heidegger (1889-1976) viewed phenomenology as a process to understand and interpret what it means to exist in the world. His view transformed phenomenology, from a tradition that focused on epistemological questions, such as, how can we know about the world? to ontological ones, such as, how does the world reveal itself to us through our encounters with it? Central to this shift in perspective is Heidegger's concept of *Dasein*, which is a fundamental aspect of all his work. Translated as "being-in-the-world", *Dasein* emphasizes the way in which 'being' or 'existence' is inseparable from the world in which it occurs, it is the essence of being human. Although Heidegger was a prolific writer and his lifework reaches out to many aspects of human existence, only the aspects that are of direct relevance to data representation will be treated here. With this in mind, I first discuss his thoughts on how people's use of equipment mediates our understanding of the world, I then follow by presenting his concept of Time.

2.3.1 *Equipment*

Heidegger recognised that what makes the world meaningful to us is that we encounter it in a practical way. In his view, human beings engage with the world around us through things and items that surround us, such things he refers to, in a very Heideggerian way, as the equipment-of-our-lives [95]. He essentially posits two important ideas that encapsulate the term equipment. First, equipment in our lives is not simply a tool, but is a tool for some task or as Heidegger phrases it: "equipment is essentially something in-order-to" [95, p.99]. To explain this concept Heidegger poses a paradox - the more useful equipment is the less apparent is its' presence, it recedes before the work toward which the equipment is oriented. For example, when we write on a page with a pencil, our attention is not focused on the pencil, instead it is on the words that are appearing on the page as we write. Only when the equipment (pencil) no longer functions smoothly does it draw attention to itself. Second is that equipment does not stand-alone, there is no such a thing as 'an equipment'. Equipment is always linked to other equipment in the way that it relies upon, works with, suggests, is similar or dissimilar to, or is otherwise related to other equipment. For example, a pencil cannot function (or exist) without something to write on, so the pencil relies upon other equipment to act as a surface to display what has been written or drawn.

Heidegger also thinks beyond the existential being of equipment, toward ways that *Dasein* is in relation to equipment. Heidegger essentially says that we encounter equipment in two forms, he calls the first form *ready-to-hand* (*zuhanden*), which he describes as what happens when we use equipment. The second form he refers to as present-at-hand (*vorhanden*) to indicate what happens when we stare at, but do not use it - such an object is encounter through pure theoretical contemplation. Based on this idea we can categorise certain equipment as being either *ready-to-hand* or *present-at-hand*. However, we may also encounter certain equipment as being both forms, depending on the context. For example, if we return again to the pencil, when in normal use a pencil may be considered as *ready-to-hand*, however if we encounter a pencil in a museum, which was, for instance, once used by a famous writer, this would be considered to be present-at-hand, as we can not pick it up and start using it, instead we merely contemplate on its past use by its original owner.

We should, however, not consider these forms of encountering equipment as being mutually exclusive. We often shift from one to the other when using equipment. Heidegger considers this *skilful coping*, to be when we shift quickly from one mode to the other in a very inexpert *unready-to-hand* way [311] [51]. To exemplify this, when a pencil is encountered as *ready-to-hand*, it is being used to write on a page, however, if our skilful coping is temporarily disturbed (if the lead tip breaks), we may shift to present-at-hand, where we contemplate on how to repair the pencil, or even *unready-to-hand*, which Blattner [16] considers as a deficient mode of *ready-to-hand*, by continuing to use the damaged pencil so we do not see through the pencil any more, as our attention is divided between the words on the page and maintaining the functionality of the pencil.

2.3.2 *Temporality*

Another one of Heidegger's ideas that is important for our understanding of how people interpret data representations, is how he conceives *temporality*. Heidegger makes a distinction between *temporality* and time, he postulates that time is what *temporality* becomes when it is reduced to clock time, or as Hei-

TEMPORAL PHASE	AUTHENTIC	INAUTHENTIC
Past	Repeatability	Elapsed entirely
Present	Making-present	Turning away
Future	Anticipation	Expectation

Table 1: Heidegger's conception of the three phases of temporality.

degger puts it *public-time*. Time, as he sees it, is orderly and chronometric, whereas temporality is diverse, a kind of primordial time [95, p.79]. The diversity of temporality also mirrors the fact that time always arrives in three phases: past, present, and future.

He reinterprets these phases, asserting that there is an authentic and an inauthentic mode for each (see Table 1). If we consider the phase of temporality know as the *future*, Heidegger thinks of this as being the world ahead of itself, where we project the possibilities of what is to come. He considers the authentic projection of the future to be *anticipation*, where we actively seek the possibilities of our future. While its inauthentic counterpart is *expectation*, where we passively await whatever the future brings. Heidegger characterized the past, as having-been, however, if we conceive of the past as being elapsed entirely, this, he believes, is an inauthentic mode of connecting with the past. When we authentically relate to the past we bring ourselves face-to-face with what Heidegger would call our *throwness*, or *situatedness* in the world. He considers repeatability to be the authentic motive for considering the past. When experiencing the present, Heidegger notes that we connect with it in an authentic mode through a *moment-of-vision*, where we rise toward the opportunities as the become available, he terms this reaction as making-present, whereas as an inauthentic mode will result in us by turning away from what is before us.

In relation to the perception and interpretation of data, Heidegger's ideas on temporality are of particular interest. If we consider, for instance, the way we experience representations of live data; one may experience the data as it is represented (in the present) in an *authentic* way through as a moment of vision (the generation of data insight) or one could act in an *unauthentic* way by turning away and shielding oneself from the representation. Live data representation also have future possibilities (data yet to be represented), which one may wait for in expectation (*inauthentic*) or in a mode of anticipation (*authentic*). Once we have perceived the data, this perception immediately becomes part of our past, we could treat this past memory as having lapsed entirely (*inauthentic*) or we could make better use of it (*authentic*) by recognizing the *situatedness* of the data, basically, that is was there for a reason and we can learn from it.

2.4 MAURICE MERLEAU-PONTY

Another thinker whose work strongly influenced my understanding of how we perceive and experience data is Maurice Merleau-Ponty (1908–1961). His approach to philosophy, and the ideas he developed can be traced back to the two thinkers I discussed already. In particular he inherited a concern for questions of perception from Husserl, and from Heidegger, he inherited an orientation toward being situated in the world. Merleau-Ponty reconciled these two perspectives by focusing on the role of the human body in perception. This is best seen in his magnum opus: *The Phenomenology of Perception*, which was first published in 1945 (with an English translation appearing in 1962), where he deals directly with the nature of the human body and of perception. The concepts that are of special interest to the study of how people experience and perceive data include his idea of the *Body Schema* and *Maximal Grip*.

2.4.1 *The Body Schema*

It may seem obvious now, but Merleau-Ponty was one of the first thinkers to recognise the important role our body plays in perceiving the world around us. He claimed that the body gives us a prior understanding of the world, through our direct perception of it, stating, "the body is our general medium for having a world" [189, p.146]. It is this aspect of his work that differentiates his ideas from other phenomenologists that came before him. Although Heidegger acknowledged that we make sense of the world around us in a practical may, he never specifically attributed the formation of meaning to the body and Husserl did not address the role of the body in any of his major writings.

Central to Merleau-Ponty's exploration of the role the body plays in perception is his idea of the *body schema*. Essentially, *body schema* is a form of bodily awareness referring to how we understand our body in space. It is a dynamic structure that reveals the body's orientation, not just towards existing, but also towards possible tasks. There are three essential features that constitute Merleau-Ponty's *body schema*: (1) although our body is comprised of different parts, we perceive it as a unified entity, (2) while he implies there is an inside and outside of the body schema, all these parts are within, and (3) humans have an innate ability to know where the body parts are positioned in relation to each other, without having to consciously think about it. He summarises these features as: "The outline of my body is a frontier which ordinary spatial relations do not cross. This is because its parts are inter-related in a peculiar way: they are not spread out side by side, but enveloped in each other." [189, p.112].

Another important aspect of *body schema* relates to how we normally experience our body. While we typically experience the external world as a spatial structure relative to us, this is not the case for our own body. To explain this, think, for a moment, about viewing the world around us while wearing dark sunglasses. One can easily imagine that we are experiencing the glasses, as the world will appear darker to us, however, we do not experience the glasses as being located somewhere in the world, they have been enveloped into our *body schema*. The same is true for our body, just like sunglasses, our body is a medium through which we experience the world. This analogy also illustrates how the *body schema*is flexible and can be extended, either temporarily or near-permanently, through the use of tools. According to Merleau-Ponty, when we become adept at using tools they become incorporated into the *body schema*, as an extension of our body parts. Thus, these tools are experienced and used as part of the process by which we engage with the external world, and not an object in-the-world that we engage with, an idea that is very similar to Heidegger's concept of *ready-to-hand*. For example, if we consider a child starting to learn how to draw with a pencil, this process involves first learning to grip the pencil correctly, which requires them to be constantly attentive to the position and angle of the pencil between their fingers and thumb. Now think about how a pencil is used by a skilled draftsman, years of practise has enabled him to use the pencil with little or no awareness of its position in relation to the body parts that are holding it. The pencil (when in use) has ceased to exist as object in the external world and has become part of the draftsman's *body schema*.

2.4.2 *Maximum Grip*

A central theme in *The Phenomenology of Perception* is the idea of the tight coupling between the body and the world. Merleau-Ponty refers to this as *the intentional arc*. Accordingly, the intentional arc is an often pre-reflective or precognitive process that brings about a unity of our senses and intelligence in a tendency to achieve a *maximum grip* [189, p.157]. This tendency is our body responding to a given situation to achieve the optimal visibility. However, we do not necessarily need to know what that optimum is, our body is simply solicited by the situation to get into equilibrium with it, or as Merleau-Ponty puts it: "Our body is not an object for an 'I think', it is a grouping of lived-through meanings which moves towards its equilibrium." [189, p.153]. Essentially, this means, when we look at an image, such as a painting, we tend to, without having to think about it, position ourselves at an optimal distance and angle to capture the entire picture in full clarity. The same idea can also be applied to other modalities, for instance, when we grasp a physical object, without thinking, we position and rotate it in our hands is a response to the form or functionality of the object. Also, when we perceive sounds our body innately responds to the stimulation to achieve the optimal conditions for listing, for instance, we may bend down and direct our ear towards a sound that is difficult to hear. In essence, getting the maximum grip involves our human body responding to stimuli to get into equilibrium with it, or as Merleau-Ponty puts it: "to get the detail and the maximum clarity of the form." [189, p.371].

There are however certain situations where achieving a maximum grip requires a cognitive response instead of a physical one. In relation to this, Merleau-Ponty questioned: what happens to our perception of an object if you are unable to see it whole? For instance, when we look at mountains from a distance—although we are unable to, we are motivated to see them from behind, but if this is not feasible, we project our own reality on to the mountains backside. According to Merleau-Ponty our perception of these hidden parts is grounded in reality and we stimuli meaningful structures, so we would perceive the other side of the mountains as normal [189, p.302]. This concept has direct implications for data representation, especially those that represent time series data. For example, when we perceive a data representation, does our perception cease at the final data point or, as Merleau-Ponty suggests, do we project/perceive into the future based on what has came before it?

2.5 DON IHDE

Phenomenology has a rich and complex background that continues to evolve today. Since the inception of modern phenomenology by Husserl at the turn of the 20th Century, a number of schools and movements have developed, each of which embrace different values and characteristics, but all adhere to the fundamental principle of phenomenology: the philosophical study of the structures of experience and consciousness. Often these phenomenological movements are identified with the thoughts and approaches of key scholars. For instance, Husserl's approach became known as Transcendental or Pure phenomenology, which is described as the study of how objects are constituted in pure or transcendental consciousness [199]. Following this, Heidegger's take on the tradition became known as Existential phenomenology; the study of concrete human existence, including our experience of free choice or action in concrete situations [322]. Whereas Merleau Ponty was known to practice Hermeneutical phenomenology, which can be described as the study of interpretive structures of experience, to comprehend how we understand and engage things in our world [155]. The final set of ideas that I present in this chapter were developed by the phenomenological philosopher of technology: Don Ihde, who initiated a school of thought known as Post-phenomenology.

2.5.1 *Post-phenomenology*

When encountering post-phenomenology for the first time, we should not confuse the use of the prefix 'Post' with a shift in subject matter or the separation of Ihde's movement from the traditions of phenomenology that came before it. It is more like a transition or evolution in thinking much in the same way post-modernism is still part of the larger project of modernity. Post-phenomenology still retains some of the important themes of phenomenological philosophy (*intentionality*, *embodiment*, and the *lifeworld*), but changes the philosophical boundaries. Ihde dismisses transcendental truths and restrictions to consciousness; instead he develops a pragmatic style (adapted from Deweyan pragmatism) that is experimental and contingent [234].

2.5.2 *Human-technology relations*

One of Ihde's most well known ideas, which transcend a lot of his major literary works, is his theory of Human-Technology Relations. This theory accounts for the various ways technology mediates people's experience of the world, or as Ihde's explains, the goal of this theory is to "show what is invariable in the way humans experience their technologies" [116, p.111]. Principally, it provides a meaningful taxonomy or framework to give an account of everyday interaction or engagement with technology. According to Ihde, the relations we have with technology can be described as: *Background*, *Embodiment*, *Hermeneutic*, or *Alterity*. While these relations can be viewed as discrete modes of experiencing the world through technology, they can also be seen together as a dimension that represents our technological mediated experience of the world, from complete emersion with technology (*embodiment*) to complete withdrawal (*background*). In the following I present a brief description of each relation, as well as presenting how this theory can be applied to the study of data representation.

EMBODIMENT RELATIONS According to Ihde, an embodiment relation is characterized by technology becoming transparent or withdrawing from our perceptual awareness. The focus of the human is not on the technology but on the content that it is referring to. Ihde presents it as being a partial symbiosis of a human and technology, where the technology is embodied and becomes "perceptually transparent" [116, p.99]. In the context of data representation an example of technology that affords this type of relationship is a digital microscope. Unlike a traditional optical microscope, which simply magnifies an image through a series of lens, a digital microscope uses optics and a digital camera to output an image to a digital display, sometimes by means of software running on a computer. Thus, the image that appears on the digital display is a representation of the data that is captured by the camera and computed by the software. When we use a digital microscope we see through the display to what is being represented. It is important to note, however, that the degree of perceptual transparency one experiences is dependent on a number of factors, including, for instance the familiarity -and experience with the technology and domain. For expert users of digital microscopes this technology offers direct experience of the phenomena, whereas novice users may view the output as static or animated visuals on a display, and not as a collection of pixels that embody the phenomenon under investigation.

HERMENEUTICAL RELATIONS The second category of Ihde's *Human technology relations* is what he calls *Hermeneutical*, which involves reading and interpretation of the technology. This is categorised as when we are focused on the technology, however, what one actually sees—immediately and simultaneously—is not the technology itself but rather the world it refers to. Ihde's analysis emphasizes the materiality of the technology being "read" while the world is being referenced. While an *embodiment relation*involves the technology being transparent, *hermeneutical* relations has a "*semi-opaque*" connection between the technology and the world [116, p.86]. Arguably, the predominant relationship that humans have with data representations is a *hermeneutical* one. If we broadly define data representations as artefacts that represents data in a certain modality, and which requires interpretation in order to form some insight about the underlying data, then perhaps we maintain a *hermeneutical* relationship with all data representations. An example that facilitates a *hermeneutical* relationship is a thermometer. When we read the output on a thermometer, instead of contemplating on the height of the mercury or the numerical display, one could argue we immediately see or envisage the world it represents.

ALTERITY RELATIONS According to Ihde, *Alterity* relations happens when the objectiveness of technology comes fully into presence, and is characterized by a relation to a "technological other", something "stronger than mere objectiveness but weaker than the otherness found within the animal kingdom or the human one" [116, p.100]. The term 'alterity' is borrowed from the philosophy of Emmanuel Levinas [159], and refers to the special experience of the presence of another person. Thus some of our relations to technology partially resemble the experience of interacting with a person or a "quasi-other" [116, p.97]. Ihde argues that *alterity* relations emerge in a wide range of computer technologies that display a quasi-otherness within the limits of linguistics and, more particularly, of logical behaviours. Arguably, no other technology exemplifies these characteristics more clearly than in-car satellite navigation systems (SatNav). Once a SatNav has been programmed, it occupies our attention as a *quasi-other*, to which we relate to by obeying intelligent directions verbalised by the device. When describing *alterity* relations, Ihde also discusses the fascination humans have always had with the quasi-autonomy of technology. This fascination is very evident with a SatNav, however, with this also comes a degree of trust involved in this relationship. When this breaks down (we reach a dead-end) this fascination and trust may turn into frustration and even rage, not with oneself but with the quasi-other.

BACKGROUND RELATIONS The final relation in Ihde's theory of human-technology relations is Background. This is understood as something that is "presence absence", something that we do not experience directly yet it gives structure to our experience. He states, "background technologies, no less than other focal ones, transform the gestalts of human experience and, precisely because they are absence presences, may exert more subtle indirect effects upon the way the world is experienced" [116, p.109]. Many automated, electronic and digital systems, such as, for instance, an air conditioning system, are experienced as a background relation, we do not directly experience the air conditioning system directly, however, our experience of the world is directly affected by it. The account given by Ihde to describe this relation may also be used to describe the concept of ambient visualizations or displays. These technologies are generally defined as a category of data visualizations that convey time-varying data in the periphery of human awareness. So, unlike most visualizations, which are experienced directly, ambient visualizations reside on the periphery or background of our consciousness.

2.6 PHENOMENOLOGY IN HCI

Originally conceived in the early nineteen eighties as a blend of psychology and computer science, Human-Computer Interaction (HCI) is concerned with the design, development and evaluation of interaction computer-based systems. While it has long since emerged as a research domain in its own right, HCI is still often regarded as the intersection of computer science, psychology, design and several other fields of study. The history of HCI research can be considered as having three consecutive phases or waves. While the first wave is categorised by its focus on large-scale, rule-based scenarios, the second focused on single individuals, who stand alone with different conditions, and the third, which encompasses contemporary HCI research, is typically considered as being focused on different individuals in a state of multi-user communication [94] [18]. Concurrent with these evolutionary phases, have been many theoretical and paradigm shifts in HCI. Recently Harrison and colledgues [91] argued that there are now three competing paradigms. The first two have their roots in human factors and classical cognitivist science, respectively, while the third has its base in Phenomenology. While the human factors paradigm tends to focus on optimizing man-machine fit, the paradigm that draws inspiration from classical cognitivism focuses on the relationship between the computer and the mind. The third paradigm discards the emphasis on the information processing model, instead it embraces topics such as the experiential quality of interaction, meaning making and the central metaphor is interaction as phenomenologically situated [91].

Winograd and Flores are considered to be the first to introduce the relevance of Phenomenology to the HCI research community through their influential book Understanding Computers and Cognition [317]. In this book they critique the use of theories from the field of Artificial Intelligence (AI) and suggest a phenomenological based approach for HCI. In particular they state that the theories of Heidegger are better suited to the study and design of technology. The findings of Winograd and Flores draw heavily from the work of Hubert Dreyfus, especially his book *What Computers Can't Do* [54], which was itself influenced by theories from Heidegger and Merleau-Ponty. The contribution Winograd and Flores offered to the HCI community can be summed up in four ideas they developed from Heidegger's thoughts, these are: (1) we should assume an *interpretive* or *hermeneutic* view of the world, (2) our ability to interpret and understand the world around us is based on our ability to be in it, (3) the rejection of the idea that we relate to things, primarily, through having representations of them in our minds, and (4) social activity is the foundation of meaning [317] [208]. Although it would be a number years before these ideas were fully embraced by the HCI community, their work marks a turn towards phenomenological thinking, which was developed further by Dag Svanœs, Paul Dourish, Toni Robertson and others at the beginning of the 21st Century.

2.6.1 *The Phenomenological Turn*

The turn of the 21st century also marked, what some consider an "embodied turn" for HCI research [208] [251]. It reflects a shift in emphasis away from modelling complex cognitive processes - as the basis of understanding interaction - and moves towards reinstating the body as central to where interaction takes place[208]. The genesis of this turn is usually attributed to the work of Paul Dourish and his book Where the Action is [52] but other notably researchers, including Dag Svanœs and Toni Robertson, also made valuable contributions.

"Where the Action is" takes a phenomenologically informed perspective on HCI by drawing on the writings of Heidegger, Merleau-Ponty, Schutz and Wittgenstein. One of the key contributions of this work is the discussion and definition of the term *embodied interaction*. Using Merleau-Ponty's *Phenomenology of Perception* [189] as a theoretical basis, he defines this new paradigm in interaction design as "the creation, manipulation, and sharing of meaning through engaged interaction with art[i]facts." [52, p.126]. Essentially, this means that it is the user (not the designer) who creates meaning, and consequently their own experience, through engagement and interaction with digital artefacts. In emphasising the role of embodiment in interaction design, Dourish proposes this as the basis for how we should approach social and tangible computing as social practise.

Another notion introduced by Dourish is that of coupling. By drawing together three aspects of meaning: ontology, intersubjectivity, and intentionality, he describes coupling as the means by which we build relationships between entities. It is concerned with making the relationship between action and meaning more effective, or as Dourish puts it: "Intentional connection that arises in the course of interaction. Designers can only suggest coupling, yet intentionally make it." [52, p.172].

Essentially, Dourish conceives *intentionality* as the relationship between actions and meaning, and coupling relates to how we manage this relationship [208]. For instance, if we take sawing a piece of wood as an example, coupling relates to how we mange the relationship between: the intention to saw (to make a table), the props that we need to execute the action (the saw and wood), the knowledge we possess to complete the action (woodworking skills), and the cultural significance of making a table for others to use.

Dag Svanæs also promoted the application of phenomenology to the study and design of technology. In particular, Svanæs advocated the use of Merleau-Ponty's work to explore the concept of interactivity, kinaesthetic aspects of interactions, and the importance of rediscovering the 'feel dimension' and the design of context-aware technology [276] [277]. By embracing phenomenology's focus on the first person and the body, Svanæs suggests this enables researchers to develop a deeper understanding of such systems from the perspective of the user, or as he puts it "an application of his embodied perspective on cognition and interaction enabled an analysis of the elements of interaction for context-aware systems." [277, p.397]. As part of an exploration into the role phenomenology can play in interactivity, Svanæs carried out a series of psychological experiments exploring how we make sense of and structure an interactive experience. These empirical studies were analysed from the phenomenological perspective of Heidegger and Merleau-Ponty [276]. More recently, Svanæs reiterated his view on phenomenology in HCI [278], by arguing that technological developments and the increased availability of digital technology, which is intrinsically tangible, mobile, social, and ubiquitous, have made phenomenology even more relevant than at the turn of the century.

Another researcher who was at the forefront of drawing attention to the relevance of phenomenology in the field of HCI and Computer-Supported Cooperative Work (CSCW) is Toni Robertson. In particular she used the phenomenology ideas of Merleau-Ponty to develop a taxonomy of embodied actions that serve communicative functions in CSCW [246] [248]. This taxonomy is intended to assist researchers and designers structure the results of field studies, to bridge the gap between work practices and the design of technology for distributed teams. This was also envisaged to help designers recognise the actions that current systems do not, or could never support [248]. Shifting the emphasis slightly, while still leveraging the concepts basic to a phenomenological understanding of perception, Robertson also showed how a phenomenological perspective, grounded in the public availability of actions and artefacts, could provide a common theoretical foundation for designers to maintain awareness of distributed activities [245] [249].

The work of Dourish, Svanæs and Robertson stimulated new discussions in HCI about the use of phenomenology as a theoretical basis for research. Since then, phenomenological notions of, in particular Merleau Ponty, has received a lot of attention. Hornecker and Buur[111] reference Merleau-Ponty when presenting their theoretical framework for tangible interaction, Fallman referred in depth to Merleau Ponty's emphasis on the role of the body when presenting a phenomenology of mobile interaction [60], Antle and colleagues use Merleau Ponty to support their inquiry on the role embodied metaphors play in physical interaction in augmented spaces [7]. Moen [195] also uses Merleau-Ponty's concern for the body when studying human movement and designing for a kinaesthetic interaction experience, and Veerapen [293] draws on Merleau Ponty's theories to examine how a new kind of being is formed subsequent to the user's interaction with the computer.

The work of Merleau-Ponty still remains highly relevant in HCI research, especially in special interest communities such as Tangible and Embodied Interaction (TEI). As the role of the body is of prime importance to many researchers in this community, the concepts of Merleau-Ponty continue to influence and inspire work. For example, the notion of embodied sense-making, which was first introduced at TEI 2015[112], and can be traced directly back to Merleau-Ponty's concept of embodiment and skilful coping. A selection of other work recently published at the annual TEI conference, which have been either directly or indirectly influenced by the work of Merleau-Ponty include: [273] [147] [49] [166] [267] [241]. Outside of the TEI community, the impact of Merleau-Ponty has also been felt by: [160] [152] [211] [50] [46] [137] [110]. For a comprehensive overview of Merleau-Ponty's influence on the field of HCI see: [278].

The work of Don Ihde has also received some attention within HCI literature. Rosenberger uses his theories to describe the experience of slowly-loading webpages [254]. While Rosenberger also draws on the concepts of Heidegger, and in particular his philosophy of technology to describe the way people experience interacting with computers, he postulates that this relationship (between human and computer) is best described using Ihde's concept of embodiment relations (as described above). He argues, when using a keyboard people are more aware of the words appearing on-screen than we are of our finger tips making contact with the keys (the technology becomes transparent). However, this, he argues, breaks down when confronted with slow-loading webpages: "the transparency of our embodiment relation that significantly changes when we experience the jarring sensation of suddenly encountering a slowly-loading webpage" [254, p.1]. He refers to this sudden shift of awareness as a transparency break, a sudden loss of transparency while experiencing the world through technology. Pierce and Paulos [226] also explored how people experience electrical energy through the lens of Ihde's human-technology relations. However, unlike Rosenberger, who used just one of Ihde's technology relations to describe a phenomenon, Pierce and Paulos sought to explore people's experience of electrical energy through all four relations (*background*, *embodiment*, *hermeneutic* and *alterity*).

While the work of Merleau-Ponty and Ihde has had an impact on theoretical developments in HCI and neighbouring fields, there is other work that relies on phenomenology in a more general sense. McCarthy and Wright take a phenomenological perspective to develop a discourse surrounding *felt life* within HCI [180] and Vaughan [292] uses this view when claiming the lived relationship between user and object is an evolving participatory act. In regards to design, Frauenberger and colleagues [72] argued that phenomenology plays a critical role in participatory design and Stienstra suggests that designers should adopt the core values of phenomenology, such as embracing direct experiences and emphasizing that life and the world are deeply intertwined [272].

2.7 CHAPTER SUMMARY

In this chapter, I presented the philosophical and methodological foundation of my research. Starting first with the historical background to phenomenology, I moved through the centuries, stopping briefly to describe some important ideas that help to understand how people experience data representations. From Husserl's use of *intentionally*, over Heidegger's concept of *temporality* and *equipment*, to Merleau-Ponty's discourse on the *body schema* and *maximum grip*, finishing with Idhe's novel concept of *human-technology relations*. The importance of these ideas may not seem relevant as yet, but as the following chapters unfold their significance will become apparent as I tease out and describe how people experience data. In the second part of this chapter I presented the role phenomenology has played in the field of HCI and showed how it has received increased attention in later years. Phenomenology in HCI is not considered to be a novel departure anymore; it is now commonly used as the basis for developing new theoretical frameworks (cf. [111] as well as the foundation of research approaches (cf. [254]. In this thesis I exploit both aspects of phenomenology. First, by using ideas developed within the tradition to help describe the way people experience data, and second, as the foundation of the methodological approach I use for the study of how people experience data.

3 DATA REPRESENTATION AND EVALUATION

If a diagram is worth 1000 words,
then it's worth 1000 words of our attention.

— (Edward Tufte)

3.1 INTRODUCTION

Following on from phenomenology, I now discuss the two other central parts of my thesis: *data representation* and *evaluation*. This chapter is dedicated to presenting a brief historical overview of data representation and describing current approaches, techniques, tools, technologies and methods used in the practice and study of data representation. In doing so, I also address issues related to representational modality and highlight the different research domains that are actively engaged in topics related to data representation. Following this, I move on to evaluation and discuss current research that relates to the type of questions I seek to answer in this thesis. I conclude by presenting commonly used approaches and methodologies that allow for the capture of people's experience of data representation[1]

3.2 DATA REPRESENTATION

Making sense of and communicating information through data representations has been engrained in human behaviour for millennia, from prehistoric cave paintings, over developments in cartography, onto more recent developments in scientific and information visualizations. Today the scientific study of data representation is typically associated with the field of study known as Information Visualization (InfoVis) [34]. While InfoVis is a relatively new field of research, which only emerged

1 Large parts of the literature review on evaluation methods in InfoViz are owed to Dr. Uta Hinrichs, co-author on [102], who helped us gain an overview of the state-of-the-arts in this field. In this chapter I extend the discussion to include other researcher fields such as HCI.

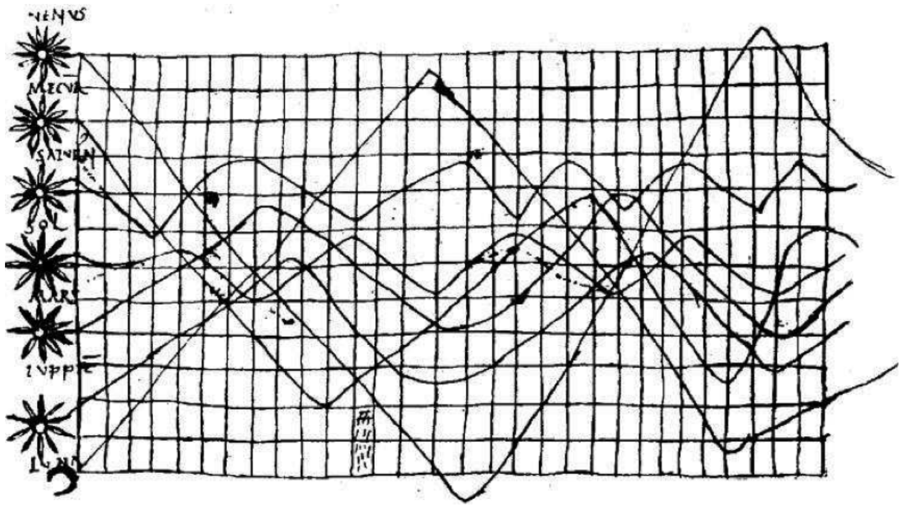


Figure 1: Planetary movements shown as cyclic inclinations over time, by an unknown astronomer.

in the 1990's, its lineage can be traced back to specific milestones dating from the middle of the last millennium. To fully appreciate and critique contemporary data representation, it is important to, at the very least, acknowledge the evolution of this discipline. Although a full historical appraisal of data representation is beyond the scope of this thesis, in the following I outline some of the key technical and intellectual milestones that enabled the practise and study of data representation to be fully embraced by the scientific and academic community, for a more thorough discussion of these developments see [74].

Amongst the earliest evidence of data being represented in pursuit of scientific goals is a 10th Century graph that depicts the movement of celestial bodies over time [287, p.28]. This graph (see Figure 1) was far ahead of its time, as the graphical nuances, such as the use of sinusoidal variation and grids, would not be fully developed until the 17th-18th Century. Somewhat later, in the 14th Century, the idea of plotting a theoretical function and the logical relationship of tablature values first appeared.

The 16th Century heralded intellectual and technical developments, including, (1) advancements in triangulation to determine mapping locations more precisely, (2) the initial idea of image capturing and the invention of the camera obscura, and (3) the publication of the first modern cartographic atlas

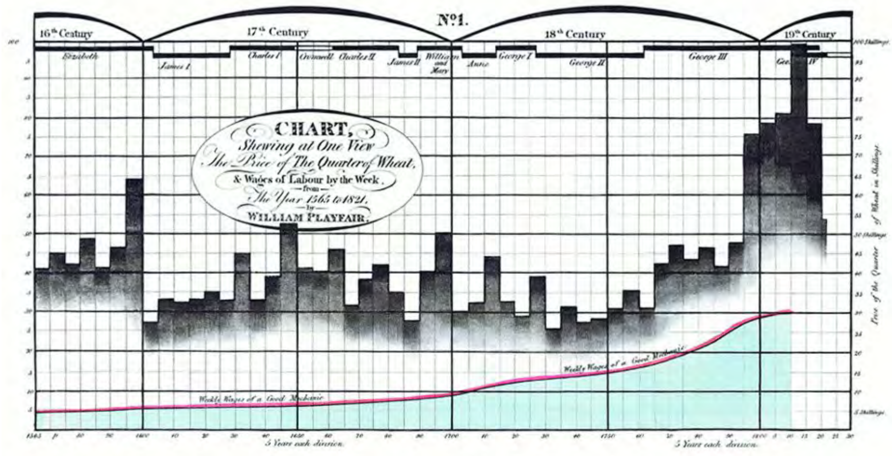


Figure 2: Chart by William Playfair (1821) depicting wages (line plot), prices of wheat (bar graph), and historical context (timelines).

(Teatrum Orbis Terrarum by Abraham Ortelius, 1570). These developments, along with others, signify for many the beginnings of modern data visualization [74]. The use of data representation increased in the 17th Century, especially for those who were concerned with physical measurement, such as astronomers, surveyors, mapmakers and navigators. Developments in the 17th Century paved the way for what was to come later. By the turn of the 18th Century the fundamental elements of modern data representation were in place, these were: (1) relatively easy access to data, (2) theories to make sense of them, and (3) ideas for their visual representation [74]. The most notable developments in the 18th Century can be attributed to William Playfair (1759–1823). Known widely as the father of modern data visualization, he invented a number of data visualization techniques used widely today, including the line graph, bar chart [229], pie chart and circle graph [230].

The graphs and charts invented by Playfair and others, such as Florence Nightingale, were the first to be used to stimulate political and social debate. For example, Playfair depicted the price of wheat, weekly wages, and reigning monarch over a 250—year span from 1565 to 1820 (see Figure 2), and used this graph to argue that workers had become better off in the most recent years. Nightingale also created many novel representation techniques, including the Coxcomb or as it's known today—the polar area diagram. She used this to persuade Queen

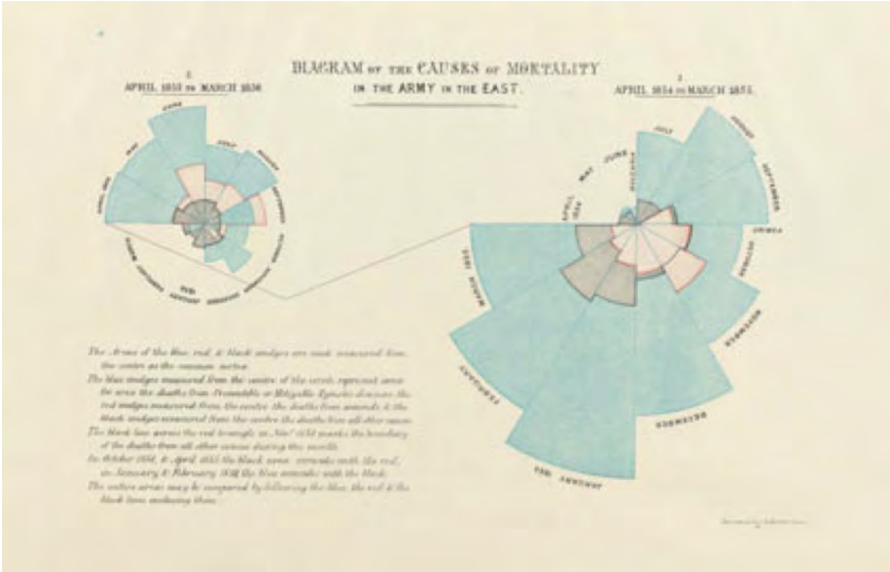


Figure 3: Florence Nightingale's Coxcomb graph depicting the mortality in the army in the Crimean War.

Victoria of the need to improve sanitary conditions in military hospitals during and after the Crimean War (see Figure 3). This new widespread use of data representation, as well as innovations in design and technology seeded an explosive growth in statistical graphics in the first half of the 19th Century, at a rate that would not be equalled until the turn of the 21st Century. As well as the array of techniques invented by Playfair and Nightingale, other representation formats invented in the 19th Century include Histograms, Time-series plots, Contour plots, Scatterplots, and so forth. Because of these, the 19th Century is now widely considered to be the golden age of graphic representation.

However, the rate of development was short lived as the first half of the 20th Century saw a shift in emphasis away from the use of visual representation towards more statistical models. It was no until the mid 1960's before enthusiasm was renewed in the visual representation of data, this was prompted by three key developments: (1) the publication of John W. Tukey's widely acclaimed work, The Future of Data Analysis [288], which called for the recognition of data analysis as a legitimate branch of statistics, (2) the publication of Jacques Bertin's landmark book, Semiologie Graphique (Semiology of Graphics) [13], which was intended to provide a theoretical foundation for data visualization, and finally (3) the creation of FORTRAN (1957), the first high-level language for computing, which enabled computers to process statistical data. It may be argued that the later, alongside other developments in computer technology, were central to data visualization flourishing in the final quarter of the 20th Century and evolving into a mature, vibrant and multi-disciplinary research area, known today as Information Visualization (InfoVis). Although there are various definitions of information visualization in the literature the one that is most commonly cited is: "the use of computer-supported, interactive, visual representations of abstract data to amplify cognition." [34]. However, the term InfoVis not only refers to the community of researchers and practitioners who are contributing or have contributed to the field of study, but also encompasses the set of tools, technologies and techniques used in the visual representation of abstract data. This aspect of InfoVis is addressed by Stuart Card, when elaborating on the definition of InfoVis: "information visualization is a set of technologies that use visual computing to amplify human cognition with abstract information" [34, p.542].

3.2.1 *Beyond the Visual Modality*

While the core value of InfoVis and its preceding fields has been focused on the visual representation of data, recent developments offer us opportunities to represent data through different modalities. As the medium used to encode data has moved from the printed page, over digital pixel, towards tangible objects, sonifications and other modalities, we have seen an increased attention around the field of HCI (cf. [205]) as well as more artistic endeavours (cf. [250]). Today, the practise and study of data representation does not exclusively reside within InfoVis, we now see related work in neighbouring fields such as Tangible Computing (cf. [213]) and Interaction Design (cf. [104].

Research on representing data beyond the visual modality can be traced back to the late 1990's with developments in Calm Technology [309], Ambient Displays [318] and Ambient Information Visualization [265]. One of earliest examples ambient or calm technology is Natalie Jeremijenko's Dangling String [126]. Produced while Jeremijenko was participating on an artist in residence programme at Xerox PARC in Palo Alto, California, this installation comprises of an 8 foot plastic string suspended from the celling of at Xerox PARC. The string is connected to a small electric motor, which is activated each time a bit of information is processed on the companies network. A very busy network causes the string to whirl fast and is accompanied by a characteristic noise, while a quiet network causes only small twitches every few seconds.

The challenge for ambient displays such as Dangling String, is to place data representations in the environment of the user or audience instead of a screen on the desktop computer, without being overly obtrusive. Although this focus still remains today (cf. [123]), developments, such as, easily accessible micro-controllers and rapid prototyping technology have expanded the field and offered new opportunities for researchers to explore ways of representing data beyond the visual modality. This approach has been further developed through novel InfoVis subfields, including Information Aesthetics [154], Artistic Visualization [300] and Data Art [171].

Some attempts have already been made to address and define data representations, which fall outside the typical classification of Information Visualization. In Pousman's [233] classification of Casual Information Visualization, he delineates this type of visualization into three categories: ambient, social and artistic. This definition also addresses the widening of the typical task driven user to that of a lay audience whose motivation for engaging with visualizations is more personally meaningful rather than for pure analytical discovery. In acknowledging this shift, Jansen and Dragicevic proposed a more people-centred approach by addressing issues related to interaction [123]. This work establishes an interaction model that can be used to help describe, compare and critique non-screen based data representations.

Beyond work that attempts to categorise different types of data representation, in the literature there are numerous theoretical and empirical studies that address issues related to the representation and perception of data beyond the visual modality. This research is spread over a broad range of research disciplines including: Psychology (cf. [96] [83] [73] [310] [194]), Scientific Visualization (cf. [210]), Information Visualization (cf. [243] [281]), Human-Computer Interaction (cf. [238] [259]), Geovisualization (cf. [90] [59]), Ergonomics (cf. [257]), Design (cf. [202]), Virtual Reality (cf. [10]), and Engineering (cf. [89]). In this literature, I identified four prominent themes: Human perception, Call for action, Surveys, and Arts based research.

3.2.1.1 *Human perception*

A number of studies investigated how using more than just the visual modality affects the capability of human perception. Warren and Rossano [83] found that tactile perception of transformation properties, such as tilt, size and length, in most cases, is as accurate as visual perception. Heller [96] illustrated how the combination of modalities (i.e. touch and visual) can enhance people's ability to process information, especially for perceiving texture. However, evidence also suggests a limit to the amount of information people can process (receive, process, remember), which differs depending on the modality or combination of modalities used, Miller refers to this as "the span of absolute judgement" [194, p.351].

3.2.1.2 *Call for action*

Throughout the years a number of researchers have called for more research to be conducted on non-visual representational modalities. For example, Roberts and Walker [244] encourage future studies to validate whether combining representational modalities will reinforce or contradict data insight revealed through different modalities. They also call for a more unified approach to the theory of visualization, to encompass the perceptual variables of all representational modalities. Tak and Toet [281] argued for further systematic empirical research to develop design guidelines for multisensory data representations or as they call them, Sensifications [281, p.558]. They claim that representing complex data through more than the visual modality facilitates a more intuitive and transparent process for the viewer/user. In particular, they suggest that these help the user to (1) acquire a wider range of detail (bandwidth expansion), (2) fill in missing information (data completion), and (3) gain a more holistic data experience (Gestalt forming) [281, p.559]. These aspects were also highlighted by Search [259], who suggests that utilizing more modalities expands the number of data variables that can be represented simultaneously. The proposed benefits of multisensory data representation are similar to those high-

Figure 4: All The People Of The World © Stan's Café. Included here by permission.

lighted for multimodal displays, including aspects such as: synergy (i.e., merging different modalities in one event or process), redundancy (i.e., communicating the same information via several modalities), and increased bandwidth of information transfer [256] [212].

3.2.1.3 *Surveys*

Exploring the state-of-the-art in data representation that utilize modalities beyond the visual modality has been attempted before. In particular, Card and colleagues [34] explored this space and defined the term Perceptualization as "a multisensory display of abstract information". Nesbitt [202] categorized data representation that utilise more than one modality by using a multisensory taxonomy based on high-level metaphors including spatial, direct and temporal. In Chapter Five, I present my own exploration of the design space for multisensory data representations. This is different from those cited here, in regards to: approach, scope, and contribution. Unlike previous attempts, I establish a design space through a systematic survey of existing examples, collected from a wide range of disciplines, and the dimensions of our design space are closely linked to the properties and qualities of representations, instead of high-level taxonomies.

3.2.1.4 *Arts Based Research and Practise*

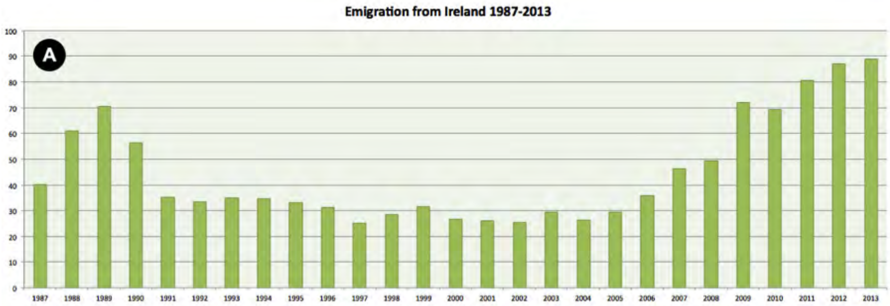
Apart from theoretical and empirical studies, other research has taken a more artistic and cultural view of data representations. Alongside the numerous articles in which new media theorist Lev Manovich (cf. [171]) highlights the cultural impact of data representations, Viégas and Wattenberg [300] have reviewed the field of artistic information visualization to investigate how artists appropriate and repurpose "scientific" techniques to create data representations. Recently, alongside these attempts to explore the theoretical foundations of artistic visualization, a large body of work consisting of artistic and often provocative explorations has received increased attention. An example is the art installation and performance piece: All The People Of The World (see Figure 4), which uses single grains of rice arranged in mountains, to represent the world's population, with one grain for each person. Individual piles of rice represent various data sets, such as the deaths in The Holocaust or the population of the United Kingdom. The creators consider this work of art not to be merely a representation of data, but also envisage it as helping people to engage in the critical issues of the day and get people to participate, understand, and to feel moved enough to take action.

3.2.2 *Physical Data Representations*

While the topic of representing data beyond the visual modality has received increased attention lately, there has been a marked increase in the study and practice of encoding data in the physical and tangible properties of objects (cf. [4] [275]). Contrary to many assumptions, representing data through physical forms is not a novel activity. Archaeologists digging in, what was once known as Mesopotamia (modern day Syria), unearthed clay tokens that are though to have been used by the Sumerians to represent numerical data. There are also examples of teaching aids from the 19th and early 20th Century that use physical representations to help their students understand complex scientific problems. However, these are rare and very little attention was given to this aspect of data representation until Zhao and Vande Moere [325] first explored the concept of Data Sculpture. In this work they define data sculpture as a data representation, which posses both artistic and functional qualities, they also establish a model of embodiment to analyse the connection between data and representation. Vande Moere followed up this research by introducing different levels of data physicality, which affect how data is mapped and perceived by human senses [196]. In recognising the importance of design in the process of data representation, while also supporting and inspiring future designs, Vande Moere and Patel [198] surveyed a collection of physical data representations, created within the context of education, and developed a bespoke semiotic model based on three categories - *symbolic*, *iconic*, and *indexical*[2] The concept of data physicality was also explored in depth by Jansen and colleagues, who sought to formalize this type of data representation as Physicalization [125] and provide a very clear definition as: "a physical artifact whose geometry or material properties encode data." [125, p. 3228]. While this work has sought to provide a boundary for this field of research, others have attempted to construct and describe the theoretical foundations for the study and practise of Physicalization. Jansen and Dragicevic's recent work [123] established a framework for visualizations beyond the desktop paradigm (including Physicalization) to help describe, compare and critique non-screen based data representations. Although little work has contributed to formation of design principles for Physicalization, Jansen and Hornbæk [124] explored the design of *Physicalizations* through the lens of one of Bertin's Visual Variables (size) and discovered that people have little difficulty recognising the difference in height between two solid bars. However, when they explored how people perceive the difference in volume between two spheres, they found that people had a lot of difficulty judging the difference. Other work that has compared the perception of data represented in 2D or 3D formats includes Dwyer's examination of 3D visualizations verses equivalent printouts [55] and Cockburn and McKenzie [42] who compared physical representations (2D, 2.5D and 3D) with virtual versions.

The work I described above explores aspects of physical data representation from a theoretical perspective, there are, however, many practitioners who have created physical data representations. In the following I describe some of these examples, starting first by introducing my own work.

2 While Vande Moere and Patel's model uses the same categories as Charles Sanders Peirce's (1839–1914) model of the sign, they are unrelated.



C

1987	40200.000	2000	26600
1988	61100.000	2001	26200
1989	70600.000	2002	25600
1990	56300.000	2003	29300
1991	35300.000	2004	26500
1992	33400.000	2005	29400
1993	35100.000	2006	36000
1994	34800.000	2007	46300
1995	33100.000	2008	49200
1996	31200.000	2009	72000
1997	25300.000	2010	69200
1998	28600.000	2011	80600
1999	31500.000	2012	87100
		2013	89000

Figure 5: Emigration from Ireland 1987-2013. (a) Traditional Representation (Bar Graph), (b) Physicalization (laser cut MDF wood), (c) Raw Data (source: Central Statistics Office of Ireland).

In the early stages of my PhD I sought to explore the potential of representing data through the tangible and tactile properties of physical objects. As part of this I created a series of physical data representations, which represent different socioeconomic data from Ireland. **??** shows one example from the series, which was created from data gathered from the Central Statistics Office (CSO) of Ireland showing the number of people who have emigrated from Ireland over the period 1987-2013. The data was processed using spread sheet and vector drawing software and then wooden disks were cut by laser and assembled by pushing a wooden rod through a hole cut in each disk. Figure 5 shows three views of the source data: (a) a traditional representation of the data set using a bar graph, (b) a physicalization of the data, and (c) the raw data collected from CSO. The purpose of creating these objects was to encourage people to reflect on the economic, social and cultural implications that surround the conceived dataset in an interesting and unique manner. It was envisaged that the physical representations would be the immediate object of interest; however as people examine the form of the object through touch, they would think beyond the object towards the topic of the data source.

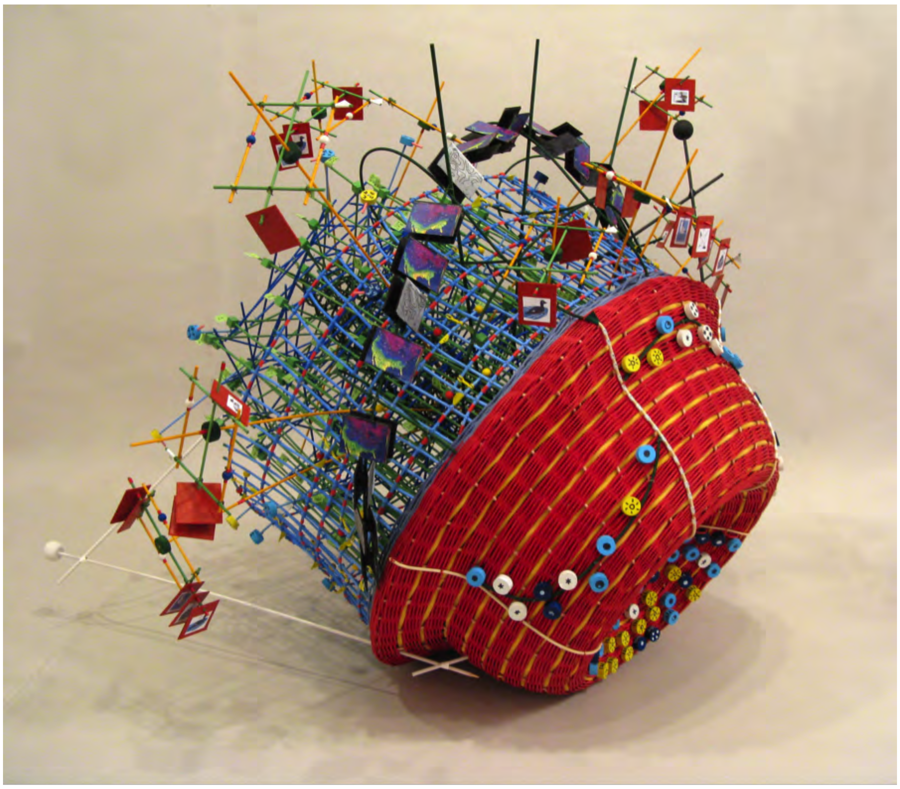


Figure 6: Barometric Pressure: Herring Cove, Cape Cod. Materials: reed, wood, data. Dimensions: 36″x36″x36′, © Nathalie Miebach, 2008. Included here by permission.

Another example of other work that has sought to represent data through physical artefacts include the intricate data sculptures by Nathalie Miebach (see Figure 6). Exemplifying the use of archived static data, this series uses environmental data collected from Herring Cove Beach, Cape Cod, USA to explore "the relationship between barometric pressure, cloud cover, soil temperature readings and bird sightings". This hanging structure can be viewed from many angles, but due to its delicate nature, no further engagement is afforded to the viewer. So, unlike the physicalization of emigration data (Figure 5) the viewers of this piece must imagine how it feels instead of touching it.

An example that actively encourages people to touch is *Strata Bench* (see Figure 7) by data artist and furniture designer, Adrien Segal. Although *Strata Bench* is considered to be a work of art, Segal incorporates many scientific and technical processes into the creation of her work. The approach she takes is also different from the two previous examples. Instead of collecting raw data and transforming this into physical objects, Segal often sources data representations, such as geo-visualizations and uses the patterns found in these visualizations to sculpt the contours of the wood. In essence, the work she creates is a representation-of-a-representation, however, it can still be considered to be a physicalization as the data is faithfully encoded into, for instance the patterns that appear on the wood.

3.2.3 *Auditory Representations*

Using sound to represent data is not a novel phenomenon, from the audible clicks of a Geiger counter that represent the number of ionization events, over the visceral beeps of an electrocardiogram (ECG) that represent the heart's electrical activity, to sound events on a computer that represent, for example, the arrival of a new email, we have all experienced or can imagine the sounds of data. However, it is only relatively recently that a concerted effort from the scientific community started to investigate the representational and perceptual properties of sound. Gregory Kramer's book, Auditory Display: Sonification, Audification, and Auditory Interfaces [143] is widely acclaimed as a landmark publication in auditory display and design. In it Kramer defines and discusses, for the first time, Information Sonification (or simply Sonification) as the use of non-speech audio to convey information or perceptualise data. He also introduces a number of methods and techniques for the practical application of sonic data representation and discusses a number of approaches to mapping data to sound parameters such as *timbre*, *tempo*, *pitch*, and *loudness*. Since then, research has shown many benefits of auditory data representation. Apart from the obvious benefit of the user's hands and eyes being free to process visual or physical data representations, while hearing a different set of data, sonifications have also been shown to facilitate the perception of multiple data simultaneously [219], allow for the perception of subtle changes in values and illuminating gradual changes [63], and it offers a way to expand the limited possibilities of representing multivariate data with graphics [146]. There have, however, been studies that highlight certain disadvantages associated with sonification, such as placing large demands on working memory and the large amount

Figure 7: Strata Bench. © Adrien Segal, 2012. Included here by permission.

of time required to navigate large data sets [303].

Much like InfoVis, Sonification is a distinct field of research dedicated to the study and practise of representing data through a single modality (in this case sound). And while Sonification emerged at a similar time to InfoVis (early 1990's), it has not received as much attention as InfoVis. My observations of this field reveal a number of reasons for this. First, building sonifications is technically more difficult that visualizations, also, unlike InfoVis, there are very few agreed principles for the design of sonifications [144] [3] [9], and finally it can be argued that the study of sonification suffers from a lack of historical precedence's that allowed InfoVis to flourish soon after it was established. Another argument as to why sonification has struggled to match the recent enthusiasm that surrounds InfoVis may lie in its use as an augmentation to other modalities, in an attempt to improve the perceptual qualities of visual or haptic representations. Apart from some notable examples – (cf. [218] [12] [56]), the majority of research relates to how sound can be combined with other modalities. The bulk of this research is also spread across many disciplines and thus sonification has become, what some may argue to be, a marginalised field of enquiry that is overly reliant on other modalities to garnish attention from the wider scientific community. The reason for this may be due to dispersed research community. Unlike InfoVis, which is nurtured by a vibrant and popular international annual conference (IEEE VIS[3]) and a dedicated periodical- IEEE Transactions on Visualization and Computer Graphics[4], there is no such counterpart for the sonification research community. Following a comprehensive review of the available literature I identified three primary research areas that sonification has been used are: *Augmenting visualizations*, *Assistive technology*, and the *Arts*.

3.2.3.1 *Augmenting Visualizations*

Numerous studies have shown the benefit of augmenting visualizations with sound to enhance the perceptual qualities of the representation. Ferguson and colleagues [63] demonstrated how sound can complement visualizations by highlighting subtle or gradual changes and emphasizing anomalies and outliers in the representational output. In the context of geo-visualizations, Krygier [146] explored the potential of using sound as a design variable and showed how it provides system designers with more choices for representing ideas and phenomena. Krygier specifically identified five ways of integrating sound into visualizations, such as (1) a vocal narration, (2) as a means of detecting anomalies, (3) to reduce visual distraction, (4) as a substitute for visual patterns, and (5) as a means of adding non-visual data dimensions [146, p.149]. Also within the domain of geo-visualization, Harding and colleagues [90] integrated novel sonification techniques with visualization and force feedback to assist the user to explore data represented within a multi-sensory three-dimensional visualization. Wheless and colleagues[312] also integrated sound into a virtual environment to improve the perception of the data. They used sound to represent numerically data, by mapping the change in values to the pitch in sound. Fisher [65] also used the pitch properties of dynamically generated sounds to represent aspects of a visualization. While these examples explore the potential of combining sound with the visual modality, other studies have compared the effectiveness of each modality at conveying certain data characteristics. Over the course of two studies Flowers and colleagues [68] [67] found no significant differences between the ability of participants to extract information from multimodal representations, using either the visual or auditory modality.

3 http://ieeevis.org/
4 https://www.computer.org/web/tvcg

3.2.3.2 *Assistive Technology*

Assistive technology is an umbrella term that refers to any device or system that helps improve the functional capacity of people with disabilities. Research on the use of sound to assist people with visual impairments has been on going since the end of the 1960's. Commonly known as "sensory substitution", this field of research aims to transform or substitute modalities linked to one sensory mode (e. g.vision) into the modality of another mode (e. g.audio)[5] . More recently, research in this area has included augmented systems (e.g. visualization and sonification) as well as traditional systems that completely substitute one modality for another. Aligned with technical developments in microcontrollers and actuators, there has also been a resurgence in this field, especially related to the representation of data through non-visual modalities. While the majority of recent research has focused on tactile displays (cf. [303] [136] [29], audio displays have also played an important role. An example of research that have sought to investigate the use of sound to help visually impaired users perceive and understand data visualizations is Zhao and colleagues work [324] who investigated the use of sound to represent statistical data for visually impaired users. In a study conducted using geographic data, they found that auditory feedback allowed for the recognition of patterns as well as helping the users to navigate maps. Lastly I note the work of McGookin and colleagues, who studied how hybrid virtual visualizations and sonification can help visually impaired users read data graphs and charts [184]. All these are examples of work that exploits the auditory modality to augment or substitute other modalities with the specific aim of making data accessible to those who cannot see visual representations of data.

3.2.3.3 *The Arts*

Another domain that has recently sought to exploit the properties of sound to create representations of data is Digital Art. While artistic representations of data are typically rendered visually (see [313] and [300] for examples and further discussion) recent work has broadened the perceptual bandwidth by integrating sonification as well as other modalities. This field of artistic endeavour is commonly known today as Data Art [171] or Artistic Data Visualization [300] and came into prominence

5 see [158] for a detailed discussion of sensory substitution

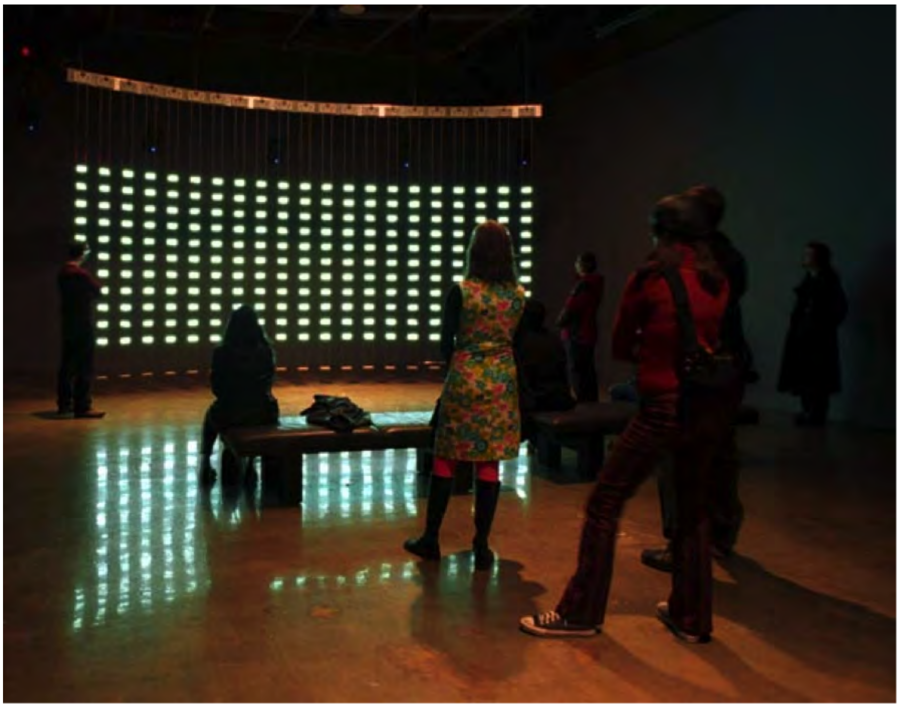


Figure 8: Listening Post by Mark Hansen and Ben Rubin. © 2001 Mark Hansen and Ben Rubin. Included here by permission.

following the rise of Information Visualization. While many reasons for to the growth in Data Art are comparable to InfoVis, such as, the mainstreaming of computer graphics, the democratization of data sources, and access to and distribution of the Internet, a motivating factor, which has be argued to be unique to Data Art is data becoming part of the cultural discourse [300, p.185]. Whitelaw [313] also addresses this point in his discourse on the practise of Data Art – "In the process of working pragmatically with data - using it as a generative resource, a way of making - data art is involved in the culturally crucial figuration of data and its contemporary domain" [313, p.1]. This is also reflected in the role data artists play in society, unlike designers of information visualizations, who have traditionally focused on task-driven concerns, data artists often disregard practical functionality and instead seek to facilitate the expression of some underlying message extrinsic to the data and provoking personal reflection [76] [154].

Artistic creations that typify this motivation and also integrate sound to communicate a message from the data source

Figure 9: Cloud Piano by David Bowen © 2014

include, *Listening Post*(2000-2001), *Cloud Piano* (2014), and *Sonicity* (2010).

LISTENING POST (see Figure 8) is an art installation created by statistician Mark Hansen and experimental sound artist Ben Rubin. Described by Hansen and Rubin as an exploration of the "information hidden in data" [87], Listening Post is made up of a series of visualizations and sonifications, which represent real-time conversations on the World Wide Web. The type of data used in Listening Post is raw text, which is scrapped from thousands of real-time conversations happening in chat rooms, forums, newsgroups, bulletin boards, and other public online communication channels. This data is then analysed and organised into topics based on the content. An arched wall, comprising of hundreds of small screens display the dynamic text, and digital-generated monotone voices, overlapping, or in strange harmonies, verbalise the text for the audience. While the visual impact of the installation is very striking, the creators of Listening Post emphasise the important role of sound in the installation – "the visual component of Listening Post acts as a kind of ventriloquist's dummy, which is animated by our sonic design" [88].

CLOUD PIANO (see Figure 9) is a sound installation created by digital artist David Bowen and driven by data collected from real-time cloud shapes and movements. The installation comprises of a piano, whose keys are actuated by robotic armature. The articulation of each key is controlled by custom software that is linked to a live video feed captured by a camera located outside of the building. When the program detects a cloud entering an area of the frame it triggers the robot to press the corresponding key, thus, he tempo and rhythm of the piece is determined by how quickly the clouds are moving. While some may consider this to be generative music, David Bowen notes that he "never really thought of it as music...I've always thought of it as a sound installation more than anything", a sound installation that is controlled by the randomness of cloud cover on any given day [274].

SONICITY (see Figure 10) is a sound installation created by British artist Stanza, which is made from the data collected across different cities. The piece integrates a number of environmental sensors that monitors the space (the building) and the environment (the city) where the installation is located. These sensors capture real-time ambient data (light, temperature, noise, and humidity), which is processed to produce a sonification of the micro incidents of change that occur around the installation over time. The technology used to collect the data for this artwork is very similar to that used by scientists who create geo-visualizations. However, the motivation and representational format is very different, while data scientists may create representations to reveal patterns in environmental conditions and also to predict future events, Stanza considers *Sonicity* to be a new way of exploring and "thinking about interaction within public space and how this affects the socialization of space." [270].

3.2.4 *Other Modalities*

While the representational modalities discussed already have a relatively long historical tradition of investigation and practise (ranging from decades to hundreds of years), the remaining modalities (taste and smell) have received far less attention from the scientific and art community. This is mainly due to the innate technical difficulties in producing and controlling the output from these modalities. Beyond this, other challenges include (1) producing specific tastes or odours on demand, (2) delivering the taste or odour stimuli to the user, and (3) eliminating the taste or odour when required [10, p.129]. Investigating olfactory displays in HCI research can be traced back to Kaye [134], this work explored the use of computerized scent output as a medium to generate data insight. Kaye postulated that the affordances of this modality are best suited to "slow-moving, medium-duration data, rather than rapidly changing information" [134, p.60]. He also noted that the associations we draw from smells varies dramatically, so the meaning one person (or culture) attributes to a certain smell may be entirely different from someone else. While modalities other than smell can be influenced by the cultural and past experiences of individuals, Kaye states that these are heightened for smell.

Studies have shown the value of using olfactory stimuli in scenarios such as sensory substitution, conveying alerts, stimulate emotional responses and increasing recall [301] [141] [40] [47]. Although these studies were conducted across many disciplines, all have strong associations with the study and design data representations. Representing data through smell is still in its infancy, however, there are some examples in the literature. *Dollars & Scents* is an olfactory display that represents fluctuations in the stock market by releasing scents into the air, such as rose, when the market is rising, and lemon when it is contracting (for more details, see [133]. Also, Smell Maps is a participatory project ran by artist and designer, Kate McLean. The project involves a group of people partaking in 'smellwalks' around cities, exploring the different aromas emanating from the city environment. Based on this experience the participants fill out information that describes the different aromas, the data is then collated and Kate produces a smell map of the city, which comprises of olfactory cues and visualizations.

Lastly, I discuss gustatory or taste displays. Much like olfactory, the information transmission capability of the gustatory sense is still largely unknown [10]. For the most part, the challenges facing the use of the olfactory sense for data interpretation also apply to the gustatory modality. While we all can recall when a certain taste evoked memories of a past event (e.g. the taste of candy as an adult stimulating childhood memories), controlling and delivering these taste is hugely problematic for olfactory displays. There are, however, some rare, but intriguing, examples including, *BeanCounter* [177] by Dan Maynes-Aminzade who was one of the first to explore this

Figure 10: Sonicity by Stanza © 2014

space and introduce the concept of Edible User Interface (EUI). *BeanCounter* consists of a rack of six hollow transparent vertical rods, each filled with different flavoured jellybeans. The system monitors activity on a local network and whenever a packet is sent across the network on one of the monitored ports, a jellybean of the corresponding flavour drops into a bowl for those who are passing by to taste.

Another example that uses food to represent data is Data Cuisine. This initiative, led by data researcher and practicing artist, Moritz Stefaner, consists of workshops where the participants explore food as a means of data representation or as Stefaner refers to it as – "edible diagrams" [271]. To date there have been five workshops, held in Helsinki, Barcelona, Berlin, Basel and Leeuwarden. One dish (data representation) produced during the Barcelona workshop is *First Date Noodles* created by the team at Domestic Data Streamers[6]. *First Date Noodles* (see Figure 11) is a representation of the sexual behaviour of young people from Barcelona. The dish consists of two portions of noodles, the straight ones represent the population who would abstain from sex on a first date and the 'noodle ball' for the others. The gender of the sample is represented by the colour of the noodles (male: blue, female: pink). An issue that is not clear from the creator's description is whether the different portions of noodles are infused with different flavours. If not, then the viewer is only required to use their sense of sight and touch

6 Domestic Data Streamers is a team of developers from Barcelona that transform raw data into interactive systems and experiences. For further information see: http://domesticstreamers.com/

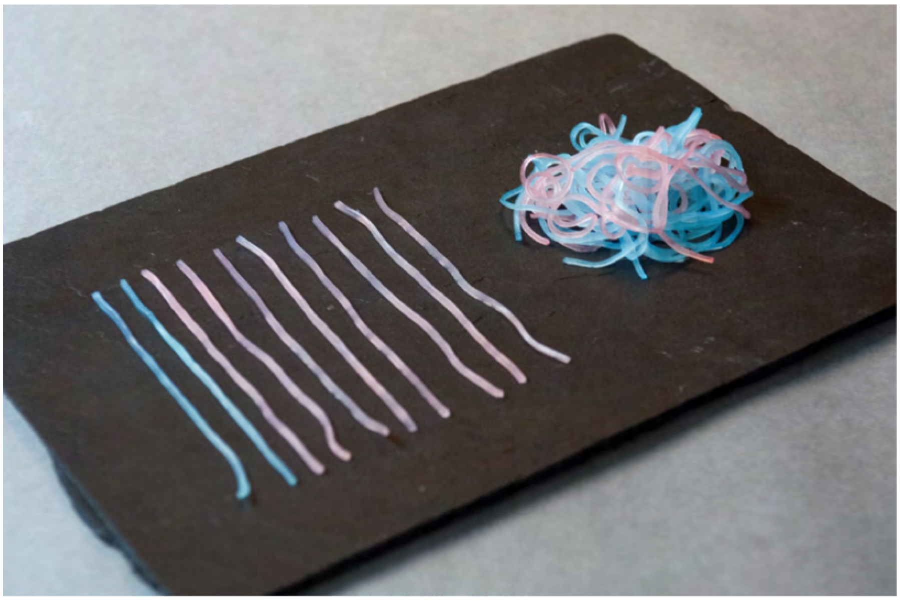


Figure 11: First date noodles. © Domestic data streamers, 2014. Included here by permission.

to interpret the data, thus this piece would be considered as a visualization or physicalization and not a gustatory or taste displays. This anomaly, however, is not reflective of the majority of examples I have reviewed. In general Data Cuisine communicates information through a combination of taste, smell, sight and touch, in what some may argue to be an almost holistic sensual experience of data.

3.2.5 *Section Summary*

In this section, I have described the various representational modalities commonly used to represent data. From here, I move on to describe various approaches and methods used to evaluate data representations, paying particular attention to qualitative approaches.

3.3 DATA EVALUATION

To date, the majority of published research on the evaluation of data representations is situated within the field of InfoVis and predominantly addresses questions regarding user performance, usability, and visualization algorithms. Studies that shed light into more open-ended questions regarding insight, discovery and experiences with information visualizations are relatively rare (cf. [150]). One possible reason for this may be attributed to the traditional application area of information visualization. Until recently, the vast majority of information visualizations were designed to support analytical tasks for expert users.

Today, however, visualizations are frequently used in more informal settings ranging from casual scenarios [233], storytelling [260], museum display [100], personal reminiscing [283], browsing for personal interest or edutainment [17] [100] [284], and community-driven urban scenarios [15]. Another reason why there is little work that aims at studying subjective experiences with visualizations is that we still lack evaluation methods that can derive reliable and rich data on insight generation, discoveries and experience.

When I talk about *experience* in this context, I mean personal responses to a data representation, which goes beyond interaction and usability aspects to focus on capturing *hedonistic*, *emotional*, and *sensory* responces to the representation as well as personal interpretations, meaning, and opinions that it may trigger. Capturing people's subjective experiences in a scientific way is a challenge. Apart from the fact that people find it inherently difficult to describe their experiences, it is also difficult for the researcher to validate these accounts due to issues such as post-hoc rationalization and humans innate desire to embellish accounts with details that did not occur during the original experience. The commonly used techniques that capture accounts of people's experiences and exploration processes have strengths and weaknesses. More rigid and controlled methods, such as questionnaires and Likert Scales lead to more objective but less rich results. More open-ended methods, such as observations, diaries, think-aloud, and interviews provide a rich account of people's subjective experience but allow for bias introduced by the researcher or participant. This may be the reason why there is little work that aims at studying subjective experiences with visualization beyond, processes of analysis, reasoning, knowledge discovery and communication [150].

While fields of research traditionally associated with the study of data representation, such as Information Visualization has not yet fully embraced experience research as an important aspect of design, Human-Computer Interaction (HCI), has a long tradition in this area. The shift from evaluating performance to researching experience has stimulated a rich discourse in HCI, around topics such as *hedonics* [93], affect [323], *empathy* [320], and *enchantment* [181]. There has also been work to extend the traditional measures of performance in HCI, which up to recently included aspects such as efficiency and effectiveness. Löwgren [165] proposed a list of *use qualities* by exploring other designers' reflections, published empirical studies, and design critiques, combined with his own first-hand design experience, with the aim of helping interaction designer's kick-start the design process and communicate design decisions to stakeholders. The use qualities Löwgren proposes combine aspects that were already employed in HCI, such as efficiency and transparency, with newly proposed ones such as *relevance*, *fluency*, *pliability*, *actability*, *surprise* and *elegance*.

3.3.1 *Describing a lived experience*

Gaining an understanding of people's experiences as well as extending the focus of evaluation may not reveal details about specific design elements. However, it does allow us to investigate how systems shape the way people feel and think as they interpret and/or interact with them. This knowledge can be used to reflect more effectively upon design decisions. As outlined in the introduction of this thesis, the primary aim of my research is to investigate and describe people's subjective experience with data representations. To accomplish this I need to capture precise accounts of people's lived experience with data representations.

In the following I discuss commonly used approaches, methods and techniques, which have been used to study how people interact, perceive and interpret systems, including those that represent data. Studying people's experience of data representations is typically situated in the field of InfoVis and thus the bulk work I reference emerged from this field. With that said, the methods utilised by these researchers are generally borrowed from other fields. Most of the methods I discuss here are proven and commonly used methods within the HCI research community, however, their use and efficacy has been questioned in the context of evaluating data representations (cf. [32]).

3.3.2 *Studying Experiences of Data Representation*

While evaluation has been a significant aspect of HCI since its inception, its role within InfoVis research has only become prominent relatively recently. Previous literature describes a range of techniques that can be applied to studying different aspects of visualization systems [36] [201] [150]. Carpendale [36] provides a thorough overview of quantitative and qualitative methods applicable to InfoVis, outlining their strengths and weaknesses. Munzner discusses evaluation methods focusing on the different stages of the visualization design process [201]. Lam and colleagues [150] identified seven InfoVis evaluation scenarios, including those that focus on understanding the data analysis process and those that aim at deepening our understanding of visualization techniques. Based on these, they provide an overview of possible evaluation goals, questions, and methods to facilitate the study design process.

Common evaluation techniques that are used to investigate how people form insight, make discoveries and subjectively experience systems and their individual features include observations, diaries, questionnaires, think-aloud procedures, and interviews (see Table 2 for a summary of their strengths and limitations). All these techniques are not necessarily specific to the study of data representation, but have been used in this context to explore analysis processes, the usability and (more rarely) subjective experiences with systems. In the following sections I discuss these methods and outline pertinent issues that affect the validity and accurateness of the data gathered.

3.3.2.1 *Observation*

Observational studies have a long tradition in qualitative research (cf. [170]). This approach was first used in anthropology, but was soon employed by sociologists and more recently it has become a commonly used method in HCI research [6]. Observational studies may take place in any setting in which people have complex interactions with each other, with objects or with their physical environment, however, in the context of HCI they typically take place 'in the wild', where the 'wild' may be the workplace, home, or some other location where the activity of interest takes place, that is, the technology of interest is used. The practice of observing people involved in technology-based activities is considered to be a valuable method for gathering

STUDY METHOD	STRENGTHS	LIMITATIONS
Observations	Provide insights into activities around exploration and analysis processes.	Insights into people's thought processes are not captured.
Diaries	First-hand capture of people's experiences with visualizations and thought processes around exploration and analysis (see, for example [120]).	Richness of data depends on the participant's commitment. Personal biases and post-rationalization may skew the data.
Questionnaires	Enable the large-scale and consistent collection of people's subjective experiences with an information visualization.	Limited level of detail—more in-depth and clarifying questions are not possible.
Think-aloud	Enables the first-hand collection of information about people's thoughts and subjective experiences with a visualization *while* they are exploring (see [305] for an example study in the InfoVis context)	The activity of commenting on thoughts and actions adds a cognitive task and therefore influences people's exploration process and their experience of the visualization in general.
Interviews	Can provide in-depth insights into peoples' experience of a visualization and their strategies of data exploration.	Introduction of biases and post-rationalization can skew the data.

Table 2: Evaluation techniques to investigate insight and subjective experiences of information visualizations.

rich descriptions [237].

In the context of studying people's engagement with data representations, observational studies are a common method to evaluate how people interact and experience these systems. The direct observation of people's interactions with a visualization, for instance, through in-situ field notes or video recordings, can provide insights into the analysis process and experience with the system. Observational studies can also be conducted in a laboratory setting or in-situ [36]. The researcher simply watches and takes notes on how people interact with the visualization, what kind of activities they engage in, what data aspects they explore and what visual elements they use (see [100] and [284] for example studies). Sometimes, interactions are video-recorded and/or computationally logged by the visualization system to allow for a more in-depth analysis of participant's interactions. The observation of people's activities around a data representation can provide insights into their general analysis process and experience with the system. However, a qualitative interpretation of observations is necessary but can introduce bias [36]. Furthermore, pure observation does not offer direct insights into participant's thought processes and experiences; important aspects that can only be contributed by the person interacting with the visualization may be missed.

3.3.2.2 *Interviews*

Interviews are one of the most common ways of gathering insights into people's past experiences. Much like ethnography and observational studies, the use of interviewing as a method of collecting data had a long tradition in other domains, such as psychology and sociology, prior to being used in HCI research. The use of interviews as a formal method in empirical research can be traced back to the development of the focused interview by Robert Merton and his colleagues in the mid-1940's [190]. Since then, many variations on interviewing have emerged, including *semi-structured interviews* [258], *unstructured interviews* [70], *problem-centered interviews* [319], *the expert interview* [191], and the *ethnographic interview* [269]. The most common forms of interviewing techniques used in HCI research today are unstructured, structured and semi-structured, and the choice of with approach to adopt typically depends on the evaluation goals and the research question. For instance, if the goal is to gain an understanding of people's response to a new design, then an unstructured interview is often the best approach. Whereas, if the purpose of the study is to probe people about a specific design feature, then a structured interview is probably a better option.

In the context of studying data representations, interviews are typically conducted to gather first-hand opinions of participants after they have interacted with a visualization system [284], or to learn about existing work strategies to inform the design of a visualization system. The data acquired during an interview can be rich in insights, going beyond potential pre-assumptions of the interviewer and superficial opinions of the participant. However, while interviews are frequently conducted to evaluate information visualizations, the type and interview approach is rarely specified when reporting on the study. In the context of studying data representations, interview questions have traditionally focused on usability aspects and do not explore actual experiences and insight generation processes. Admittedly, these latter aspects are difficult to capture in an interview—without introducing bias and post-rationalization. Similar to questionnaires, interviews typically involve a list of pre-defined questions but, in contrast to questionnaires, they have the advantage that the interviewer can flexibly adapt to participants' statements and comments, modifying or asking follow-up questions during the interview. If used correctly, the data acquired during an interview can be rich in insights, going beyond potential pre-assumptions of the interviewer and superficial opinions of the participant. However, interviews also contain bias, introduced by leading questions from the interviewer or by the participant who may be influenced by a subconscious desire to align to the interviewer's anticipations (demand characteristic effects [48].

Furthermore, a commonly known problem with interviews is people tend to post-rationalize their activities and experiences, in that they often report what they believe or imagine they were doing at the time, instead of what they were actually doing. To overcome this and other issues some researchers have sought to conduct a retrospective interview while showing the interviewee a video recording of their interactions (cf. [236]). Video-recall can increase the accuracy of the described experience while also reminding the interviewee of details that would have otherwise been forgotten. However, as it is a fundamental requirement to have the original event video reordered, this limits the study situations and settings this method can be applied to; it usually means that the study has to be conducted in a laboratory or similar setting. Furthermore, watching the video during the interview can also influence the description or accounts of the experience. For instance, watching the event unfold on video can stimulate new thoughts that were not evident during the original experience.

3.3.2.3 *Questionnaires*

Questionnaires are a common way to collect information about people's subjective experience with a system, both in controlled laboratory settings as well as field studies. In contrast to interviews, for example, questionnaires are a powerful way of collecting data about people's experiences with a system on a large scale; they can be handed out to many people and made available over a long period of time. This can be useful for large-scale evaluations in public settings such as museums [100]. Typical ways of eliciting people's experiences with a system in form of a questionnaire are Likert Scales and/or open-ended questions [163]. Named after its inventor, psychologist Rensis Likert, this method requires study participants to rate their experience with a system on a (five- or seven-point) quantitative scale. This approach produces quantitative data on participant's subjective experience, which makes it easy to compare, for instance, different systems or groups of participants. However, Likert Scales reduce rich subjective experience to pre-defined categories; important details and subtleties of people's experiences may not be captured. In addition, they do not reflect the reasons for participant's ratings. Open-ended questions can be included into questionnaires to allow participants to describe their experiences in their own words, hence, resulting in rich accounts of (sometimes unanticipated) experiences. However, the level of detail that participants provide through open-ended questions can vary dramatically. Furthermore, statements may be ambiguous and, depending on the study setting, it may not be possible to ask the participant to clarify their comments.

3.3.2.4 *Diaries*

Diaries can provide rich data about the analysis process, the role of the system in this process, and discoveries from an individual participant perspective as part of longitudinal studies [75] [19]. The use of documents for study has a long tradition in qualitative research; for example, diaries can be seen as traces of personal experiences or records interactions [66]. First used in Cognitive Science research (cf. [206]), diaries were subsequently introduced to the HCI community in the early 1990's through Kirakowski and Corbett's book on HCI methods [138]. One of the first HCI empirical studies to use diaries was by John Rieman [242]. In the context of HCI, diaries are used to capture activities that occur in the everyday lives of participants and sometimes used as part of a cultural probe study (cf. [77]). During diary studies participants are provided with objects to use in their everyday lives and are asked to regularly record their insights and experiences using a written diary. Although the entries in diaries are usually recorded in written format, there have been examples of studies that have provided participants with technology to record their interactions. Browne and colleagues used diaries to collect data on the different strategies people employ when capturing information, such as pen and paper, sounds, images and notes [28]. In this study participants were provided with a camera and were asked to take a picture every time they captured information in any form. Palen and Salzman's study [214] also provided participants with technology to make records of their daily activities, but in this case each participant was asked to used mobile and landline telephony to make voice-mails instead of writing on paper.

Diaries can also provide a rich picture of people's analysis process using systems, their experience as part of the process, as well as resulting discoveries and insights (and, possibly their meaning for the participant). However, paper based diaries rely heavily on participants commitment to regular diary keeping, and the consistency of written accounts may vary or change over time (e.g., the level of detail may decrease over time). Also, the participant may introduce personal biases in form of post-rationalization [221], a common problem when it comes to eliciting accounts of personal experiences.

3.3.2.5 *The Think-Aloud Protocol*

Another method used to elicit people's experience, which has been regularly used in HCI research since the 1980's is the Think-Aloud protocol. Early work by Newell and Simon [203] is often cited as a major landmark in bringing about its wider acceptance, although various works by Ericsson and Simon (cf.[57]

[58]) are more commonly referenced. The Think-Aloud protocol can help to extract information about people's experiences with interactive systems in-situ, which may quickly fade away after the interaction [57] [162]. Several researchers have argued that the think-aloud protocol can help to identify the cognitive processes responsible for people's behavior and actions that may not be visible otherwise [130] [84]. However, thinking-aloud is not a process that people naturally engage in. The activity of commenting on thoughts and actions (as they occur) adds a cognitive task and, hence, can skew people's experience of their exploration process and their experience with the system or data representation in general [36] [221] [220]. Furthermore, the addition of thinking-aloud as an extra task can lower participant's awareness of how and why they explore certain aspects of the system.

3.3.2.6 *Focus Groups*

Focus groups have been in use since the middle of the 21st century. Originally called focus interviews, they were used by social scientists to examine the morale of the U.S. military during World War Two. Although the technique has been widely used in market research, difficulties in demonstrating rigor in analysis and fear of researcher bias meant that the technique was not fully embraced by HCI research until the 1980's [45]. Focus groups can be conducted at various stages of a research project, during the preliminary or exploratory stages of a study or as a method of evaluation. Their main purpose is to obtain perceptions on a defined area of interest in a natural, non-threatening environment. Most importantly, for researchers interested in exploring user-experience, the data that gathered is qualitative, and consists of experiences, opinions, ideas, and motivations for behaviour, rather than "figures and facts" [200]. Mazza and Berre first proposed using focus group studies in the context of InfoVis to evaluate techniques and tools [179]. They claim that focus groups offer researchers an insight into why certain visualizations work or not and can be used to "uncover potential problems and suggest improvements that would not have been revealed with other analytic and empirical evaluation techniques" [179, p.80]. Although Mazza and Berre highlight the positive aspects of using focus group studies, there are also problems associated with this technique, including, difficulties in arriving at a consensus, no agreed method of analysis and it may become dominated by assertive and vocal individuals.

Focus groups also offer design researchers a flexible technique that can be employed at various stages of the design cycle—to elicit user needs, for feedback on concept sketches or prototypes, or to let participants generate new ideas. Focus groups can also be used for final concept refinement. Tremblay and colleagues [286] highlight several reasons why focus groups is a highly relevant and rigorous approach for refining and evaluating design artefacts, these include, its ability to allow for the emergence of ideas or opinions that are not usually uncovered in individual interviews, and offering design researchers the opportunity to collect large amounts of rich data. They also help to reveal information in a way which allows researchers to find out why an issue is salient, as well as what is salient about it [200]. Focus groups are also a very efficient form of exploration and evaluation, however, because of their open approach, a skilled, unbiased moderator is needed to mediate and refocus conversations. Another known issue with focus groups is the lack of clear procedures that could guide newcomers to the approach [2]. Nevertheless, focus groups are widely used in HCI, and often in combination with other approaches (cf. [178] [30]).

3.4 CHAPTER SUMMARY

The aim of this chapter was to provide a review of the state-of-the-art in data representation and evaluation. To achieve this I first presented a brief history of data representation, focusing at times on important milestones that have influenced the trajectory of the field. I then showed how data representation today is not exclusively visual by pointing to a surge in research dedicated to the study of representational modalities beyond the visual modality. Each of these modalities: physical, auditory, olfactory and gustatory posses their own unique characteristics that can be used to communicate information and facilitate data insight. While research on representational modalities other than visual is still relatively new, there is now a growing community of researchers who strive to exploit their full potential.

I also reviewed current practises in evaluating data representations, drawing primarily on examples from InfoVis. A review of the literature shows that the study of data representation is skewed toward evaluating traditional usability concerns, such as effectiveness and efficiency and the methods used are typically quantitative. There have, however, been some studies that have attempted to explore issues more closely related to the focus of my research – experience. Studying people's experience of data representations is a difficult task, which is made even more difficult by the lack of proven or accepted methods within InfoVis. Up to now, InfoVis researchers have borrowed qualitative methods from HCI and applied them to the study of data representation, these include: observational studies, diaries, questionnaires, the think-aloud protocol and interviews. While these methods have been relatively successful at revealing issues related to the experience of systems, they have limitations. To overcome the limitations associated with these methods, in Part Two of this thesis, I introduce two methods (the Repetory Grid and Elicitation interview technique), which have yet to be used in the study of data representation, but allow for the elicitation of participants meaning structures of events/artefacts and for the capture of precise accounts of experience. Before then, in the next chapter, I draw together the three theoretical aspects discussed so far – phenomenology, representation and evaluation – by presenting a phenomenological informed design and evaluation study.

4

DATA, DESIGN AND *DASEIN*

"It doesn't feel like a computer, but I know it is kinda one, wouldn't it be nice if all computers felt so natural in your hands."

— (Anonymous participant)

4.1 INTRODUCTION

In Chapter 2, I presented Phenomenology as the philosophical foundations of my research approach; this was followed in Chapter 3 with an overview of the state-of-the-art in data representation and evaluation. I now draw these three aspects together in the form of a design exercise and analysis of data-driven prototypes in use.

I start this chapter with an overview of the background to this project and introduce two prototypes that were created to represent scientific data to a casual audience. These prototypes were designed to be deployed in a public Space Observatory, where a series of user studies were conducted. I used these studies to better understand how people experienced the data represented through the prototypes. I conclude by interrogating the prototypes in use through the prism of philosophical thought by Edmund Husserl, Martin Heidegger, Maurice Merleau-Ponty and Don Ihde, as I apply phenomenological theories and ideas to the exploration of people's experience of tangible data representation [1]

4.2 BACKGROUND

The prototypes I introduce here are: H_3 (see Figure 12, B) and the Solar Radiation Dowsing Rod (see Figure 13, A), which

1 The design and implementation of the prototypes presented in this chapter (H_3 and the Solar Radiation Dowsing rod) has already been described in [101]. In this publication we primarily described the prototypes and only discussed some observations, here I extend the discussion and analysis of participant reactions, and also discuss the prototypes from the perspective of philosophical phenomenology.

Figure 12: (A) Solar Radiation Dowsing Rod, (C) Mobile Radio Telescope

were designed to be deployed in Blackrock Castle Observatory, Cork, Ireland—a working Space Observatory that also contains a museum that is open to the public. H_3 is a small hand held devise that represents the levels of Hydrogen in deep space, which is captured by a nearby radio telescope (see Figure 13, A). The user triggers H_3 to represent the data by shaking the cube, this gesture causes an embedded microcontroller to request the latest reading from the telescope and once this is received H_3 it represents the data through vibration. The Solar Radiation Dowsing Rod also represents astrological data, which are the levels of solar radiation captured by a motorised radio telescope situated on the roof of the Observatory (see Figure 12, B). The user can point the rod in the air and once he/she selects the heading, this is sent to the telescope, which in turn points in the same direction and scans for solar radiation levels. The telescope then sends this data back to the rod, which causes vibrations based on the intensity of the radiation.

4.3 DESIGN CONCEPT

The overarching design concept that underpins the creation of both prototypes was to offer casual users the opportunity to interact with complex scientific data in a natural and intuitive manner. The data, which both prototypes represent, is not normally presented to a lay public audience; instead, it is utilized by experts to analyse certain phenomenon in the solar system and deep space. The goal of the design process was to create prototypes that would facilitate non-analytical data insight using tangible interfaces. I envisaged the prototypes not to be replacements for traditional information visualizations, but to compliment the range of tools available when representing data to the wider population. This project was a collaboration with Blackrock Castle Space Observatory and the Irish National Space Centre, who provided me with access to scientific live data as well as a public exhibition context. In the design of both prototypes I prioritised three aspects: the *type of user*, the *modality of the representation*, and the *mode of interaction*.

The prototypes were designed to generate curiosity and awareness of the represented data, as well as acting as a compliment to more traditional information displays located in the observatory, which use text, motion graphics and imagery. They were also designed to be crossmodal representations by encoding data in vibro-tactile and auditory feedback simultaneously. Unlike multimodal representations, where each modality is used to transmit a different type of information, crossmodal representations use different modalities to present the same data [158]. As an everyday example of a crossmodal display, most of us recognize the sensation of being alerted to an incoming call or SMS on our mobile phones through sounds while also vibrating.

A key feature envisioned in the design process was how users would interact with the data. Based on the notion of *embodied interaction* [52] [111] [153], I explored various ways of promoting the physicality of the interaction as well as exploring body motion and spatiality to free the representation from the traditional screen based format.

In the early stages of the design process I decided to use two separate data sources and to develop a unique design concept for each. One of the sources of the data is a 1.4GHz receiver on a 32-meter (diameter) radio telescope that measures hydrogen levels in deep space (see Figure 13, A). The other is a 2.4GHz receiver on a 2-meter (diameter) radio telescope that reads solar radiation levels within our solar system (see Figure 12, B).

In regards to the real-time Hydrogen data, I envisaged this to be perceivable by visitors anywhere within the Observatory. To facilitate this, I developed a concept that allows visitors to carry

Figure 13: A) 32m Radio Telescope, (B) H_3

a data-driven responsive cube with them as they move about. When the visitor interacts with the cube (by shaking it) the latest Hydrogen levels are displayed through vibration motors embedded in the cube. The intensity of the vibration is mapped to the levels captured from the telescope (the higher the stronger the vibration). A core characteristic of this concept is to allow the visitor to use the device while simultaneously reading information displayed using other modalities (text, video and imagery) about Hydrogen and other related phenomenon presented throughout the Observatory.

As the telescope that monitors solar radiation levels can be directed at a specific point in space I sought to offer control of this functionality to the user as well as representing the data read by the telescope. To do this I borrowed the metaphor of a dowsing rod. Traditionally this tool is used to locate underground water sources; it is said that people feel the rod pulling them towards these sources. The reason I chose this metaphor is that experts may use the representation of solar radiation levels as an indicator to locate objects in our solar system. I envisaged the user selecting a position in space by pointing the rod upwards, and confirming this by pressing a button located on one of its handles. The coordinates of this heading are sent to the telescope, which then manoeuvres to point in this direction. Once the telescope has reached the heading it sends the solar radiation level from this point in the solar system back to the rod. This triggers the rod to vibrate, with the data value mapped to the intensity of the vibration (see Figure 14).

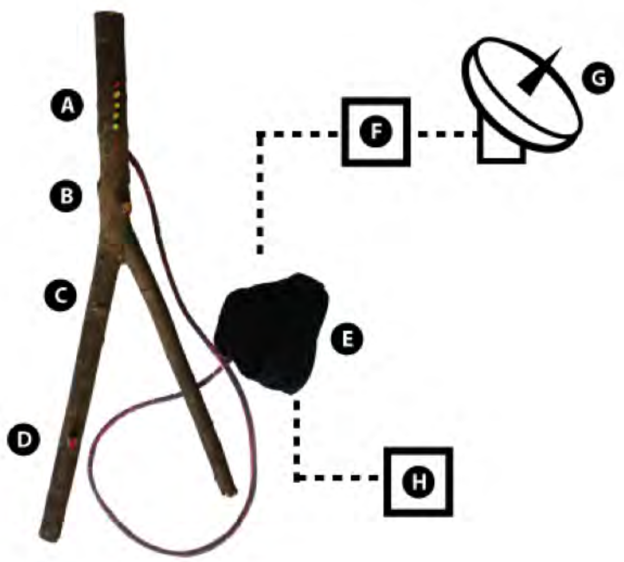


Figure 14: The Solar Radiation Dowsing Rod system design. (A) LED strip (red, orange, green), (B) embedded IMU module, (C) two embedded 5v vibration motors, (D) push button, (E) armband pack including a microcontroller, 9v battery, wireless radio frequency module, (F) PC connected to telescope, (G) 2-meter radio telescope with 2.4GHz receiver, (H) COSM Server.

4.4 IMPLEMENTATION

DATA Besides of developing two bespoke data-driven artefacts, I also had to develop a strategy for real-time acquisition of data from both telescopes, and to communicate this wirelessly to each device. To acquire the data I utilized the COSM [31] platform. A custom program on the computer attached to each telescope collects the latest data and sends it to an account on COSM. Any computer connected to the Internet can then retrieve this data.

H_3 H_3 is a wireless cube (7cm side length) constructed from semi-opaque Perspex. To perceive the latest hydrogen levels users gently shake the cube. This action is detected by an accelerometer connected to a microcontroller within the cube. The microcontroller then sends a request to COSM for the latest data using a wireless radio frequency module. When this data is retrieved, it activates four vibrating motors fixed to the internal faces of the cube, which vibrate for four seconds. When they stop, the user may shake the cube again.

SOLAR RADIATION DOWSING ROD When developing the Solar Radiation Dowsing Rod device I tested numerous types of wood for the most effective transmission of vibrations and finally choose ash. Embedded in the wood is an Inertial Measuring Unit (IMU) module (that includes a 3-axis accelerometer, gyroscope and a compass module), a LED strip (green, red and orange), a push button and two 5-volt vibration motors. An armband pack is connected by wires to the rod and contains a microcontroller, a wireless radio frequency module and a 9v battery. To communicate the latest heading of the dowsing rod, a custom program retrieves the pitch and yaw values from the IMU and writes these to a text file, which is uploaded to a server via FTP. A custom script on a computer connected to the telescope continuously listens for this file to be updated. Once this happens, the script parses the values and instructs the motors on the telescope to rotate to this heading. While this is happening, three orange LEDs flash in sequence to in-form the user that the telescope is moving. When the telescope has reached the new heading, it reads the solar radiation levels and uploads these to the COSM server (see Figure 14 for system design).

The microcontroller constantly listens for updates on COSM and once it reads a new value it activates the vibration motors embedded in the rod for four seconds and turns on a red LED for this time. The duration of time between choosing a new heading and the vibration commencing depends on the distance the telescope must rotate; the longest wait is approximately five seconds.

Initially both prototypes were designed to represent the data through the haptic modality only. However, when I produced the first prototypes I discovered that distinctive sounds were a by-product of the vibration of the wood and plastic. When the vibration motors in H_3 spin fast, they produce a loud high-pitched sound whereas the soft wood in the rod dampens the vibration to produce a lighter 'humming' sound. I believed that these sounds enhanced the use of the devices and thus explored numerous techniques before choosing one that produced the clearest audio feedback.

4.5 USER STUDY

To assess the user-experience of the prototypes I presented them to visitors of Blackrock Castle Observatory, which is open to the public all year round. Over the course of one week approximately one-hundred visitors used the devices and I conducted observations and some informal interviews with these visitors. This study did not focus on usability issues; instead I was more interested in observing people's interactions with the prototypes and probing them on how they felt while using them. In the following, I present this study and elicit some initial observations from the results. I then use the gathered data again to explore the use of the prototypes through the lens of phenomenological theories and ideas.

4.5.1 *Procedure*

Over the course of one-week I attended the Observatory and offered the prototypes to visitors. Those that used the prototypes ranged in age from 5 to 65 years old. Before visitors began to use the prototypes, they all signed a consent form; following this I briefly explained each of the devices. All visitors indicated that they have an interest in Space, however, none had any prior knowledge of issues related to Hydrogen levels in deep space or solar radiation levels in the outer atmosphere. I was onsite at all times to assist the participants and the interactions were captured using video- and audio recording equipment. When appropriate, I asked the visitors about how they felt and what they were imagining when using the prototypes, these responses were recorded through field notes.

4.5.2 *General User Observations*

I observed that users were continuously switching their attention and gaze when interacting with both prototypes. Once they began to use the dowsing rod, they would look upwards (away from the device) to aim at a point they sought to target. On occasions, users looked through the windows to use visual reference points such as the Sun and Moon when selecting a heading. Once they confirmed this point (pressed the button), their attention then moved to the dowsing rod, until it began to vibrate. At this point they would again gaze upwards at the point they had chosen. When asked what they felt while they looked at the dowsing rod, most answered that they were imagining the telescope rotating and felt that they must keep the rod still while this took place. Whereas, when they looked upwards, participants indicated that they felt their attention should be focused on where the vibration and sounds are coming from:

> *"It's up there somewhere that is making this thing shake and buzz."*

This switch of focus was also observed with users of H_3. As designed for, the users walked around the observatory, browsing other information about Hydrogen in Space and other related phenomenon (see Fig. 4.4). Although they were able to interact with the prototype while walking around, when the device began to vibrate they stood still and did not look at the device, but continued to read other information. One participant stated:

> *"That kind of thing [pointing to a printed image of a hydrogen cloud] feels like this [referring to the vibration of the cube] it sounds fuzzy but it feels as clear as the image and the sensation stays in your hands for a while, kind of like an echo".*

Referring to the connection between H_3 and the phenomenon (data) it represents, another participant remarked:

"It is so weird to think that the buzzing [I feel] in my hands has been caused by something so far away, and if you really think about it's so far away that it doesn't even exist any more, that is so strange"

While this seems to show that the buzzing feedback feels real and physically present, participants seem to know (intellectually) how far the source is away, this may make the experience more memorable then a static graphical representation.

I also observed a high level of social interaction around both devices. On many occasions the prototypes were the centre of attention for groups of visitors and in particular families. As one member of the group interacted with a device, the other members probed them with questions related to how the experience felt:

P1 *Does it hurt?*
P2 *No it tingles, kinda like an electric shock but nice.*
P1 *Does it feel stronger than before?*
P2 *Yes, I think the radiation levels are higher at this part of the sky*
P1 *You must be pointing at the sun*
P2 *No I think I would know if I was pointing at the sun, that would definitely hurt me.*

This relates in particular to the vibro-tactile modality, as the user of the prototype is the only one who can perceive this. On occasions, groups attempted to share the experience by having several members touching parts of the device. During these occasions they would compare how they perceived the characteristics of the feedback. When observing families, I noticed both devises seemed to encourage parents to explain their interpretation of the data to children. Feedback from parents revealed that using the prototype was an enjoyable experience for all members of the family because they offered easy access to the data. One parent remarked:

"Although I know very little about radiation out there, it helped me explain what I do know to 'L' [10 year old daughter] when I saw how excited she was as it buzzed in her hand. Now I have to learn more, to

answer all her questions when we get home."

Finally, my observations revealed some misconceptions that people had while using the dowsing rod. On many occasions, people pointed the rod at objects within the Observatory, such as computer screens and power supplies, anticipating that these objects would have high levels of radiation. Also, some people were reluctant to point in a direction if another person was in their line-of-sight and rather chose to walk around them to point at a clear area.

In this section I presented some observations collected during the deployment of the prototypes in the Observatory. In the next sections I use the data gathered during this study to explore the prototypes use through the lens of philosophical phenomenology. I focus specifically on the theories and ideas by Edmund Husserl, Martin Heidegger, Maurice Merleau-Ponty and Don Ihde.

4.5.3 *Through Husserl*

The first concept that I use to explore people's experience of the prototypes is Husserl's theory of *Intentionality*. Unlike the other ideas that I will discuss later, this theory does not specifically relate to the way we experience objects, tools or equipment, instead, it suggests the general structure of human experience. In Chapter Two, I described Husserl's theory of *Intentionality* as: all human experience involves an activity, and is referential to something external. Thus, for a critique of people's experience of the prototypes we must examine the activities people were engaged in, as well as what was being referenced, when using the prototypes. To this end, I frame this exploration around five questions: (1) what are the activities? (2) what are the references? (3) were the activities practical or cognitive? (4) did the activity change over time? And finally (5) did the reference change over time?

4.5.3.1 *Activities*

In regards to the activities people were involved in when using the prototypes, these can be divided into those related to interaction and those of perception.

INTERACTION In regards to the interaction with H_3, I observed people holding the cube in their hand as they moved throughout the observatory, but on occasions they would shake the cube to request a reading from the telescope. Once the cube began to represent the reading (through vibro-tactile feedback), people generally stood still, stopped shaking the cube and help it still to perceive the data representation. The generally interaction activities that I observed with the dowsing rod involved people standing in one place and pointing the rod at different headings. Once they decided upon a heading, they would press the button on the rod and wait for a response (vibro-tactile feedback).

PERCEPTION When observing people's engagement with both prototypes I noticed different ways of perceiving the representations. For instance, with H_3, some would hold it close to their ear so that they could hear as well as feel the data, while others would hold the cube in one hand and place the palm of their other hand on one of the faces of the cube. In some cases, when people were in groups they would encourage others to place their hand on the cube as well, so that the act of perception was shared between different members of the group. Whereas with the dowsing rod, people generally maintained the heading of the rod when perceiving the representation, although on some occasions they would lower the rod or even bring it closer to their ears to perceive both the sound and the haptic feedback. When in the act of perception people generally were silent, although on some occasions I observed people communicating their reaction, in real time, to others around them, for example: "It feels really so tingly, I can even feel it going up my arms..."

4.5.3.2 *Referential*

When I think about what people are referencing as they work with the prototypes, I divide this into two main categories. I noticed people switching their attention between the source of the data and the properties of the prototypes. Generally, when people first picked up the prototypes they would refer to the physical and visual properties of the prototypes, by commenting on their size, weight, texture, components, colour etc. For instance, one person remarked when he first picked up H_3:

"It's hard to believe that this little thing can see into space, there is hardly anything to it just a few wires and a battery"

I also recorded numerous user comments about the texture and shape of the dowsing rod, for example:

"It doesn't feel like a computer, but I know it is kinda one, wouldn't it be nice if all computers felt so natural in your hands."

People generally continued to reference the properties of the prototypes until they activated the communication between the prototypes and the telescopes, they would then begin to reference the source of the data. When perceiving the representation emitted from both prototypes, I overheard people commenting on the representation of phenomenon, for instance, one person spoke about finding something large with the dowsing rod as follows:

"I think I have found something big here, I must have pointed at a star or planet or something, it feels way stronger than before, could it be the moon? It must be big if it feels so strong."

Another person spoke about perceiving weak vibrations emitted from H_3:

"There is nothing out there now, I can't seem to feel anything, what am I supposed to feel? Surely there has to be something out there but I can't seem to pick it up"

When I explore people's experience of the prototypes through the lens of Husserl's theory of intentionality, I can see that the structure of this experience is mediated by a number of different activities. I also see that these activities reference different elements over time. I observed activities such as walking, standing still, shaking the prototype, pressing a button, pointing to the sky, holding objects to their ear, talking, listening and many more. I also noticed different points of reference, such as the properties of the prototypes and the data source and these references seem to change over time depending of the context of use.

4.5.4 *Through Heidegger*

In Chapter Two, I introduced Heidegger's thoughts on equipment and *temporality*. In the following I explore people's engagement with the prototypes through the lens of these concepts, first dealing with equipment and then *temporality*.

4.5.4.1 *Equipment*

One of Heidegger's key ideas, in relation to how we encounter the equipment of our lives, is the way he describes equipment as being either *ready-to-hand* or *present-at-hand*. In the Observatory where the prototypes were deployed, visitors are surrounded by information about celestial phenomenon in the form of textual descriptions, photographs and diagrams. The way these objects are used by visitors can typically described as present-at-hand as they facilitate only theoretical contemplation, in other words they are designed to be looked at and not through. In saying this, there may be situations where visitor's encounter with this equipment switches to *ready-to-hand*, in particular when they become immersed in the content and do not realise anymore that they are looking at a poster or reading text on a screen. However, these artefacts were not the focus of my observation during the study, instead I concentrated with observing visitor's encounters with the two prototypes. These observations revealed the way visitors encountered the prototypes (equipment) switched depending on the conditions of use. For instance, once they had become familiar with the prototypes—after using them for a prolonged period of time—these encounters could be described as *ready-at-hand*, as the phenomena (data source) became the primary focus instead of the equipment. On these occasions the users acted through the prototype, but the technology itself retreated from their immediate attention. Indications that pointed to this includes, the user not looking at the prototype when in use, instead their attention and gaze was directed upwards toward the data source (deep space). I also observed other types of encounters, such as when users were coping with situations, for instance, during times when the prototype malfunctioned. On these occasions, the user became conscious of the prototype and it became the object of their attention, so switched from *ready-to-hand* to *present-at-hand* or even *unready-at-hand*, as the user contemplated how to regain the functionality of the prototype.

4.5.4.2 *Temporality*

An interesting concept to use when examining people's experience of and interaction with the prototypes is Heidegger's thoughts on *temporality*, especially considering the real-time nature of the data being represented. Heidegger postulated that humans conceive the phases of *temporality* (past, present and future) in either an *authentic* or *inauthentic* mode. In regards to the future phase of *temporality* I noticed people acting in an *authentic* mode, in a manner that could be considered anticipating what is to come rather that waiting in expectation. I conclude this as, firstly as the phenomenon being represented is invisible and far away from the user so their expectations were limited, but also I observed numerous reactions to the representation that could be described as surprised, for instance:

"wow, that was a like a jolt or an electric shock almost..."

I observed very few reactions that indicated the representation was something that the user expected.

In regards to the present phase, I again observed people acting in an authentic mode. Generally, I observed people reacting to the representation in a positive sense, causing them to immediately respond either through bodily gestures or speech. I did not observe anyone ignoring or, as Heidegger puts it, "turning away" from the representation.

The final phase of *temporality* is the past; here Heidegger states that we act in an authentic mode through repeatability, or continually reflecting on or making use of what has happened already. The opposing (*inauthentic*) mode he describes as when people consider the past to have elapsed entirely and thus we forgot about what has happened. Again, I observed the predominant mode in use was *authentic*. I observed people continually reflecting on past representations to seemingly assist them to interpret the present representation. For instance, when one participant felt the vibro-tactile feedback using the dowsing rod he remarked:

"This is much weaker than the last one, there was definitely something back there but nothing here, I must of hit thin-air"

4.5.5 *Through Merleau-Ponty*

In Chapter Two, I presented two of Merleau-Ponty's ideas in relation to the role our body plays in the perception of the world around us. With respect to people's perception of data, I specially subscribe to his idea of the *body schema* and his notion that we continue to attempt to gain a *maximum grip* on surrounding stimuli. In the following I apply these notions to my observations of people's use of H_3 and the Solar Dowsing Rod.

4.5.5.1 *Body Schema*

As noted in Chapter Two, body schema is a form of bodily awareness referring to how we understand our body in space. As Merleau-Ponty puts it: our body is the medium by which we experience the world, however, our body schema is flexible, and when we become adept at using tools or equipment these can be enveloped into our overall *body schema*.

When observing both prototypes in use, I noticed that as people became more adept at using them, their attention moved from the prototype towards what was being represented (staring into space). When people were first handed the prototypes, their attention was fixed on the physical object, but as time passed, especially when using the dowsing rod, their attention appeared to be on the data source (in the far distance). I observed people looking beyond the end of the rod toward the point in Space they wanted to take a measurement from (as can be seen in Fig. 4.1a). I also observed similar behaviour when using H_3. When this prototype was first given to visitors in the observatory, typically, they would begin to shake it to capture a reading from the telescope and their gaze would be fixed on the cube. However, as they became more adept and familiar with the prototype, they began to walk around the Observatory, shaking the cube at regular intervals but rarely looking at the cube. This was most evident when people stood in front of other displays, such as photographs, text or diagrams informing the visitors about hydrogen in deep space. During these occasions I observed people reading or looking at the textual information or photographic displays, while simultaneously shaking and perceiving the data representation (see Figure 15).

Figure 15: H_3 in use during the deployment study at Blackrock Castle Observatory.

4.5.5.2 *Maximum Grip*

Merleau-Ponty's concept of *Maximum Grip* pertains to people continually striving toward an equilibrium with the world, or, in more simplified terms, when we want to look at, feel, listen, taste or even smell things around us we are solicited by objects that emit stimuli to place ourselves in the best position to perceive the stimuli. My observations of people using the prototypes revealed many occasions when both prototypes solicited people to gain a maximum grip on the representation. For instance, when people began to feel the vibration they would grasp the objects in a different way. I noticed occasions when people would use their fingers when pointing or shaking the prototypes, although, when the prototypes emitted the vibrotactile feedback they would change their grip and place the surface against the palm of their hand. I also noticed people reacting to the auditory representation by bringing the cube and dowsing rod closer to their ear, this was also evident when the prototypes were being shared within a group, the person in control would extend the prototype into the middle of the group to allow all of the members to hear or feel the representation. Other members would sometimes respond by bending down closer to the prototypes to better hear the sounds emitted from the prototypes.

4.5.6 *Through Ihde*

Don Ihde's theory on Human-technology relations involves four different relationships we have with technology (*Background*, *Embodiment*, *Hermeneutic*, or *Alterity*). From observing the prototypes in use, I conclude that two types of relations were evident: *Hermeneutical* and *Background*. In Chapter Two, I presented Ihde's definition of *Hermeneutical relations* as: when we focused on the technology, what one actually sees - immediately and simultaneously - is not the technology itself but rather the world it refers to. This was evident when people perceive the representation emitted by the two prototypes. On these occasions I noticed people referencing the source of the data instead of the technology used to produce the representations:

"...it feels way stronger than before, could it be the moon? It must be big if it feels so strong"

It should, however, be acknowledged that this type of relations only became apparent when people began to activate the prototypes. Up to this point, when the prototypes were in their hand, people generally seemed to consider them as an unconnected piece of technology without truly understanding their purpose or functionality. However, once they began to perceive the representation, the relationship between them and the technology quickly shifted and they did not refer to the technology but beyond to what the technology was representing.

The other type of relationship that I observed was *Background Relations*. I observed this occurring between the user and the technology that is used to capture the data (the telescopes). *Background relations* arise when we make use of something that we do not directly experience; yet it gives structure to our experience. In this case, the user never comes in contact with or directly experiences the telescope, however, these technologies have a direct impact on their experience of the data. Essentially, without the telescopes the user would only experience the dowsing rod and cube as static physical objects.

4.6 CHAPTER SUMMARY

In this chapter, I started by describing the motivation, design concept, and development of two bespoke data-driven artefacts that embody live data through tangible interfaces. These prototypes allow visitors to a public Space Observatory to perceive complex scientific data that would normally only be viewed and analysed by experts. Over the course of one week I observed and interviewed visitors while they used the prototypes. My general observations indicate that the tactile experience of the information representation engaged visitors and felt less abstract, more real than graphic representations. Moreover, it triggered social interactions and conversation both about the perceived signal and its meaning. These preliminary findings indicate that representing complex data through non-traditional modalities seems to be appealing for a casual user.

I also analysed the use of these prototypes through the prism of the phenomenological concepts of Edmund Husserl, Martin Heidegger, Maurice Merleau-Ponty and Don Ihde. This analysis shows that interacting with and perceiving data represented through tangible artefacts is a complex and multi-layered process. We see that the *intentionality* involved requires the users to use multiple *activities* and the point of *reference* changes over time (from the prototype to the data source and back). I also described the typical encounter visitors had with the prototypes as being *ready-to-hand*, but on some occasions, such as when the technology malfunctioned, this encounter switched to *present-at-hand*.

Applying Merleau-Ponty's ideas on the role of the body, I showed that once people became familiar with the prototypes they became part of the users *body schema* and were experienced as an extension of the medium (their body) they use to experience the world around them. I also showed how the prototypes solicited people to alter their position to best perceive the various representational modalities used in the prototypes. Finally, I presented two different relationships that people have with the technology in use. One of which involves the user seeing through and beyond the technology to the data source (*Hermeneutical*), and the other (*Background*) which occurs with a technology that is hidden from the view of the user (telescope).

The aim of this chapter was to conduct a study that involved the design and evaluation of tangible artefacts that represent scientific data for a casual audience and to then capture people's experience with these prototypes - through the lens of phenomenological ideas. The remaining chapters of this thesis will focus on Phenomenology from the perspective of a research approach and not its' philosophical ideas.

5 A DESIGN SPACE FOR MULTISENSORY DATA REPRESENTATIONS

"Multisensory data representations are a class of data representation that have a clear intent to reveal insight by encoding data in more than one representational modality and require at least two sensory channels to fully interpret and understand the data."

5.1 INTRODUCTION

In Chapter 2 and Chapter 3, I addressed the conceptual and methodological foundations of my research by introducing aspects such as phenomenology, representational modality, and evaluation techniques. I then drew these aspects together through a design exercise in Chapter 4. To conclude the theoretical Part of my thesis, I now present a systematic analysis of the literature and the state–of–the–art in data representations over the last 150-years. In particular I focus on representations that require more than one sensory channel to fully interpret and understand the data.

The work I present in this chapter spans the entire duration of my PhD. One of the first tasks I undertook shortly after starting to work on my PhD was to create and start populating a database that included examples of data representations that utilised modalities beyond vision. I categorised these examples as data sculptures (more recently physicalizations), sonifications, data represented through smell and taste and haptic data representations. As the database began to grow I started to notice that some of the representations were difficult to categorise. As these utilized more than one modality, they could not be defined as a *visualization*, *physicalization*, *sonification* or any other known category of representation, but could be described and categorised as Multisensory Data Representations. This prompted me to carry out a review of the literature to search for previous work on multisensory data representation. Through this I discovered that while work on multisensory data representation has been on-going across many disciplines since the mid-1970's, no one had surveyed the state-of-the-art of this type of representation. With this knowledge in hand, in the summer of 2012 I commenced a widespread survey with the aim of establishing a design space for of Multisensory Data Representations. While the database is still growing - as I continue to find new examples - almost four years after stating the survey it is finally complete and in this chapter I present a design space for multisensory data representations[1].

Drawing on techniques and theories adapted from Thematic Analysis and Prototype Theory, I analyse 154 examples of multisensory data representations to establish a design space along three axes: *use of modalities*, *representation intent* and *human-data relations*. I frame the discussion by presenting how a selection of examples, chosen from the collection, fit into the design space. This not only informs my own research but can also draw the attention of the HCI, InfoVis and Design Research communities to aspects of data representation that have hitherto been either ill-defined or underexplored. I conclude by discussing key research challenges, which emerged from the exploration of the design space and point out future research topics.

5.2 BACKGROUND

As discussed in Chapter 3 the study of data representations beyond the visual modality, in particular the physical representation of data, has recently received increased attention (e.g [4] [123] [275]). Reviews, such as [233] [196] [325] [279] also provide a comprehensive overview of the state-of-the-art in data represented beyond the visual modality. Notwithstanding these developments, I see limitations in the literature. First, research has tended to focus on a single modality (cf. [215]) and few studies have surveyed research across different disciplines, for example InfoVis and HCI. Also, while research is continuing on

1 The work presented in this chapter is also described in a manuscript, in review with the journal Interacting with Computers. This manuscript was previously submitted to three other conferences (ACM TEI 2014, IEEE VIS 2014 and ACM TEI 2015. While the work received mixed responses from reviewers, I was repeatedly encouraged to continue with this line of enquiry. In this chapter I present the final version of my design space exploration, which is an extension of the submitted article. While this research was a collaboration with my PhD supervisor (Prof. Dr. Eva Hornecker), I was responsible for the vast majority of the work, which was overseen and reviewed by my supervisor.

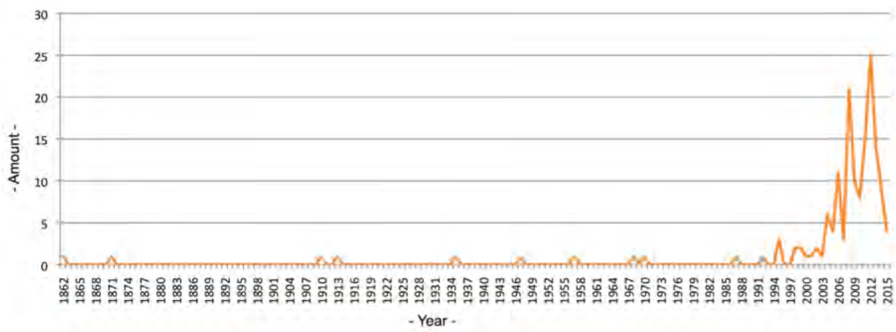


Figure 16: Year of publication/creation of the 154 examples from the survey (x-axis: year, y-axis: amount) (see **??** for full list of examples)

multisensory data representation (cf. [210] [244] [281] [259]) few efforts have surveyed existing representations to identify key research and design challenges. In this chapter I draw together data representations from a wide range of disciplines (artistic, design and scientific), which originated over a long time span (1862–2015), and to analyse these along the same criteria (see Figure 16).

I do this by first introducing the definition of *Multisensory Data Representations* and follow by exploring the potential of multisensory data representations and discussing their value, for example how they offer a more holistic sensory experience and allow the people to interpret the data in a manner that is personal to them. The contribution of this chapter is as follows: First, I define, for the first time, *multisensory data representation*. Second, from 154 existing examples, I survey the state–of–the–art in multisensory data representations. Third, I establish and discuss a design space for multisensory data representations and finally propose a research agenda based on research challenges and questions that are presently underexplored.

5.3 DEFINING MULTISENSORY DATA REPRESENTATIONS

The aim of this chapter is not to reclassify current data representations or prescribe a new domain, I am more interested in surveying an array of data representations across many disciplines to encourage a debate about the potential for using more than one representation modality. Recent literature has

Figure 17: A: Fundament with permission from Andreas Nicolas Fischer [64] B: Measuring Cup with permission from Mitchell Whitelaw 2010 [315]. C: H3 by Hogan and Hornecker [105]. *All Included here by permission.*

labelled data representations that do not rely exclusively on visualization as *Sonification* [143], *Physicalization* [125], *Data Sculpture* [325] *Non-visual visualization* [196] or *Cross/Multimodal displays* [108]. However, in the context of this research, these terms pose difficulties. The sonification of data typically relies on a single modality (auditory), while categorizing visualizations as non-visual is also problematic, as the visual modality often remains an integral communicative aspect of the representation, e.g. when physicalizations can be touched and seen. I therefore prefer the term cross-modal or multi-modal display. Nevertheless, they are also problematic as the focus is on the output of the representation and not on the sensory channel used to interpret the data. There are, however, terms that have already been defined that more closely fit the type of data representation we explore here, these are: *Sensualization* [210], *Sensification* [281] or *Perceptualization* [34]. But as my aim is not to reclassify examples in my collection I discuss work situated across many domains together under the umbrella term: Multisensory Data Representations. I define this class of representation as follows:

"Multisensory data representations are a class of data representation that have a clear intent to reveal insight by encoding data in more than one representational modality and require at least two sensory channels to fully interpret and understand the data."

5.4 DESIGN SPACE ANALYSIS

Design space analysis is a valuable approach to represent design rationale. Maclean and colleagues [168] identified it as a tool to help designer's reason about design, while also helping others to better understand why certain design decisions have been made. With this in mind, my aim was to survey the design space of data representations that seek to communicate across more than one sensory channel. The main goal of exploring this space is to bridge the gap between theoretical concerns and the practicalities of art and design, thereby providing an overview of the possibilities, as well as identifying key research challenges and questions when representing data beyond the visual paradigm.

5.4.1 *Methodology*

In order to systematically understand the study and design of *multisensory data representations* I surveyed existing examples, which fit the definition outlined above, collected from fields such as scientific research, design and art contexts. I identified international conferences and periodicals that publish the most articles related to this topic; these include ACM Conference on Human Factors in Computing Systems, ACM Conference on Tangible, Embedded and Embodied Interaction, IEEE Information Visualization Conference, ACM Transactions on Computer-Human Interactions and IEEE Transactions on Visualization and Computer Graphics. As well as journal articles and papers, I also examined posters, and demos, where applicable. Furthermore I conducted a comprehensive online search for examples of work outside of academic publications, in particular for artworks and surveyed work from online networks, such as Creative Applications[2] , research labs such as AVIZ[3] , archives of digital art exhibition, such as Ars Electronica[4] and personal websites of artists, designers and researchers.

When gathering examples for the survey I only included work that fully met my definition of multisensory data representation. I excluded, for instance, work that relied predominantly on a single human sense to interpret the data or where the data mapping is overly ambiguous with little or no intention to reveal any data insight. My collection by now contains 154 entries, and was used as the basis to establish the design space. The full list of examples included in the collection can be

2 http://www.creativeapplications.net/
3 http://aviz.fr/
4 http://www.aec.at/

seen in **??**[5] . I acknowledge that there may be some examples missing from the collection, mainly due to the lack of exposure surrounding the piece i.e. no publications or exhibitions. However, I feel that the examples in the collection are a fair representation of the state-of-the-art in multisensory data representation.

5.4.2 *Analysis*

The goal of this research was not to develop a taxonomy of multisensory data representations, instead I was more interested in analysing a large collection of representations and to establish a vocabulary when describing them. This can then be used to shed light on the choices designers face when creating multisensory data representations. Once I felt I had exhausted the search for examples I commenced the process of analysis. The overall goal of the analysis was to establish dimensions of the design space and categorise each example in the collection against these dimensions. The methodology I used is based on Thematic Analysis [23]. This is a grounded approach, typically used to analyse interview transcriptions to present an accurate portrayal of how people feel, think, and behave within a particular context [81]. It is based on a set of procedures designed to identify, examine, and report patterns (themes) that emerge from the data. In the context of our study we followed five discrete phases: (1) familiarization, (2) thematic coding, (3) abstraction, (4) structuring, and (5) categorisation (see Table 3).

FAMILIARIZATION The first phase of analysis involved repeatedly reading articles, interviews, descriptions and watching demonstration videos related to the examples in the collection. This was done to familiarize myself with examples in the database even more. As with many qualitative study approaches, this is an essential phase of the data analysis, as it allows the researcher to gain an overview of the data, which later helps in the identification of thematic codes [81].

THEMATIC CODING During the process of familiarization I annotated the examples with keywords and phrases that describe the key characteristics of each representation, which in-

5 I also make an online version of this database available at http://www.tactiledata.net/mdr/database.csv

PHASE	NAME	TASKS
# 1	Familiarization	- Indebt analysis (reading, viewing and/or using) examples from the collection
# 2	Thematic coding	- Annotate these examples with keywords - Coding of example - 2nd pass on Coding - Confirm codes
# 3	Abstraction	- Extracting themes from the codes - Validating themes
# 4	Structuring	- Establishing the dimensions of the design space - Validating dimensions
# 5	Categorisation	- Categorise each example from the survey under the dimensions established. - Confirm categorising

Table 3: Methodological phases used to analyse the examples in the collection.

cluded aspects such as functionality, use, context, data source etc. Based on these annotations I derived an initial set of thematic codes from the data (see Table 3, column 3). Thematic codes can be defined as parts of the data relevant to the research questions that capture the qualities of what is being investigated [23]. The process I followed was open coding, where codes were only defined as they emerged from the data. After careful coding of all examples, preliminary codes were assigned and then validated, and minor adjustments applied before the list of codes was finalized. Only codes that featured more than three times were utilized for further analysis.

ABSTRACTION AND STRUCTURING Once I had completing the coding, I commenced the process of sorting the codes into themes. Themes are broader than thematic codes in that they capture important details and meaningful patterns within the data [24]. I produced an initial set of themes, which were then reviewed and refined together with my supervisor (see Table 4, column 2). These themes were then used to establish the dimensions of the design space, which are: use of modalities, repre-

DIMENSIONS	THEMES	THEMATIC CODES
Use of Modalities	Multimodal Representation, Cross-modal Representation, Sensory Modality Representation Modality Different materials in use, Data insight through experience	Multimodal, cross-modal, wood, acrylic, sound, water, visual, physical, digital, analogue, food, light, paper, print, taste, experience, intuition, feel, hear, taste, smell, touch.
Representation Intent	Casual Representations, Utilitarian Representations, Work of Art, Reveal Little Data Insight, Reveal Large Data Insight	Artistic, casual, functional, fun, work, formal, serious, public, art gallery, performance, learning, school, awareness, personal, science, environmental, social
Human-Data Relations	Interactive Systems, Non-interactive Systems, Live Data, Archived Data	Active, interactive, engaging, dynamic, passive, non-interactive, database, archived, live, static, responsive.

Table 4: Design Space analysis. Column 1 shows the dimensions of the design space, column 2 shows the themes established from the codes and column 3 shows a selection of prominent thematic codes extracted from the data.

sentation intent and human-data relations (see Table 4, column 1).

CATEGORISATION The final phase of analysis involved categorising the examples in the collection against the dimension of the design space. The approach I took for this phase is adopted from Prototype Theory [252]. Prototype theory is a mode of graded categorization typically used in Cognitive Science, where some members of a category are more central than others. In the context of my research, I applied aspects of this theory when sorting examples from the collection into the three dimensions of the design space. I specifically adhered to the two notions, which, over time, have been assimilated into prototype theory. First, *Family Resemblance*, made popular by Ludwig Wittgenstein, where members of a category (in my case:

dimension) may be related to one another without having any properties in common that define the category [253]. Second, I subscribed to the notion of *Generality*, where some members of a category (dimension) may be "better examples" of that category than others [149]. To explain this process further, for my design space dimension of representation intent, the decision on which end of the dimension each example should be placed was based on the available literature, including testimonies from the creators as well as independent reviews of the work. In some cases, there was very little information available, so I had to make a judgement based on personal experience of the domain. Once this process was completed, a database was produced that lists the *title, credit, year, number and type of modality, data type*, and *mode of interaction* of each example in the collection.

5.5 DESIGN SPACE

I established the design space along three axes of dimensionality: *use of modalities*, *representation intent* and *human-data relations*. The dimensions of the design space can be though of as design choices or questions that system designers must address when creating a multisensory data representation. In the following, I discuss these dimensions of the design space individually; I then use this space as a basis for discussing important design and research challenges and proposing a set of recommendations and guidelines for the future study and design of multisensory data representations.

5.5.1 *Use of Modalities*

The first dimension of the design space is Use of Modalities. It is based on the themes: multimodal representation, cross-modal representation, sensory modality, representation modality, different materials in use, data insight through experience (see Table 4, column 2, row 1). Hoggan and Brewster [107] have already made a distinction between cross-modal and multimodal interaction. In cross-modal interaction, different information is transmitted via different modalities, while multimodal interaction refers to the same information being transmitted by each modality. I apply the same concept to data representation. For instance, Ryoji Ikeda's installation Data.anatomy[civic] encodes different data, derived from the latest Honda Civic car, in auditory and visual outputs, thus I consider this to be an example of cross-modal representation [118]. However, Tac-tile [302], encodes the same data in sounds and vibration to allow visually impaired users to browse graphical information, this I consider to be a multimodal representation.

In regards to sensory modality and representation modality I also apply a distinction between these two types of representations. I use the term representation modality, when referring to the representational artefact, as this relates to the representational format, medium or material that the data is encoded in. However, when referring to modality from the perspective of the user/audience, I use the term sensory modality; this refers to the human sensory channel used to perceive and interpret the data. The rationale for this differentiation arose during the survey when I found multimodal data representations that may not be considered as multisensory, as they only require one sensory channel to interpret the data. An example of this can be seen in Nathalie Miebach's series of intricate data sculptures: Changing Waters (see Figure 22). Although this piece, which is a physical representation of weather and oceanic data, incorporates numerous modalities and materials, the viewers rely mainly on their sense of vision to interpret the representation. I do however acknowledge that its three-dimensional form may affect the perception of the representation, as people can imagine what it would be like to touch. Piaget and Inhelder [131] were first to explain that spatial concepts, such as form, distance, space etc. are perceived and understood as internalized actions and not as mental images of external things. Search [259] also notes that bodily movement is an integral part of the perceptual experience, which helps to interrogate and understand virtual and physical objects in space. Thus I consider Changing Waters, and others like it, to be multisensory. Although the viewer is not allowed to touch the piece, when they physically navigate around the representation their perception of the data may be altered during this process when vision interrelates with kinaesthetic experience. This may not be defined as touch, in the traditional sense, however, kinesthetic body movement, combined with the variety of materials in use may result in a wider sensory experience, a phenomenon that does not appear in traditional two-dimensional representations such as bar graphs.

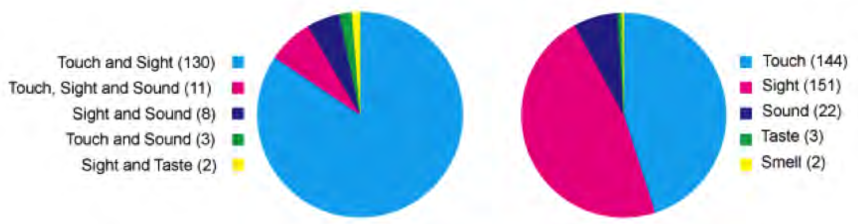


Figure 18: A: Pie chart (right): distribution of sensory modalities used in combination with other modalities. B: Pie chart (left): Combinations of sensory modalities.

The use of alternative representation modalities and materials can be mapped to a similar shift in approach to computing in general. Over the last two decades, HCI subfields such as ubiquitous computing [309], tangible interaction and computational materiality [121] have sought to free computing from the traditional computer and display monitor. Data representations have gone through a similar shift, albeit from analogue to digital representations. Starting in the late 20th century, assisted by the proliferation of personal computing and the democratization of data, a systematic research effort was coordinated, under the umbrella of InfoVis, to explore the use of digital pixels as units of data representation.

In the following, I first discuss the use of sensory modality in multisensory data representations, following this I focus on modality through the lens of materiality. I conclude my discussion of this dimension by highlighting a recently emerging trend, which does not encode the data in modalities but through the experience of using data-driven artefacts.

5.5.1.1 *Sensory Modalities*

The analysis of the 154 examples shows that the predominant sensory modalities required (as part of a set) to interpret the data is sight (151) and touch (144) (see Figure 18, B). While 22 also required the audience to interpret the representation by listening to the representation, only five examples were found that incorporated other sensory modalities (taste and smell). Regarding the combination of senses to interpret the data, 139 required touch and sight and 11 required more than two sensory channels (see Figure 18, A). One example of a representation

Figure 19: Tac-tile system. Graphics tablet augmented with a tangible pie chart relief, with dynamic tactile display [302]

that requires more than one sensory channel to fully interpret the data is Tac-tile (see Figure 19). Tac-tile allows visually impaired users to browse graphical information using tactile and audio feedback. While the user browses pie charts with a stylus pen, the data is transmitted to the user's non-dominant hand through vibrotactile feedback as well as the pitch of a sound emitted through speakers. Using more than one modality to represent data is not only a remit of assistive technology; we also found examples in other domains. Visual artist Ryoji Ikeda's installation Data.anatomy[civic] [118] immerses an audience in an audio-visual experience driven by "the entire data set of the latest Honda Civic car". This multisensory experience offers the audience a unique insight into the complexity of modern car design and manufacturing processes by mapping data points to sounds and dynamic graphics.

Another example from the arts is Perpetual (Tropical) SUNSHINE [1], this installation emits heat and light through a 'screen' composed of several hundred infra-red light bulbs. The data driving this installation is transmitted by weather stations situated all around the Tropic of Capricorn, which measure the real-time intensity of the sun. Typically, ambient temperature,

Figure 20: Perpetual (Tropical) SUNSHINE by fabric | ch [1]

which is controlled in part by the sun, is translated into numerical data and represented in the format of Fahrenheit or Celsius, however, this installation directly translates the heat and amount of light emitted from the sun to the heat and light from infra-red bulbs (see Figure 20). An example that relies on taste, smell and sight is the recent work of the design researcher Moritz Stefaner [271]. An experimental research project, Data Cuisine explores food as a means of data representation or as Stefaner refers to it as – "edible diagrams".

MATERIALITY To fully appreciate the role representational modality plays in multisensory data representation I must also address materiality. The materials used in the representation of data not only dictates (in most cases) the sensory channel used to perceive the data, but they may also have a metaphorical role. Gross and colleagues [80] recently asserted "materiality of computation is best observed indirectly through the artefacts that employ it and interactions with those artefacts" [80, p.639], whereas Vallgårda and Redström [290] claim that computation needs to be combined with other materials before we can consider it to be a material itself. However, Dourish and Mazmanian [53] argue that digital information (data) should be considered a material, in that it is only ever encountered

Figure 21: A. *From Over Here* by Paul May [176]. B. *Form Follows Data* by Iohanna Nicenboim [204]

in material form, and its properties are revealed in the process of interacting with these forms. In attempting to apply these concepts to the materiality of data representation, it is easy to reconcile this with Gross and colleagues assertion that computation (or data) is best viewed through representational artefacts, however, the other concepts of informational materiality seem to conflict, as Dourish and Mazmanian [53] disagree with Vallgårda and Redström [290]. Thus, I lean towards Vallgårda and Redström's view, as data is inherently imperceptible and can only be experienced through the lens, form, sound or taste of what is representing it, for example, data is viewed through the digital or analogue marks of a visualization, while data is experienced by viewing and touching the three-dimensional form of a physicalization.

I here focus on the materiality of the objects and surfaces which the data has been encoded in. Table 5 shows the range of materials used to represent data in the 154 examples I surveyed, sorted by the sensory channel used for interpreting the representation. It should be noted, however, that some materials may be interpreted using several sensory channels, such as wood (sight and touch). When investigating materiality, I framed the analysis around the following question: *is the motivation for material choice metaphorically linked to the data source?* From the examples I surveyed I only found a few that use materials I consider to be metaphorically linked to the data source.

One example is Paul May's 'From Over Here' (see Figure 21, A), which comprises of numerous laser-cut paper cards, each representing a month of articles from the New York Times

SENSORY MODALITY	MATERIAL AND MEDIUM
Visual	*cardboard, ink, paper, light, water, rice, wood, badges, metal, wicker, shape memory alloy, plywood, precious metals, vinyl*
Haptic	*textiles, plastic, wood, ceramic, metal, sand, Lego, string, nails, beads, pins, wire, rubber bands, glass, sponge*
Auditory	*Metronome, midi, electronic motors*
Gustation	*Bread, fish, meat, sweets, noodles*
Thermoception	*Infra-red light*

Table 5: List of materials sorted by the sensory modality used to engage with the material.

(1992-2010) that relate to Ireland. The length of each card is mapped to the numbers of articles from that month. To explore this representation, people are encouraged to handle and rearrange the cards. The tactile quality of the material (paper) facilitates this as well as referencing the source of the data. The choice of materials used in Iohanna Nicenboim's (see Figure 21,B) series Form Follows Data is also metaphorically linked to the data source. This incorporates a collection of domestic objects, whose traditional form has been altered and controlled by personal data. The inner form of a ceramic coffee cup has been produced to represent the amount of coffee that a person consumes every morning over the course of a week. In Hal Watts piece *Can We Keep Up?* the choice of materials is also closely linked to the data source. Constructed out of compressed cellulose sponge, it is laser cut to the shape of a country, where the thickness of the sponge represents domestic water usage data from that country [308].

The majority of examples I surveyed showed no evidence that the material choice has any metaphorical connection to the data source. To exemplify this, I return again to Nathalie Miebach's woven sculpture Changing Weather (see Figure 22). Although the perception of movement in this piece may resemble the sometimes-chaotic nature of the represented weather conditions, the material, which consists of wicker, yarn, thread and plastic, is not related symbolically or metaphorically to the data source. Although there maybe no direct link between the choice of materials and the data source, the materials and tech-

Figure 22: Changing Weather with permission from Nathalie Miebach [193]

niques used to assemble this piece certainly add interest and intrigue. This strategy is often employed by data artists who seek to offer more than just data insight, by creating aesthetic, provocative, and engaging work that sometimes facilitates the generation of meaning that goes beyond the topic of the data source.

5.5.1.2 *Beyond Representation Modality*

During the survey I also found nine recent examples that utilize properties beyond representation modality to communicate information about the data source. Although the data in these may be encoding in the physical or digital properties of the artefact, the generation of data insight is primarily facilitated through the experience of using the data representation. An example of this is Melanie Bossert's "*The World's Best Spintop*" (see Figure 23, A). This piece consists of a number of 3D printed spintops, where the shape of each spintop is a translation of political, environmental, health, education, and economic data from a specific country. Once the data for the country is collated, an algorithm generates the shape of a spin top, if a country performs ’poorly’ the generated shape will be irregular and the handle will be small, which results in the spintop being difficult to set and maintain motion. However, if the data indicates that the country has performed ’well’ the shape will be more symmetrical and the handle will be long enough to grasp (making it easy to set in motion). Although the data is encoded in the physical properties of the spintop (much like the other physicalizations mentioned already) the data can not be fully interpreted until the spintop is in motion, which means the data has been encoded in the shape as well as the performance of the representation. Another example that encodes data beyond the traditional modalities is *Life Don’t Mean A Thing If It Ain’t Got That Swing*(see Figure 23, B), a usable swing installation that encodes data related to the satisfaction levels of a countries population in the architectural properties of the swing i.e. the length of rope, the height of the seat etc. People interpret the data through the enjoyment of their ride on the swing, so if the data indicates that the people of a country are unsatisfied the length of the swing will be short and the seat will be narrow, making the experience of swinging less appealing or exciting.

Another example is the collaborative artwork Change Ringing by artist Peter Shenai and composer Laurence Osborn (see Figure 23, C). In this climate data, representing changes in temperature over the last century, is encoded in the shape of six cast bronze bells. Again, the data translated into the physical properties of the objects, however, the audience cannot fully interpret or perceive the data until they hear the different sounds that emanate when each bell has been rang. All these examples illustrate a new departure for the use representation modality, away from representational modalities such as visual, physical, sound, smell and taste to new ways of encoding data in the performance, affordance and experience of the data representation.

5.5.2 *Representational Intent*

During the analysis of examples in the collection I extracted five themes related to the system designer’s intention when creating multisensory data representations. These are: *casual representations*, *utilitarian representations*, *work of art*, *reveal little data insight*, and *reveal large data insight* (see Table 4, column 2, row 2). These describe the motivation for creating the representa-

Figure 23: A: The World's Best Spintop with permission from Melanie Bossert [21]. B: Life Don't Mean A Thing If It Ain't Got That Swing with permission from James Pockson [213] C: Change Ringing with permission from Peter Shenai [264]

tion and the purpose of using it. The intent and motivation of those who create multisensory data representations is no different to those in many other areas of art and design. Some work is designed to serve utilitarian needs and convey information in a clear manner, while others take a more open-ended approach, by seeking to evoke an emotional response or triggering conversations or debate about a concern related to, or inspired by their work. Traditionally, the primary purpose of data representation has been to provide people with an analytical tool that enhances human cognition about a task, and the primary value has typically been assessed along the lines of effective and efficient discovery of information [316]. More recently, however, some have attempted to broaden the meaning formed from interpreting representations to include more open-ended insight, such as creating awareness and evaluating the emotional response to the representation (cf. [197].

Through my exploration of the design space I categorize representational intent along the dimension of utilitarian to casual, as I feel these terms capture the essence of all themes that make up this dimension. Data representations whose intent I define as being utilitarian target a specific audience to reveal data insight related to a explicit task, such as using coloured building blocks to represent production problems within a large organization [216]. Whereas the intended audience of casual representations is much broader, and the exploration of data may be more open-ended and not related to a work task, such as a piece of data art located in a gallery space (see for example Changing Weather by Nathalie Miebach Figure 22). In my survey, the majority of examples (115/154) were created for a casual audience. I base this classification (utilitarian or casual) on a number of factors, including the description provided by the creators of the representation, the domain the work was created in (i.e., scientific or artistic), as well as my own interpretation/experience.

5.5.2.1 *Utilitarian*

Returning again to the work of Wall and Brewster, Tac-tile provides a good example of a multisensory data representation developed primarily to serve the functional needs of its users [302]. In explaining their motivation for Tac-tile, Wall and Brewster point toward the "lack of access to data visualizations" for people with visual impairment [304, p.10], which hinders them from engaging in "numerate disciplines such as maths, economics or the sciences" [304, p.17]. In creating Tac-tile, they offer people, who have a visual impairment, a representation that allows them to explore and interpret data using both auditory and haptic perception. Another example from the survey that serves the utilitarian needs of a broader section of society is Water Usage, a prototype design by Nadeem Haidary [85]. This piece contains a visible compartment within a faucet, which acts as a visualization of the amount of water consumed each time the faucet is used. A description of the work by the designer states: "As water flows out, a small portion of the water gets redirected through a valve into the faucet's glass chamber, showing the person how much water they are currently using." Although there is clear effort by Haidary to create a smart, playful and striking design, the primary purpose of this product is to make the user aware of water consumption. Another example that assists in an explicit task is the Rearrangeable 3D Bar Chart created by Yvonne Janson and colleagues [123], which was created to compare the efficiency of physical and virtual data representations. This representation can be viewed and held when interpreting the data and is created to replicate all the features of a virtual bar graph.

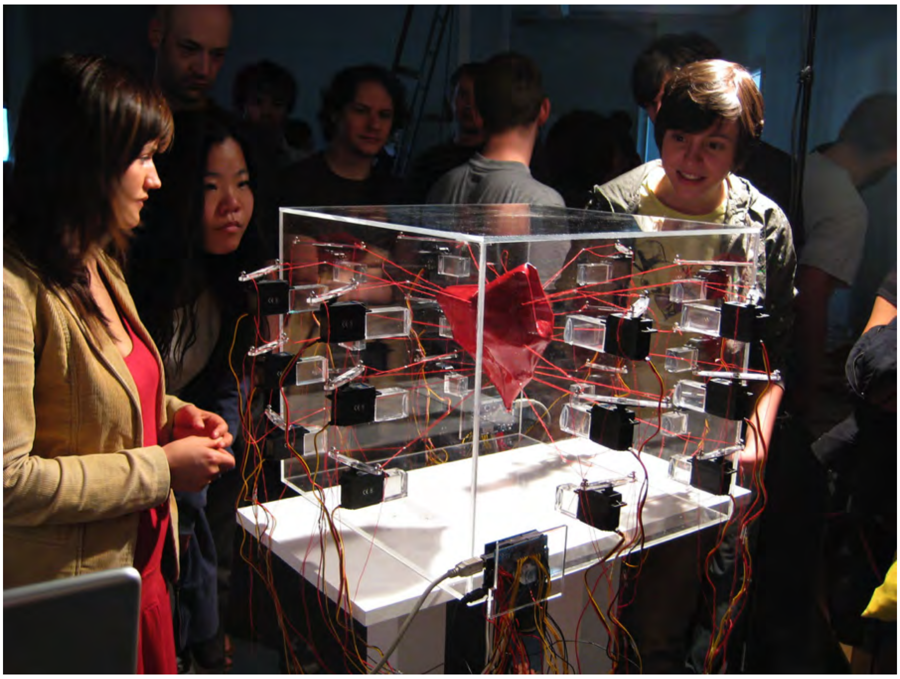


Figure 24: Pulse. A live-visualization of social data by Markus Kison [140]

5.5.2.2 *Casual Use*

At the other end of this dimension are representations that are created for a more casual user/audience and typically represent non-critical data. This type of representation may be seen as a medium for artistic expression that draws attention to an issue/concern or an informal information display situated in our work or home life. Over the past decade an increasing number of artists have used data as part of their work to make statements and encourage public debate on various cultural, political or social issues. Viégas and Wattenberg discuss, in detail, some of this work [300].

I believe that expanding the perceptual field of representation beyond the visual modality offers practitioners more scope to create representations that evoke personal meaning in their audience. Although no research has focused on the affect multisensory representations have on people, in subsequent chapters I will show that the meaning acquired by people when interpreting representations that use non-traditional representational modalities such as haptic and auditory is different from what is generated through the visual modality. A multisensory data representation that exemplifies this is Pulse [140], created by Berlin based artist Markus Kison (Figure 24). A live-visualization, Pulse uses social data - from private weblog communities such as www.blogger.com. The piece is framed around the concepts developed by Robert Plutchik's in his book *Psycho-evolutionary Theory of Emotion*. Pulse translates emotion-based tags found in recent blog entries via an algorithm into a series of instructions that manifest in sounds and temporal sculptural forms generated by a shape-shifting object. The artist is intentionally vague about the process of mapping the data, leaving it completely open to interpretation of the audience. In comparison to this, the mapping used in lgail Reynolds piece "Mount Fear" is very clear (see Figure 25, A) and although the data source represented in this piece (violent crimes in East London between 2002-2003) would normally be associated with more utilitarian data representations (i.e. see Figure 25, B), I consider this piece (and others like it) to be casual as it is displayed within an art gallery and its purpose is to draw attention to an issue/concern and to trigger debate.

The type of data insight revealed to the viewer through both of these examples varies, but it is clear that the data insight revealed is not intended to assist in any work related task. However, this is rarely the intention of the artists, it is more about provoking the audience to interpret the work in a way that is meaningful to them. A key characteristic of representations that lie at this end of the representational intent dimension is the open-ended and personal nature of the data insight revealed. It is rare for the artist/designer to intend the same meaning or insight to emerge for everyone who engages with the piece, while at the opposing (Utilitarian) end of the dimension, the intention is to reveal similar data insight for everyone who engages with the data representation.

5.5.3 *Human-Data Relations*

The final dimension of the design space addresses the interaction between people and multisensory data representations as well as the nature of the data in use. This dimension was derived from combining the themes: *interactive systems, non-interactive systems, using live data,* and *using archived data* (see

Figure 25: A: Mount Fear with permission from Abigail Reynolds [240], B: The distribution of London crime rates (source `http://maps.met.police.uk/`)

Table 4, column 2, row 3).

The digital age has allowed us to move beyond the printed page to bits, pixels and atoms, and has opened new possibilities for designers to offer engagement with data in ways not possible before. Digital technology also meant that live data streams can now be represented through various dynamic interfaces. Exploring the phenomenon of interaction is a fundamental aspect of HCI research, however, apart from some notably examples (cf. [27] [33]) it has received far less attention within the InfoVis community. This may partially be due to the different relationship that users have with digital artefacts in the context of InfoVis as opposed to HCI. This was first illustrated by Ware [306], who identified the concept of asymmetry in data rates, where more data flows from a visualization to the user than from the user to the system. Thus, the interaction is more about altering or exploring the representation than about inputting data.

My design space analysis explores the mode of interaction in terms of *active* verses *passive* engagement, these axes represent the themes: *interactive systems* and *non-interactive systems* (see Table 4. Column 2, row 3). I follow this by addressing the type and nature of the represented data source (*dynamic* and *static*), which corresponds with the themes: *using live data* and *using archived data*. I categorise these themes under the same dimension as they often relate. A data representation that requires interaction to fully interpret the data I define as active, whereas I consider representations that do not require or encourage interaction as being passive. While I acknowledge that all data

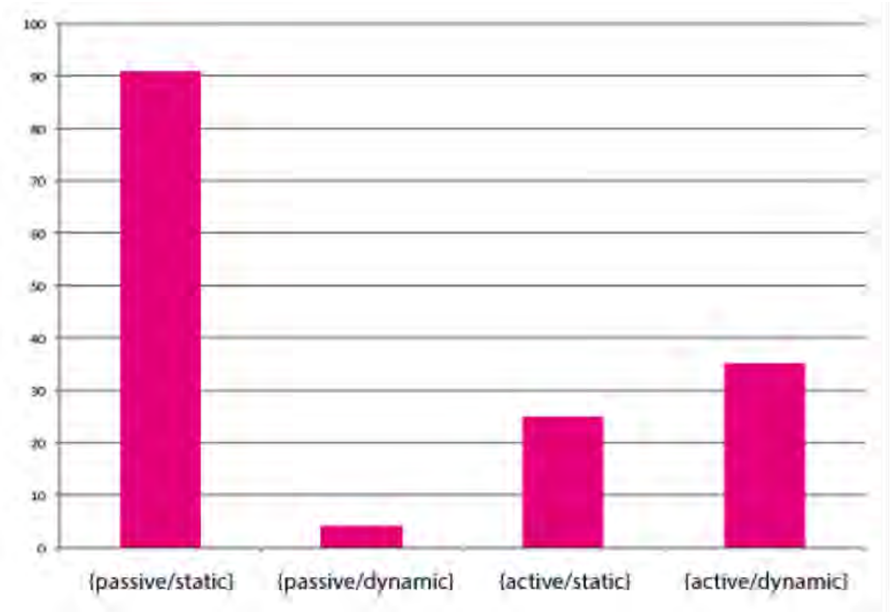


Figure 26: Design space dimension: human-data relations, showing the combination of *interaction mode* and *nature of data*.

representations (multisensory or not) require some level of engagement to gain meaning, I only consider these to be active if they require people to intentionally manipulate the representation or data. I consider data to be dynamic if it is live or multidimensional, whereas data that is fixed and archived I consider static. When analysing the examples in the collection, each could be categorised under one of four possible options: *passive/static*, *passive/dynamic*, *active/static* and *active/dynamic*. Following the analysis of examples, I found *passive* interaction and *static* data to be the most frequent combination (91), while *passive* interaction combined with *dynamic* data is the least common combination (4). The distribution of data types is more even when combined active interaction: *active/static*: 25 and *active/dynamic*: 35 (see Figure 26).

5.5.3.1 *Interaction Mode*

passive My survey shows that the dominant mode of interaction with multisensory data representations is passive (93) (see Figure 27, B). Datafountain [188] exemplifies this, as it does not facilitate or offer any means of interaction beyond looking and listening to the representational output. This work uses water fountains as an information display (see Figure 28), it in-

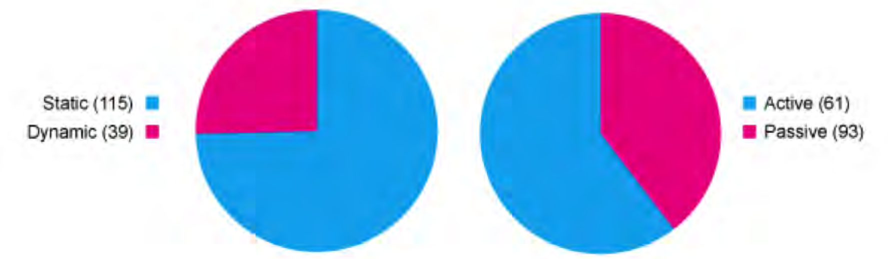


Figure 27: Design space dimension: human-data relations. A: Nature of data. B: Interaction mode.

corporates jets of water whose height is controlled by live data. In one application of this concept the creators mapped the latest value of three international currencies to corresponding water jets. The creators consider Datafountain to be an example of calm technology or an ambient information display that remains at the periphery of our attention. As the audience has no control over the representation, I consider this to be passive engagement, however, the nature of the data is dynamic as it is collected from a live data stream. An example that I also consider to be passive is Fundament by Andreas Nicolas Fischer (see Figure 17, A), although this piece affords and encourages physical contact with the material that the data is encoded to (wood), we cannot manipulate the data source or representation in any way, this process is purely about perception and interpretation.

ACTIVE Many examples (61) in my survey facilitate and encourage active engagement between the user and the data representation. An example that exemplifies this is Wable, which comprises of a motorized physical bar chart that represents the online activity of a person logged into the system [148]. Each of the physical bars can be configured to link to online social network accounts, such as www.twitter.com or www.facebook.com. The system monitors these accounts, and if activity increases (e.g. re-tweets, or shared posts) the bar rises (or visa-versa). A slider button incorporated into the physical interface also allows viewing of past activity. Wable facilitates active engagement while also being dynamic by linking to live data streams, however, the user does not enter any data into the system. Although I acknowledge that the interaction with Wable is quite

Figure 28: Data Fountain with permission from Koert Van Mensvoort [188].

limited, the system does allow the user to choose which data stream is being represented which may facilitates a sense of ownership for users of the system. An example that facilitates much more interaction between the data and the user is Virtual Gravity (see Figure 29). Using Google Insights[6] as the data source, this system represents past search queries of the user. Using a tangible placed on a smart surface the user 'grabs' two words and places them on a digitally mediated physical weighing scale. The frequency of the searches is represented through weight, which means that the more searches the heavier the word will become and thus moving their side downwards. The complex interaction of Virtual Gravity facilitates a rich and informative engagement between the data and the user and allows for indebt exploration of the data [99].

5.5.3.2 *Nature of Data*

When I analysed the thematic codes applied to the examples in the collection I identified a number that related to the na-

6 https://www.google.com/insights/

Figure 29: Virtual Gravity with permission from Silke Hilsing [99].

ture of the data, these include: *dynamic*, *database*, *archived*, *live* and *static*. These were then used to establish the themes: *using archived data* (static), *using live data* (dynamic), which I now use as the basis of my discussion on this aspect of the dimension. I could consider these data properties as polar dimensions (see Figure 27, A); however, some data could be considered as possessing the characteristics from both poles. For instance data.anatomy[civic] [118] represents a data set which, due to its size and multidimensionality, may be perceived as being dynamic, whereas, in fact, the data that drives this installation is retrieved from a static archived data set. An example of a multisensory data representation that uses static data is From Over Here (see Figure 21, A). Although the data represented in this piece is relatively large and spans a long period of time (8 years), it is neither live nor multidimensional. Each datum is a single integer, which, when added represents the number of New York Times articles that refer to Ireland over a given period of time.

Representing dynamic data, in particular live data, can be challenging, especially from a technical perspective, as the representational artefacts require a constant connection to the data source, which in turn continually updates the representation. One example from the collection that generates a multisensory representation of data, which is both live and multidimensional is The Rhythm of the City [82]. This art piece translates geotagged content from social media platform, such as www.twitter.com, www.flickr.com and www.youtube.com, into the rhythm of a physical metronome in real time (see Figure 30). Each of the 10 metronomes in the installation is linked to a different city around the world, the more online conversations, stories and media (relating to the city) that are uploaded to the web, the faster the rhythm of the metronome becomes, thus representing the city's pace of life.

5.5.4 *Plotting the Design Space*

Over the previous sections I introduced and discussed the design space for multisensory data representation. I now select twenty representations from the collection and trace their position in each dimension to present a snapshot of how the design space is populated. When selecting the twenty examples I wanted to show a fair representation of the breadth of the design space and examples included in the collection. For instance, the majority of examples in the collection are situated at the casual end of the dimension: Representational Intent, this is reflected in the twenty examples chosen, and was similarly done for the other dimensions. The examples used include: *Live Wire (Dangling String)* [126], *Illuminating Clay* [228], *Tactons* [25], *Mount Fear* [240], *Tides and Poles (series)* [192], *Weather Bracelet* [314], *Paper Note* [268], *Data Cuisine* [271], *From Over Here* [176], *Underwater* [22], *Google Eye* [20], *Smell Maps* [185], *Touching Air* [231], *Sensetable* [217], *Centograph* [285], *Pulse* [140], *Taste Maps* [186], *Data Fountain* [188], *Season in Review* [282], *Virtual Gravity* [99], and *Edible Bits* [177].

Figure 31 shows the three dimensions of the design space, and each of the twenty examples are placed into a group along each. Thin coloured lines trace the trajectory of the representations through each dimension, similar to a parallel coordinates plot. However, unlike a typical parallel coordinates plot, the axis labels are different in each column (dimension). When inspecting the graph two zig-zag patterns emerge, these patterns represent a correlation between different dimensions of the design space. First, we can see a collection of representations that use two modalities, are also (with two exceptions) casual in intent. These also utilize static data and are generally passive (see

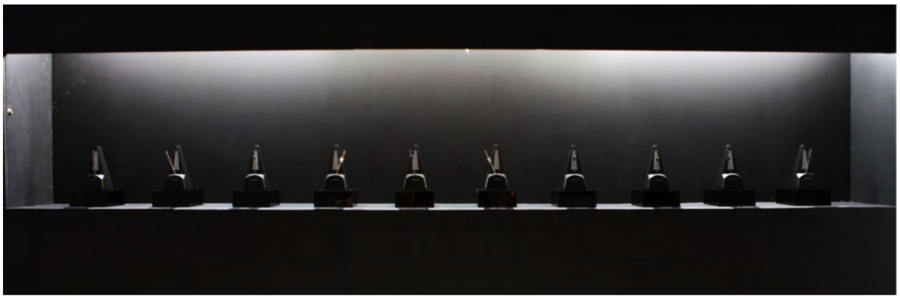


Figure 30: The Rhythm of the City with permission from Varvara Guljajeva.

Figure 31: green shading). Whereas those that use three modalities tend to be utilitarian in intent, with dynamic data and offer user interaction. These patterns are also evident when we increase the number of examples in the parallel coordinate plot.

I previously highlighted the pertinacity of representations, which offer interaction, to be coupled with dynamic data, whereas passive representations are more likely to use static data. This trend also appears when I populate the design space with examples. However, Figure 31 shows us further correlations between separate dimensions of the design space. These zig-zag patterns raise a number of fundamental questions, including: *Why do casual representations, more often than not utilise only two modalities, while utilitarian representations use more?* Although I do not have any clear evidence that explains this trend, I can surmise that increasing the use of modalities provides people with more options to generate insight from the data, while the generation of rich data insight may not be the priority of the creators of casual representations. I can also question: *why do casual representations tend to offer passive engagement with static data, but utilitarian representations tend to be interrogated through active interaction with dynamic data?* The reason for this trend may also be related to the type of data insight that is offered by the representations, or maybe, the level of data insight generated is a reflection of the type of data and mode of interaction.

5.6 DISCUSSION

When I analysed the design space it provoked three key research questions and challenges that have as yet to be fully addressed. These are: (1) *Does adding modalities add value?* (2) *How*

Figure 31: Parallel Coordinate plot of 20 existing multisensory data representations across three design dimensions. Coloured lines trace each representation's position along the design space.

do multisensory data representations affect and change the user experience? and (3) *When is a representation not a representation?* In the following I discuss each of these individually. Derived from this discussion, I address the research areas that are presently underexplored and list five key recommendations for addressing these issues.

5.6.1 *Does Adding Modalities Add Value?*

Once I had analysed the design space regarding the use of modalities, I questioned: *Does adding more representational modalities add further value to the representation?* It may be argued that additional modalities increase the richness of a representation by stimulating more sensory channels. However, adding modalities may also increase the cognitive demand on people to reveal data insight. Research in cognitive psychology suggests that extraneous cognitive load is caused by unnecessary cognitive processes [128]. For instance, if a representation uses two or more modalities to represent the same data (cross-modal) without revealing anything new, this not only creates redundancy, but can also increase the cognitive load required to interpret the representation [69].

Notwithstanding these concerns, research in instructional design has demonstrated that increasing the range of modalities used in a presentation can increase its' effectiveness in terms of enhanced learning with less mental effort [280]. Although work has commenced (particularly in the field of visual analytics) to investigate the cognitive and perceptual capabilities needed to explore complex data representations (cf. [128]), this research has tended to focus exclusively on mono-modal, visual representations. Thus, more research is required to investigate under what conditions the addition of modalities increases the performance and enhances the user-experience of data representation. From an artistic perspective, expanding the sensory perception of a data representation, which may result in possible overloading of audience's cognitive processes, could be a deliberate strategy by the artist.

When discussing the representational intent dimension, I categorised representations as being either casual or utilitarian. I believe that multisensory data representations at either end of this dimension benefit from expanding the use of representational modalities. For instance, representations created to assist people with an explicit task, such as Tac-tile [302] offer the option to perceive data using two discrete sensory channels. Not only does Tac-tile demonstrate the functional value of combining modalities, it was also found that it can potentially "support collaboration and communication between visually impaired people and sighted colleagues working with a shared representation" [304, p.1132]. At the other end of this dimension, where the purpose of a representation is not task related, but reveals or draw attention to an issue or concern, I argue that the generation of data insight is merely a part of the overall experience that the creator is hoping to achieve and in some cases the generation of insight is not the end of the cognitive process but is meant to act as a trigger for further contemplation about the data source. Whether the intention of the creator is to support a task or draw attention to a concern, data representations that stimulate more than one sensory channel, I argue, facilitates a more holistic sensory experience and allows the user/audience to interpret the data in a manner that is personal to them.

5.6.2 *Do Multisensory Data Representations Affect and Change the User Experience?*

In my design space analysis I distinguished representations that allow user engagement from those that do not (*active* verses *passive*). I also surveyed representations along the trajectory of representational intent from utilitarian to casual. This analysis showed that not alone do multisensory data representations allow for the full spectrum of human interaction, but also, the type of insight people generate from these varies from analytical discovery over awareness to intrigue or even curiosity. I believe that the main challenge that this holds for the research and design community is the approaches we take and the methods we employ when evaluating multisensory data visualizations. Chen and Czerwinski [39] have already stressed the need for improved methods in areas such as task analysis, usability evaluation and usage analysis. However, apart from rare examples (cf. [321], the vast majority of empirical studies evaluate the usability of data representations based on traditional measures such as efficiency and effectiveness. The InfoVis research community have recently began to acknowledge the shortfall in approaches and techniques to measure non-analytical aspects of information visualizations. Lam and colleagues [150] point to a lack of work that studies people's subjective experiences of information visualization and Vande Moere and Claes [197] have recently advocated incorporating qualitative and tacit aspects in future research on physicalization. Jackson and colleagues [122] encourage the use of design processes such as sketching, ideation and critique, that are widely used in related design fields as a form of early evaluation, while North [207] discuss the benefits of complementing low-level studies with insight-based evaluation strategies. Beyond the evaluation of use, there have also been attempts to assess the perceptual qualities of data representations. Most notably, Lang [151] discussed the role of aesthetics in data representation as being more than just a vehicle to engage the user but an integral part of the "science" of representation. Although I recognize that there is an inherent difficulty in measuring non-analytical insight facilitated by data representations such as awareness, intrigue and curiosity, the field of HCI has recently witnessed a renewed interest in evaluating such properties (cf. [320]). Employing methods already used in HCI, to measure the value of data representations will help researchers to better understand the way people make sense from multisensory data representation. There is some evidence that shows representational modality does affect the way people experience data, however, to date, there is little research that examines the affect that multisensory data representations have on people's ability to generate insight.

5.6.3 *When is a Representation Not a Representation?*

The final question concerns the purpose of creating multisensory data representations. Although this question could be asked of any data representation (multisensory or not), it was provoked by my exploration of the design space and in particular the dimension of representational intent. In my analysis of this dimension I have shown that there is a wide range of scientific, design or artistic intent in their creation. While the purpose of representations that reveal explicit information is clear, those that facilitate the generation of more open-ended or personally meaningful insight can be equally valuable for the intended audience. This is illustrated by Kosara who argues that the goal of data representations with this intent are unlike other forms of representation, in that they are used to "communicate a concern" rather than facilitate explicit data insight [142]. With this in mind, I believe that designers and researchers need to be mindful when employing novel mapping techniques, where the primary aim is provoke open interpretation and personal reflection in the audience. In this case, the data may become merely a medium and is not integral to the information that is being transferred to the audience. I do recognize, however, the boundary between a data representation and a piece of art is sometimes hazy, and it is not always the intention of the creator to define which side of the line the representation is positioned. Quite often it is left to the audience to appreciate the work as an artistic creation or as a carrier of information, and the value of the work may lie in blurring or shifting this line.

5.6.4 *Underexplored Areas and Future Challenges*

I conclude this exploration by highlighting research challenges that are hitherto underexplored and warrant investigation for this field of research to evolve and expand. My survey showed that the predominant combination of senses required when interpreting the representations is touch and vision (130). Although data sonification is a vibrant field, my survey showed that combining the perceptual qualities of sound with those of vision or touch is still somewhat rare (11). Also, apart from a few recent examples (e.g. [271]) data is very rarely interpreted using the other senses: taste and smell. I also note that using humans' innate ability to detect other stimuli, beyond those governed by the traditional senses is underexplored. Apart from Perpetual (Tropical) SUNSHINE (Figure 20), which relies on our ability to sense temperature, we found no examples that rely on our sense of, for example, balance, pain or our kinesthetic sense, to form meaning from a representation.

I also note that the majority of examples in the survey (72%) were aimed at single users. Apart from some notable exceptions (cf. [217]), both traditional and multisensory data representations have typically been created with the purpose of communicating to a single person. Moving representations beyond a single modality may provide an opportunity to expand the size of the audience, while also supporting collaboration. In similar terms, the size of the data set typically used in representations to date is small. During my review I found very few (3) that represented large data sets. What is commonly known today as Big Data has received minimal attention in regards to extending the modalities that represent these extremely large data sets.

The final aspect of multisensory data representations that I see as being relatively underexplored is the concept of submodalities, in particular the properties of the different representational modalities that can be exploited to create a successful data representation. The field of cartography has a rich tradition of investigating these properties, which dates back to Jacques Bertin's seminal work on visual variables published in 1967 [13]. First identified for use in sign-systems, Bertin identified seven visual variables (*position, size, value, texture, colour, orientation and shape*) and presented a set of rules for their appropriate use, based on whether the visualized data are nominal, ordinal or quantitative. While research has continued over the years to validate Bertin's visual variables (cf. [41], MacEachren's work [167] has extended these variables to account for the use of computer technology. His extended list visual variables include: *location, size, crispness, resolution, transparency, colour value, colour hue, colour saturation, texture, orientation, arrangement* and *shape*. Much like MacEachren's work, the vast majority of research to date on visual variables has focused of their refinement to account for new technology or different context of use (cf. [35].

There have also been some attempts to transfer Bertin's concept across to other modalities. Krygier [146] explored the use of sound as a design variable for the representation of data. Using Bertin's work as a reference point, he surveyed the use of sound as a representational modality in existing systems to establish the sound variables: l*ocation, loudness, pitch, register, timbre, duration, rate of change, order*, and *attack/decay*. Vasconcellos [291] also explored Bertin's variables, but this time in relation to tactile cartography. While Vasconcellos translated Bertin's principles to a tactual format, she did not identify or validate any variables that are unique to tactile perception, such as, for instance, pressure, vibration, or temperature. More recently, in the context of physicalization, Jansen and Hornbæk [124] have revisited Bertin's variables, by investigating how people interpret data encoded in the size of three-dimensional objects. They present empirical evidence that show physical bars achieve the same levels of perceptual accuracy as two-dimensional bars.

Apart from Krygiers work on sound variables [146], there has be no research that has attempted to systematically establish or validate design variables for representational modalities other than visual. I have also found no work which seeks to explore the combination of design variables from different modalities. For instance, if a representation encodes data in the visual and physical properties of an artefact, we could leverage the principles developed by Bertin to interrogate and use visual variables, however, what would be the equivalent variables for the tactile modality? We could possibly surmise that these would include *pressure, vibration, temperature, texture, weight, shape,* or *orientation*, however, empirical work is needed to establish, confirm and validate these.

5.7 RECOMMENDATIONS

In this section I outline five key recommendations that are meant to provide practical guidance to other design researchers who wish to study and create multisensory data representations. The first highlights issues from a user-centred perspective, the next three relate to representation and sensory modality, while the final one needs to be addressed at an interdisciplinary level.

5.7.1 *Methods and approach to evaluation*

The approach to evaluating the success of multisensory data representations needs to reflect the purpose of the representation. Although there is on-going research within the InfoVis research community to investigate how analytical discovery is made, and how meaning is formed from visualizations, more attention is needed to evaluate representations whose purpose is more open-ended. This mirrors the challenges being met by third-wave HCI researchers [18]. I believe that methods used in HCI are also applicable to the evaluation of multisensory data representations that have similar intent, such as evoking hedonic or emotional responses. Another issue that can be addressed through new approaches to evaluation is the users' cognitive demand when interpreting data through more than one modality. Further fundamental research is needed to better understand how multisensory representations impacts on people's ability to form meaning from the representation.

5.7.2 *Beyond touch, vision and sound*

I have shown that the main representational modalities currently used in multi-sensory data representations are visual, haptic and sound. I believe that there is potential in harnessing the perceptual qualities of other modalities to represent data for all the human senses. Although the use of alternative modalities, such as olfactory or taste may be problematic for generating accurate data insight, combining these with more familiar ones may yield potential for a truly holistic sensory experience of data.

5.7.3 *Beyond visual variables*

It is almost 50 years since Jacques Bertin published his work on visual variables [13]. The principles he postulated are still closely adhered today by visualization designers. In order to effectively harness the attributes (variables) of modalities other than vision we must first understand how these can be used to effectively and accurately communicate information. Having a complete taxonomy of the variables of all modalities will assist researchers and designers to better understand the role that they play in the representation and interpretation of data. Exploring other modalities in this way may also allow creators of data representations to complement a variable from one modality with another without causing confusion for the user/audience.

5.7.4 *Data insight through experience*

During my survey I highlighted a new phenomenon in data representation, where the data is not encoded in the representational modalities but in the behaviour, affordance and experience of the data representation. I believe that this approach has the potential to be a key milestone in the evolution of data representation much like the developments in computer technology allowed data representations to be live and dynamic, and developments in off–the–shelf microcontrollers and rapid prototyping technology allowed data representations to be physical. Presently, the examples that utilize this approach are exploratory pieces created within the Arts. However, as data representations are now commonly used in casual contexts such as libraries, museums, or at home, facilitating data insight through peoples innate ability to perceive how something feels (experience) is worthy of further exploration. Peter Shenai, one of the creators of the swing installation *My Life Don't Mean A Thing If It Ain't Got That Swing* talks about this approach to data representation as allowing him to push the interactive medium to its limits, up to and including the point of malfunction, as the malfunction or breakdown of the artefact, in this case a swing, serves as a reminder to the user that the data has been skewed strongly in one direction [263]. This is a departure from how HCI researchers presently think of and address the concept of (mal)functionality. Alongside this, I believe that representing data through experience can further harness people's natural instincts and can offer researchers a platform to generate data insight in a more natural and intuitive way.

5.7.5 *Multidisciplinary collaboration*

The interpretation of data through multiple channels is not exclusive to any one community. My survey shows that it is practiced by a range of professionals and enthusiasts including academics, researchers, designers, artists, engineers and even hobbyists. While acknowledging that intentions may vary greatly, I see great potential and benefit from encouraging and supporting open collaborations between these disciplines and practitioners. By harnessing the logical and technical skills of information scientists and engineers with the visually perceptive skills of designers and sensitivity of artists, I believe that data can be represented in a manner that is artistic, engaging, aesthetic, informative and insightful.

5.8 LIMITATIONS

In this chapter I presented a design space for multisensory data representations based on a survey of contemporary and historical examples I collected over time. However, I wish to acknowledge some of the limitations of this survey. First, although I have attempted to gather as many examples as possible, the list is not complete, as I may have not been aware of some works due to their limited exposure. Second, the examples in the collection have been produced in a wide range of different domains, such as HCI, InfoVis, Art, and Design. This has meant that the documentation related to each example can vary dramatically. In research fields such as HCI and InfoVis the description of and motivation for creating work is easy to find and typically quite detailed. Whereas, examples that are situated in fields, such as, art and design, do not always have easily accessible documentation about the work. In these cases I had to rely on a combination of 3rd party critiques and my own experience and interpretation to place the work within the dimensions of the design space. Finally, I acknowledge that the reader may object to the dimensions of the present design space and/or the terminology used to define and describe them. However, I do not intend this research to be authoritative. The aim of this research is not to reclassify current data representations or prescribe a new domain, instead I envisage this work as a catalyst to promote debate, inform design and encourage future research to move towards a design space for *multisensory data representation*.

5.9 CHAPTER SUMMARY

In this chapter I defined, for the first time, Multisensory Data Representation. Using this definition, I collected, collated and analysed 154 state-of-the-art representations and established a design space using methods and techniques adopted from Thematic Analysis and Prototype Theory. The three dimensions of the design space are: *use of modalities*, *representation intent*, and *human-data relations*. Derived from the analysis of the design space, I addressed key research issues, including: questioning the value added by expanding the sensory channels required to interpret a data representation. I also discussed issues from the users perspective and explored the boundaries between representation and art. I concluded the discussion by highlighting underexplored areas and future challenges and then presented five key recommendations aimed at providing practical guidance to other researchers and practitioners who wish to study and create multi-sensory data representations.

Part II

METHODOLOGIES AND EXPERIMENTS

In Chapter 3, I highlighted some of the difficulties associated with capturing people's experiences with the methods that are commonly used in HCI, identifying themes common across a group of individuals adds further difficulties due to the subjective nature of experience. In the context of my own research these issues become even more of an issue as it is my aim to capture precise accounts of people's "lived" experience. In this part of my thesis I introduce two methods (the Repertory Grid and the Elicitation Interview Technique) that are used to elicit accounts of experience and present three studies that exemplifies the use of these methods in the context of understanding how people experience data representations. While the Repertory Grid Technique has been used sparingly in HCI, it is typically conducted with individual participants and the gathered data is analysed using quantitative forms of analysis. In the next chapter I will describe an adaptation to the technique that allows for the efficient capture of qualitative data within a group setting. The Elicitation Interview technique, however, has only been used on a few occasions in HCI and there is no literature that describes its use in evaluating people's experience of data. In Chapter 7, I describe this technique and present an empirical study I conducted to exemplify its use in the context of studying people's experience of data representation. The final chapter in this part is dedicated to presenting a study that incorporates the Repertory Grid and Elicitation Interview Technique to probe deep into how people experience tangible data representations.

6 ADAPTING THE REPERTORY GRID TECHNIQUE

6.1 INTRODUCTION

The aim of this chapter is threefold; I Data representation has become a popular tool to facilitate sense-making, discovery and communication in a large range of professional and casual contexts. However, evaluating their role and impact is still a challenge. In particular, we are lacking techniques to help us understand how representations are experienced by people, moving beyond usability issues and considering hedonistic, emotional, and sensory reactions - important aspects when it comes to understanding the role of representation modality as part of analysis processes and insights generation. With this in mind the aim of this chapter is threefold; I first introduce the Repertory Grid (RepGrid) technique as method of collecting data on how people construe their experience of objects, people or events. I then present my adaptation of the technique, which involves blending it with a focus group session to allow for the capture of first-hand accounts of experience during the study. I test this adaption by conducting a study that seeks to reveal how representational modality affects people's experience of data. Following this I present an experiment that was designed to validate and confirm the adaption by comparing two side-by-side RepGrid studies (traditional verses adapted).

Early in my PhD I identified the RepGrid technique as a useful method to empirically elicit and evaluate people's subjective experiences and meaning structures [119]. The RepGrid has been proven to be a valuable technique in phenomenological studies to better understand user experience and the perceived qualities of computational objects (cf. [60] [119]. One of the main reasons why the RepGrid is useful for this purpose, is that it provides an established method for eliciting user's personal constructs, in distinction to other similar methods such as *Semantic differential*, which is usually based on predefined, given constructs [182].

Early in my studies I envisaged the RepGrid as a method that would allow me to evaluate the prototypes I created by capturing accounts of people's experience of using them. I also viewed it as a method that would allow me to evaluate multiple prototypes at once by comparing and contrasting people's experience of them. However, when I reviewed the literature on the technique I soon realised that there maybe some limitations with the traditional application, which may impede me from capturing the type of data that I was seeking (first-hand accounts of people's experience). A traditional application of the RepGrid is conducted with individuals, which can be extremely time-consuming and demanding on the researcher and participant. The captured data is also typically analysed using quantitative methods, which excludes the personal remarks of participants during the study. In this chapter I present my adaptation of technique, which incorporates a focus group session that allowed me to capture rich qualitative data. The adaptation I present here is a collaboration between my supervisor and me and has already been described in [103] [104] [106]. While I was responsible for the majority of work, from the design of the studies, over conducted the studies, to analysing the data, Prof. Dr. Hornecker provided valuable advise on all phases of the studies. The reason we published the findings at these conferences was to introduce the adaptation to the wider research community and to collect expert opinion from anonymous reviewers and attendees. I now draw these together to shed further light on the adaption and provide the reader with an overview of our methodological adaptation that is used again in final chapter of this thesis. These studies also form the foundation of my investigation into how representational modality affects the way people experience data.

6.2 THEORETICAL BACKGROUND

The Repertory Grid technique is a method of collecting data during a structured, reflective process where the individual participants reveal how they construe their experience of objects, people or events. Dating back to the mid-1950's the technique was first used in a clinical setting, but soon spread to domains as diverse as Marketing (cf. [173]), Management (cf. [225]) and Training (cf. [109]). The RepGrid Technique is a methodologically extension of George Kelly's Personal Construct Theory (PCT). Kelly proposed this theory as a replacement for the two major approaches to human understanding at the time – Behaviourism and Psychodynamics [135]. He suggested that instead of treating people as 'subjects' we should look at them as if they are scientists who are continuously trying to make sense of events around them. They do this by construing and constructing personal theories that allow them to predicate future encounters and behaviours.

Central to his theory is the idea of the 'construct'. Constructs, as the name may suggest, are grounded in the psychological concept of Constructive Alternativism, and are based on the belief that humans draw their understanding and description of the world based upon their own personal experiences and that they distil these into labels (Personal Constructs). For instance, we may judge an event in our lives as ranging from *happy to sad*, *uplifting to boring*, *memorable to forgetful* and so on. Kelly argued that - good only has meaning when compared to bad, thus, all constructs are bipolar dimensions (i.e. *happy - sad*), therefore a personal construct is a bipolar dimension of meaning and allows people to compare two or more elements. To illustrate the idea of 'constructs' further let me present the following scenario:

John, a married father of new-born twins, discusses buying a new car with his friend Mark, who is single with no children. Talking about the criteria that would influence John's choice, he mentions the importance of space. John also suggests that he would prefer a car that was economical to drive and maintain. These are two of John's constructs. Reacting to this, Mark explains that these issues would not concern him (they are not part of his construct system) he would much rather own a car that offered a faster top speed and 'looked good'. John goes on to explain that his brother also has a growing family and he needs the extra space when he goes away on trips. John had formed his 'space' construct on the basis of his conversation with his brother, and this construct is one that he will use when buying a car. Mark didn't have that construct, because his experience was different from John's; and so he would not have used it when thinking about buying a new car – at least, not until he starts a family himself, he may then modify his construct system.

6.2.1 *The Fundamental Postulate and the Eleven Corollaries*

To amplify his Personal Construct Theory, Kelly affirmed a fundamental postulate and eleven corollaries. The fundamental postulate states "A person's processes are psychologically channelized by the ways in which they anticipate events" [135, p.46]. This can be interpreted as people's behaviour is driven by the way in which he/she anticipates events, or in relation to the afore-mentioned scenario; John believes that he will need extra room in his new car for his children based on a conversation he had with his brother, this will be one of the main criteria he will use when he decides which car to buy.

The eleven corollaries (see Table 6.1) may be interpreted as follows: People's construct systems are composed of bipolar dimensions (*Dichotomy corollary: John's expects his new car to be spacious and not cramped*) and these are represented as constructs (*Construction corollary: spacious or cramped*). People may be influenced by other people's constructs (*Sociality Corollary: John's conversation with his brother*). Unlike concepts, constructs are not used for all things in all circumstances (*Range corollary: spacious or cramped only relates to the interior of the car and not the engine compartment*), but some constructs are applicable to many events (*Modulation corollary; spacious or cramped could also relate to the size of the boot*). Constructs are always arranged in a hierarchy (*Organization corollary: John places the issue of space ahead of how economic the car will be*), but may be influenced by events or experience (*Experience corollary: in the future John may decide that space is not as big an issue as how economical the car runs*). People differ from each other in their construction of events (*Individuality corollary: John and Mark have completely different criteria for buying a new car*). However, people are similar to the extent that they see meaning in events similarly (*Commonality corollary: John and Mark both understand why one another have different expectations for a new car*). People are also aware that they may choose either dimension of the construct (*Choice corollary: Mark may also decide that he needs a spacious car*), while others may choose to ignore their personal values (*Fragmentation corollary: John may think about reducing some of the extra room for a more sporty looking car*).

COROLLARIES	DEFINITION
Construction corollary	A person anticipates events by construing their replications.
Dichotomy corollary	A person's construct system is composed of a finite number of dichotomous constructs.
Range corollary	A construct is convenient for the anticipation of a finite range of events only.
Modulation corollary	The variation in a person's construction system is limited by the permeability of the constructs within whose range of convenience the variants lie.
Organization corollary	Each person characteristically evolves for his convenience in anticipating events, a construction system embracing ordinal relationships between constructs.
Fragmentation corollary	A person may successively employ a variety of construction systems, which are inferentially incompatible with each other.
Experience corollary	A person's construction system varies as he successively construes the replications of events.
Choice corollary	A person chooses for himself that alternative in a dichotomized construct through which he anticipates the greatest possibility for the elaboration of his system.
Individuality corollary	People differ from each other in their construction of events.
Commonality corollary	To the extent that one person employs a construction of experience, which is similar to that employed by another, his processes are psychologically similar to those of the other person.
Sociality corollary	To the extent that one person construes the construction process of another, he may play a role in a social process involving the other person.

Table 6: The eleven corollaries of personal construct psychology, as defined by George Kelly [135].

6.2.2 *The Repertory Grid Technique*

George Kelly suggested the Repertory Grid technique as a method to systematically elicit these personal constructs [135]. Over time, the technique has been used across many disciplines and has been extended and customised to best-fit particular contexts of use [71]. However, generally, each variation and adaptation of the technique still maintains three major components: *Elements, Constructs* and *Links*. *Elements* are the objects, people or events that are under investigation during the study. The participant, as part of the study, may be asked to select these elements themselves, but in most cases the researcher will provide the participant with a set of elements. *Constructs* (described above) are the bipolar descriptions or attributes that the participant assigns to each element. These constructs are usually elicited during an interview that takes place after the participant has been made familiar with the elements used in the study. *Links* is the method of connecting the elements to the elicited constructs. Links help to explain how each participant construe each element relative to elicited constructs and is typically accomplished by rating or ranking the elements against each personal construct.

In a traditional application of a RepGrid study the researcher presents participants with elements in groups of three. Once they have become familiar with the elements they must identify where two of the elements are similar (Convergent pole) but dissimilar from the third element (Divergent pole). What emerges is a bipolar dimension (personal constructs), see for instance PC1 in Table 6.2, this bi-polar dimension ranges from *Dynamic – Stable*. Using this bipolar dimension, the participant is asked to rate all the elements on a 1-7 scale (1: Convergent pole, 7: Divergent pole). In Table 6.2 the example RepGrid shows that the participant rated Element A as 2 against PC1 (*Dynamic – Stable*) but rated Element B as 7 and C as 6. This rating shows that the participant construes Element A as being relatively Dynamic but unlike the other two elements which he considers to be Stable. Once this has been completed a RepGrid (see Table 6.2 for an example RepGrid) is produced that represents how the participant construes their experience of the elements under investigation.

		A	B	C	
PC1	*Dynamic*	2	7	6	*Stable*
PC2	*Fun*	1	6	5	*Boring*
PC3	*Interactive*	2	2	6	*Static*
PC4	*Difficult to use*	6	6	1	*Easy to use*
PC5	*Engaging*	2	6	1	*Non-engaging*
PC6	*Comfortable*	2	1	6	*Uncomfortable*
PC7	*Digital*	1	2	6	*Analogue*

Table 7: Example RepGrid that shows the bi-polar constructs (column 1 & 5) and the ratings applied to the 3 elements under investigation.

6.2.2.1 *The RepGrid in Use*

While the use of the RepGrid within the HCI community peaked in the early 1980's (for a historical overview, see [62], we have recently seen a resurgence of interest in this technique [61] [92] [187] [44] [79] [56] [289] [97] [98] [164] [156] [26] [147]). That being so, the use of the RepGrid in HCI has been less plentiful than in other research fields. The earliest example of its use in HCI is in 1980, when Quinn investigated the RepGrid technique as a method to assess cognitive complexity as a correlate of creativity [235]. This was followed by Jerrard[127] who employed it to analyse design decision-making. More recently, there have been further attempts to adopt the use of the RepGrid within HCI. Most notably, Hassenzahl and Wessler [93] suggested that personal constructs, elicited during a RepGrid study might have the potential to reveal design relevant data. They note that designers are mainly interested in the differences between products rather than differences in individuals, thus examining personal constructs elicited from a group of individuals might reveal rich insight about the artefacts that they interact with. It could be argued that Hassenzahl and Wessler's article revitalized interest in the RepGrid technique within HCI. Since then we have seen the RepGrid technique used in HCI (and neighbouring fields), such as Cunningham's attempt to classify audio within the context of sound design [44], Bang [8] used it to explore people's emotional experiences with fabrics, and Fallman and Waterworth [62] employed it to explore how people interact with mobile phones.

GROUP SETTING One of the key adaptations to the RepGrid technique that I present in here is the use of a group session to elicit personal constructs. Conducting a RepGrid study within groups is not completely novel; in the past there have been some varied attempts to incorporate group sessions. The main concern that all of these approaches have in common is how can you explore people's shared meaning or inter-subjectivity, within an idiographic context. Hall and colleagues conducted their data gathering with researchers acting as facilitators in a peer group setting using a process that seems to have been similar to brainstorming [86]. In this study they provided groups with topics (elements) to discuss, these sessions were facilitated, recorded and transcribed. In the analysis no grid was produced, instead the researcher extracted the themes (constructs) that they best felt described the topics that were discussed by the group. Watson used a modified RepGrid study and suggested that grids can provide information about interpersonal relationships within groups, psychological features of individual group members and changes occurring in individuals taking part in group therapy [307]. More recently McWhinnie and colleagues [187] used a group session to identify a set of elements to be used in a study, the constructs were then elicited individually (off site) using a RepGrid kit that the participants were given. They present an interesting approach to comparing different individuals grids by pairing participants and getting them to rate each others grids, they used this in conjunction with a method suggested by Shaw and Gaines [261] for comparing grids, based on identifying consensus, conflict, correspondence and contrast between participants elicited constructs. The approach that Alexander and colleagues [5] presents is most similar to the adaption I present in this chapter. During a workshop session a group of participants elicited both the elements that would be investigated as well as the constructs that would be used to rate the elements against. Over a period of two weeks, group members, independently, and in different places, assigned values to the cells, which associate constructs with elements. The group then met again to discuss the values that each assigned to the elements. This session revealed differences in the individuals' understanding of the elements and constructs and made them reconsider their individual interpretations. The main difference between this approach and mine is the reason for adapting the RepGrid, which they subsequently renamed as Reflection Grids, was to explore the technique not as an evaluation tool but as a method to assist team members in collaborating by making the individual concepts (personal constructs) explicit and hence allowing joint concepts to be formed.

6.2.2.2 *RepGrid Limitations*

While there is a renewed interest in the RepGrid technique, there has also being a number of concerns raised recently in relation to the integrity and application of the technique. Although the RepGrid technique has evolved over time, it is still predominately used to probe and uncover idiosyncratic views from individuals. This can be problematic if the objective of the research is to seek homogeneity across individuals' perceptions. In certain cases, researchers, who strive for congruity, found it difficult to achieve this when employing methods typically associated with the analysis of RepGrids. Also, although the data collected during a RepGrid study reveals a lot about what the participant experienced when interacting with the artefacts under investigation, it offers very little about why they experienced them in this particular way. In regards to the analysis of the gathered data, Karapanos and colleagues [129] argued against averaging as a common practice and instead proposed Multi-Dimensional Scaling (MDS) approach that accounts for the diverse views. While the data gathered during a typical RepGrid study can be analysed both quantitatively and qualitatively, it normally lends itself more to the former. It has also been noted that the procedure of conducted a RepGrid study is extremely cognitively demanding for both the participants and the researcher [71]. A comprehensive RepGrid study also requires a lot of time to organize and conduct, each interview can take up to 40-minutes to complete and for rigor it is suggested that a study should involve at between 12 and 15 participants [71].

6.3 THE ADAPTATION

To address these limitations I designed an adaptation to the traditional application of the RepGrid technique to allow for the collection of rich qualitative data in a manner that would not be exhausting for the participant or researcher. I did, however, seek to maintain the integrity of the original technique by preserving the fundamental characteristics such as *elements*, *personal constructs* and *links*. In the following I present this adaptation, which involves blending the RepGrid technique with a focus group session to investigate people's experience of representational modality. Instead of analysing the collected data using quantitative methods, I employ discourse analysis to elicit findings from the study. I follow this by presenting a further experiment, which incorporated two side-by-side studies to valid the adaption against the typical application of the technique. I also use this experiment to probe people's experience of representational modality.

6.3.1 *Study 1: Blending the repertory grid technique with focus groups*

The aim of this study to explore how representational modality affects the way people perceive and interpret data. To accomplish this I employed an adapted approach to RepGrid technique to allow me capture first-hand accounts of people's experience. The study incorporates a focus group session into the classical procedure of a RepGrid study, where consensus is achieved through dialogue between multiple participants. This dialogue is captured and transcribed and forms a fundamental part of the analysis. I not only propose this methodological extension but I also present a novel way of analysing RepGrid data by tracing the emergence and shared meaning through discourse analysis of the transcribed group sessions.

This study explores people's affective responses when experiencing data represented through different modalities. In particular, I was interested in investigating how data representations that address haptic/tactile and sonic perception are experienced. In the following I describe the creation of three data-driven artefacts that all represent the same dataset. I also present the procedure followed to elicit the participant's personal constructs attributed to each artefact during a focus group session, which form the basis of the group RepGrid. The analysis examines this grid and traces the emergence of one exemplary personal construct as well as highlighting other emergent themes. The findings consist of a number of elicited constructs that illuminate how the affective qualities of data driven artefacts relate to the type of modality in use.

6.3.1.1 *Design Process*

The goal of the design phase was to produce three data-driven artefacts that each represents the same dataset. As a first step, I selected a data source to be represented. The main criteria was that it must be socially relevant and from a trustworthy source. A number of datasets were identified that included economic, environmental, demographic and geographical data. From these I selected a dataset that represents the latest global urban outdoor air pollution figures from almost 1100 cities in 91 countries. For the study, the annual mean PM10 ug/m3 for six countries (Greece: 44, Ireland: 15, India: 109, Egypt: 138, United Kingdom: 23 and Turkey: 66) were used and all the data-driven artefacts produced represented this same dataset.

I envisaged the RepGrid study utilizing the 'triad' technique, which involves participants identifying a quality dimension of three given objects, such that two of the objects are similar in some way and the third is relatively dissimilar [71]. For this reason, three modalities were identified and a prototype was designed for each. These are: *SonicData* (auditory modality), *DataBox* (cross-modal (haptic and auditory)) and a *Bar Graph* (visual modality) (see Figure 6.1). Besides using different representational modalities, two of the artifacts (*DataBox* and *SonicData*) require active manipulation to elicit information, whereas the Bar Graph only requires the participants to look at it. Also, *SonicData* and the Bar Graph both use a single modality to represent the data, with *SonicData* utilizing an alternative modality to the 'standard' visual modality. *DataBox* is defined as employing a cross-modal representation. Cross-modal, in the context of this research, uses more than one modality to represent the same data. Its use of the different senses allows the characteristics of one sensory modality to be transformed into stimuli for another sensory modality [158].

SonicData is a bespoke device that represents data by playing sonic tones at certain frequencies through a tactile interface. Users of *SonicData* are presented with a labelled surface and a small coloured wooden cube. Placing the cube over each label triggers a sound whose frequency represents the urban air pollution of this country. The frequency is mapped to the level of air pollution; high pollution results in a high frequency sound and low pollution will result in a low sound, e.g. 1380 Hertz

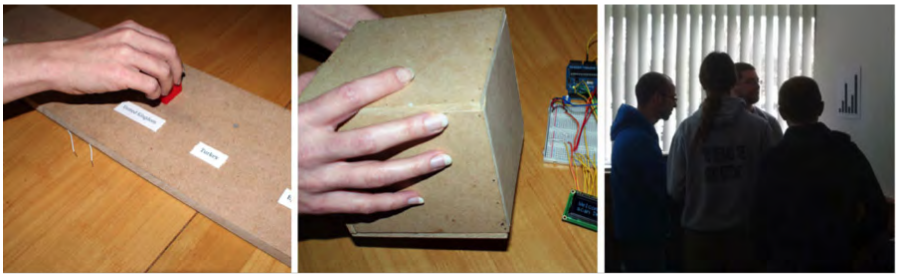


Figure 32: Data-driven artefacts. Left: SonicData, Middle: DataBox, Right: Bar Graph.

(Egypt) and 150 Hertz (Ireland).

DataBox is a wireless cube device (10cm3) created for this study, which represents the dataset through haptic and auditory feedback. The six faces of the cube represent the six countries of the dataset. When the user hovers each face over a scanning station, an LCD display located within this station shows the name of the selected country. *DataBox* immediately responds by knocking on the internal walls. The rate of knocks corresponds to the level of air pollution, e.g. 15 times per minute (Ireland) and 138 times per minute (Egypt). DataBox consists of a microcontroller and 12-volt solenoid housed inside a hollow wooden box, and has RFID tags on the inside of each face. When hovering the box over a RFID reader it reads the closest tag, sends a message to the LCD, and wirelessly transmits a message to the microcontroller that controls the knocking.

The *Bar Graph* utilized a common and recognisable visualization format. The printed graph (42cm x 21cm) was labelled with the names of the six countries on the x-axis and the data was represented using solid black bars on the y-axis. I was conscious that including such a recognisable format might influence participant's responses, especially considering the unique nature of the other prototype. However, the rationale for including such a standard format was to remind the participants that they were interacting with artefacts that serve the purpose of representing data.

6.3.1.2 *Participants and Procedure*

Fifteen individuals (11 male) participated in the study, with a mean age of 22 years (Min = 19, Max = 24). The participants were all final-year digital media students and members of the same class and thus were already accustomed to discussing topics in front of one another during group critiques. It was a conscious decision to involve a group of participants who knew each other already and would feel comfortable discussing their personal experiences in front of each other. The session took place in a large room with all three artefacts located at separate corners of the room. The study entailed, firstly, dividing the group into three subgroups. The subgroups then had 15 minutes to engage with each of the data artefacts (45 minutes in total). This was followed by a group discussion, which I facilitated and involved all 15 participants. The study was recorded using three video cameras directed at each artefact and three digital audio recorders positioned alongside each artefact. Transcripts were produced from audio files recorded during the familiarisation sessions and formed the basis of the analysis.

The following sections briefly describe the phases followed during a typical RepGrid study, and then highlights the variations to these while conducting my adapted study. For the purposes of this study, three artefacts (*SonicData*, *DataBox* and the *Bar Graph*) were pre-selected, providing the elements to be examined. Participants are made familiar with the elements before the phase of construct elicitation begins. A typical RepGrid study would normally conclude by having the participants rate each of the elements on a 5-7 scale for each construct. This study did not include this stage, as the main objective was to reveal the emergence of these constructs through an inductive approach to the analysis.

ELEMENT FAMILIARIZATION This stage allows for the participants to become familiar with the elements used in the study. The researcher typically introduces each participant to the elements and allows some time to interact with these. Generally this phase of a RepGrid study is quite informal and not treated as of critical importance. However, for the study presented here this phase was central. Following a short introduction to the three data artefacts, all participants were allowed 45 minutes to interact with them. The participants were divided into groups of four, spending fifteen minutes interacting with each data artefact before moving on to the next in a round-robin pattern. All groups were encouraged to openly discuss their perception and experience as well as discussing the pertinent qualities of

Figure 33: Focus Group session to elicit personal constructs from individuals.

the artefacts with each other.

CONSTRUCT ELICITATION During this stage, participants are normally interviewed individually to elicit personal constructs. Instead, in this study a group discussion was conducted (see fig. 6.2), which I mediated. The method used in this session was the minimum-context triad form of construct elicitation. From a triad of elements the participants are asked to describe how two elements are similar (Convergent pole) but differ from the third (Divergent pole). This dimension is the personal construct. The session commenced by asking participants to write down as many personal constructs as they could think of. After a few minutes they were asked to explain their constructs aloud and the group openly discussed each of these. This discussion also generated further new constructs. These were elicited by the researcher 'laddering' the discussion by asking participants 'why' certain constructs are important to them [43]. Constructs were only recorded if the majority of the participants agreed. This process was repeated until participants could no longer think of meaningful distinctions or similarities among the triad of artefacts.

6.3.1.3 *Findings*

The analysis went through four steps, from filtering and collapsing the elicited constructs, over classifying them as ergonomic or experience-oriented (hedonic) to tracing their emergence and finally highlighting major themes exposed during the study.

FILTERING In total 35 sets of bi-polar constructs were elicited during the group discussion session. For this analysis, the list was shortened to 27 constructs by collapsing those that were semantically related into one construct. For example I collapsed the constructs Novel and Innovative into the one construct (Novel).

CLASSIFICATION As the objective of the study was to examine the participants affective responses, I focused the analysis on constructs that demonstrate affective or hedonic qualities (cf. [93]) rather than ergonomic qualities (task-orientated and related to traditional usability principles such as efficiency). Hedonic quality (HQ) comprises of quality dimensions with no obvious relation to tasks, such as novelty, innovativeness, attractiveness etc. [93]. From the list of 26 sets of constructs, 13 were classified as HQ. The RepGrid (Table 6.3) shows the elicited (HQ) personal constructs (PC1-13). It illustrates, for instance, that the group characterized both *DataBox* and *SonicData* as 'Novel' but unlike the *Bar Graph*, which was characterized as being 'Familiar' (PC1). They also agreed that *SonicData* and the *Bar Graph* should be described as 'Organic' whereas *DataBox* was 'Artificial' (PC13).

TRACING The objective at this stage was to trace the emergence of the hedonic constructs in order to better understand the meaning associated with these constructs. This was achieved by examining the transcribed familiarization and group session as well as field notes taking during and after the study. It is important to note that as part of this study the field notes were an integral element and were used as a step toward data analysis [200]. To demonstrate this process, in the following I trace the emergence of PC3 (Instinctual—Cerebral).

Table 6.3 shows the group agreed that *DataBox* and *SonicData* should be described as Instinctual whereas the Bar Graph was described as Cerebral. This reliance on instinct was evident during the Familiarisation Session. While interacting with the *DataBox* and *SonicData*, the participants were continuously seeking real-world analogies for further insight into the artefacts. On numerous occasions, participants in all three familiarisation sub-groups compared the output from DataBox to the characteristics of living beings, such as *"It's like a heartbeat"*, *"It feels like it is dying"*, *"India is dead"*. One participant also remarked that the knocking on the box could be compared to *"the pump-*

		A	B	C	
PC1	*Novel*	<	<	>	*Familiar*
PC2	*Experimental*	<	<	>	*Traditional*
PC3	*Primal*	<	<	>	*Intellectual*
PC4	*Fun*	<	<	>	*Boring*
PC5	*Warm*	<	<	>	*Cold*
PC6	*Colourful*	<	<	>	*Black & White*
PC7	*Playful*	<	<	>	T*ask-orientated*
PC8	*Immersive*	<	<	>	*Non-immersive*
PC9	*Sonic*	<	<	>	*Silent*
PC10	*Sophisticated*	<	<	>	*Non- Sophisticated*
PC11	*Intensive*	<	>	>	*Subtle*
PC12	*Strong*	<	>	>	*Weak*
PC13	*Artificial*	<	>	>	*Organic*

Table 8: The Group RepGrid: Element A: *DataBox*, Element B: *SonicData*, Element C: the *Bar Graph.* Personal constructs (Hedonic Quality) elicited during the RGT study, the arrows for each artifacts points to the pole of the dimension. A: DataBox, B: SonicData, C: BarGraph

ing of our lungs and the beating of our heart". The participants also used real-world analogies while using *SonicData*, however, these tended to be more artificial in nature, the following extract illustrates this point:

P3: *Greece sounds like a dialling tone.*
P2: *The UK is kind of nice, it sounds like a small ship.*
P5: *Yeah, like a sonar.*
P2: *No, it sounds like you are dialling a phone.*
P1: *Then the high-pitched ones are the highest* ones.

During the Construct Elicitation session the group explained this personal construct further by describing the graph as a thing that you have to learn to use. They explained how they have been taught to use bar graphs throughout their education and they see them merely as tools; one participant remarked *"You can tell instantly which is the worst of which is the best - there is no confusion, you do not have to look any further"*. The mapping used in the other artefacts, however, were new to the participants. They spoke about not having any prior training in the use of these and having to rely on their instinct to understand what the output represented.

6.3.1.4 *Themes*

Based on the analysis of the transcripts against the RepGrid produced during the focus group session I identified four themes (Linguistic, Consequences verses Implications, The Felt Dimension and Rating) that shed light on how representational modality affected participant's experience of the data.

LINGUISTIC An interesting theme that emerged from the study was that the language used by participants while interacting with the *DataBox* and *SonicData* was, in general, more emotive than with the Bar Graph. There was frequent use of expressive descriptions such as: annoying, hurts, beautiful, healthy, alarming, relaxing, dead, urgent, fun, torture, irritating and intense; used in relation to the *DataBox* and *SonicData* that was not evident in the conversations about the Bar Graph.

CAUSATION VERSES AFFECT It was also found that the group's discussion when using the Bar Graph during the familiarisation session generally related to speculating about the causes of pollution, whereas discussions around the other artefacts generally related to the effect that poor pollution has on the inhabitants of the countries. This is highlighted in the following extract from the familiarization session:

[Bar Graph]
P1: *...It looks like poorer countries have more pollution than richer countries.*
P2: *yes*
P3: *but why is Egypt more polluted than India?*
P2: *but isn't India poorer*
P3: *that has got nothing to do with the air?*
P2: *but generally poor countries are more polluted as they have so many people there...*

[SonicData]
P3: *... the sound of each is so annoying*
P4: *imagine living in Egypt, it would be pretty annoying to have such pollution also*
P5: *as well as India.*

P3: *Greece is by far my most favorite one*
P2: *No, mine is the United Kingdom...*

[DataBox]
P12: *... that could be healthy Ireland?*
P11: *Healthy Ireland! No, cause if my heart was beating that slow I would be almost dead*
P13: *Yes, but what we are feeling at the moment is Egypt*
P12: *Yeah, but that feels healthy*
P13: *Yeah, that sounds good, it sounds like progress, it sounds like it's going well...*

THE FELT DIMENSION Another theme to emerge was the participants way of phrasing how they experienced and interpreted the data artefacts. When using the *DataBox* they talked about "feeling" the data and associated it with a human-heartbeat. On occasions when the frequency of knocks decreased, the participant holding the *DataBox* remarked that they felt the country was "dying". Affective responses were also evident with *SonicData*. Participants described some of the sounds as being "annoying" or "painful" and equated unpleasant sounds with increased pollution.

RATING Also, in relation to *SonicData*, the participants spoke about which sound was their favourite, and used this as an attempt to map the least and most polluted countries. The following exchange exemplifies this:

P5: *I like that one the best* [Greece].
P8: *I like that one* [UK].
P5: *What's next, Turkey, India and Egypt.*
P7: *Think about it though, what is the nicest to listen to?*
P5: *Greece is nice.*
P7: *I like the UK.*
P8: *The lower ones are nice so the pollution must be low.*
P5: *Yes, I like the lower ones.*
P9: *My favourite's Greece.*

These behaviours may be interpreted as the participant's affectively responding to the *DataBox* and *SonicData* in a manner that was not evident with the Bar Graph. While I did expect the responses from the DataBox and *SonicData* to be more extreme than the Bar Graph, given this format does not leave much space for interpretation, the acute difference in the style of language used by the participants when describing their experience was noticeable and somewhat unexpected.

The affective response to *DataBox* and *SonicData* is furthermore reflected in the *RepGrid* (Table 6.3), where participants tended to associate these more often with what could be considered the more emotional and fun-related pole of a construct (e.g. *primal, fun, warm, playful, immersive*). Interestingly, *SonicData* was considered artificial (and not *organic*).

6.3.1.5 *Other Observations*

During the familiarisation session I observed a distinct difference in how the three groups situated themselves and moved around the artefacts. While interacting with *DataBox* and *SonicData* the members of a group were continuously switching positions in order to interact with the artefacts but also to observe others interacting with the artefacts. This was not evident with any group at the Bar Graph. In this case, all members of a group stood motionless in front of the graph until they were asked to move to another artefact. I also noted that when a member of the group talked about *DataBox* and *SonicData* that the other members sought to maintain eye contact throughout the discussion. This could be described as an attempt to discover more about what others were saying and feeling as they used the artefacts. Conversely, when the groups were viewing the Bar Graph they tended to consistently look at the graph, even when other members were speaking. In this case, the choice of representation might contribute to this behaviour pattern – the Bar Graph representation has an orientation, and even if it would be on a piece of paper on the table, it would not be as easy for the group to surround it as this was for the other two data artefacts.

While this study highlights evidence which supports the case that representing data using non-visual artefacts evokes more affective responses, I also observed that the participants had some difficulty mapping the data to the representational output, for example, whether frequent knocking (*DataBox*) represented a high or low rate of pollution. In the early stages of the session participants spent some time discussing this issue. However, once consensus was met, the conversation soon switched to issues related to the source of the dataset.

6.3.2 *Discussion and Summary*

This study investigated people's affective responses when experiencing data represented through different types and levels of modalities. I explored this by conducting an adapted RepGrid study using three data-driven artefacts, which each represented the same dataset. During a focus session with fifteen participants, thirty-five personal constructs were elicited. For the purpose of analysis this list was shortened to thirteen that demonstrated a hedonic quality. It is clear from this list that the participants perceived *DataBox* and *SonicData* as being more similar than the Bar Graph. Apart from the obvious novel characteristics of these artefacts over the familiar format of the Bar Graph, we also believe that the interactive quality of these artefacts influenced the participants to see them as more alike.

In the analysis I chose one personal construct Instinctual—Cerebral and traced its emergence using field notes and transcriptions from the group session. This analysis reveals that the participants relied heavily on instinct, previous experiences and real-world analogies to infer data insight and meaning from both *DataBox* and *SonicData*. Conversely, the participants found that the Bar Graph is a tool they have been trained to use over a long period and thus did not engage them emotionally. They tended to have more abstract, causality-oriented discussions about the content of the Bar Graph, whereas they were more concerned about what the data represented by the *DataBox* and *SonicData* would mean for people's lives, and used more emotive language to describe the data.

This study shows that, given a group that is comfortable discussing with each other, a group approach to the RepGrid can be useful, in particular, in allowing us to trace the emergence of constructs from participant's direct initial responses to the elements. In the next section I present a study that sought to validate this adaptation, which was also conducted for the purpose of exploring people's experience of representational modality.

6.3.3 *Study 2: Comparing the approaches and confirming the adaptation*

In the previous study I showed how the traditional application of the RepGrid technique could be adapted to collect rich accounts of experience instead of numerical ratings. In the study I describe next I continue with the same line of enquire and also valid and confirm the adaption of the technique. I also sought to address some of he limitations of the previous study, these include the clear disparage between the visual modality and the other two. I sought to reduce the design features of the three artefacts to focus the participant's attention on the representational modalities and away from other aspects such as interaction styles, aesthetics and materials. With these issues in mind I designed an experiment that would incorporate two studies, each of which investigated the same set of artefacts. One would follow the procedure and methods of analysis of a traditional RepGrid study, while the other would incorporate the adaption described in the previous sections. In comparing these approaches, I will illustrate how using a blended approach can validate and reveal further meaning about the data collected. Furthermore, I will demonstrate that this can be achieved in a more natural manner than that of a typical RepGrid study, which can be extremely demanding for both the participant and the researcher while the study is being conducted.

6.3.3.1 *Methodology and Data-Driven Interfaces*

As part of this study a new set of data-driven interfaces were created that represent one data stream through the haptic, visual and auditory modalities. The source of the data is a live stream of the Hydrogen levels in deep Space. This data is gathered by *Blackrock Castle Observatory* and the *Irish National Space Centre*, both based in Cork, Ireland. The rationale for using this source was that I have worked with this data in the past (see Chapter Four) and it has proven to be a reliable and constant stream of data. To acquire the data I utilized a commercial cloud based data collection and retrieval system (COSM). A custom program on the computer attached to the telescope collects the latest data and sends it to an account on COSM, and then any computer connected to the Internet can retrieve and utilize this data (see Fig. 6.3:4).

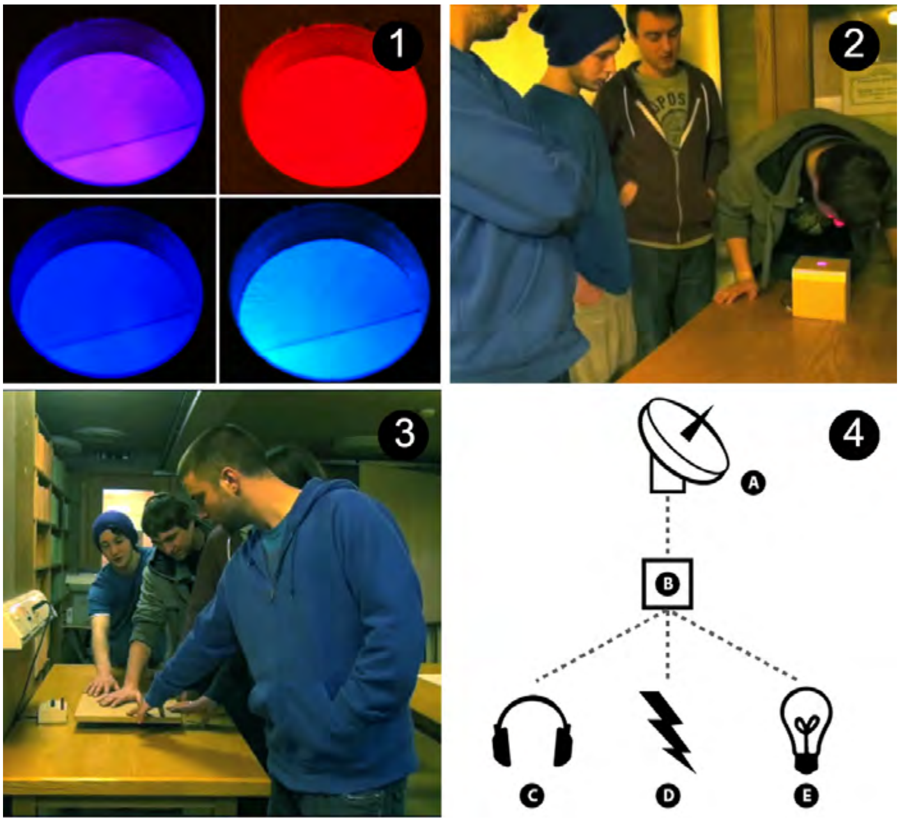


Figure 34: Sample range of colours emitted from the visual interface. 2:Visual Interface, 3: Haptic Interface and 4: System Design (a. Radio telescope b. COSM server c. Auditory interface d. Haptic interface e. Visual interface.

When designing the three data representation interfaces I prioritised simplicity and clarity, and envisaged producing three prototypes whose primary function was to represent the data via a particular modality.

THE HAPTIC INTERFACE represents the data through the haptic modality utilizing vibro-tactile feedback (see Fig. 6.3:3). It consists of a 30cm x 30cm wooden surface that comfortably accommodates only two hands. The rationale for such a size was that all three modal interfaces should be similar in regards to the number of people who could interact with them at any one time. Nevertheless, as Fig. 6.3:3 illustrates, participants figured out ways to share the experience by putting their hands close together on the board. The vibration is generated through ten 5-volt motors that are embedded into the underside of the wood. The speed of these motors is controlled by a microcontroller that is connected wirelessly to a computer. Through a custom program, a constant connection is maintained with the COSM server where the latest value retrieved from the radio telescope is stored. The speed of the motors increases or decreases depending on the latest reading (high levels cause strong vibration while low levels cause weak vibrations).

THE VISUAL INTERFACE represents the data through a range of colours, from green to red, which is emitted from six RGB LED's. The interface consists of a hollow wooden cube (10cm side) with a 2cm hole in the top face (Fig. 6.3:2). A microcontroller, which is housed in the interior of the cube, controls the colour of the light being emitted from the LED's. It is connected wirelessly to the same program as the haptic interface. When the program captures high values it instructs the microcontroller to emit red light from the LED's. If, however, the reading is low, it instructs the LED's to glow green. Values in-between these two extremes cause the LED's to emit the range of colours in the colour spectrum between red and green (i.e. medium values triggers purple light, medium-high values triggers orange light and so on), Fig. 6.3:1 shows a selection of different colour ranges emitted from the cube.

THE AUDITORY INTERFACE utilizes a custom program that dynamically generates a digital sound and plays this through a set of head-phones. The headphones are connected to a computer running the program all the interfaces are connected to. The frequency of this sonic tone represents the latest data values. When the program reads the latest value from the COSM server it translates this value into a certain frequency. The higher the Hydrogen values the higher the frequency of the tone and visa versa.

6.3.3.2 *Procedure*

In all, 24 individuals (8 female) participated in both studies, with a mean age of 24 (Min = 21, Max = 28). They were also final-year digital media students, but none participated in the previous study. Initially, the participants were divided into two groups of 12, with one group participating in Study 1 (the traditional RepGrid approach) and the other in Study 2 (the blended approach). Both studies were conducted in a large room, where the three data interfaces were positioned in separate corners. The follow-on interviews and focus group session also took place in the same location. The following sections describe the procedure followed by both studies, divided into the various stages of a RepGrid study (Element Familiarization, Construct Elicitation and Rating.) In each case I will first describe the typical traditional procedure and follow this by presenting the proposed amendment.

6.3.3.3 *Element Familiarization Session*

STUDY 1 (TRADITIONAL): This stage of the study is dedicated to making the participant familiar with the elements that are under investigation. I introduced each participant to the elements separately and allowed some time for him/her to interact with them. At all times there was only one participant and I in the room. Following a short explanation of each interface, each of the 12 participants was allowed 15 minutes to engage with all three elements. I was present in the room at all times to answer any questions, while also encouraging the participants to move between all the interfaces and not to stay with one for too long.

STUDY 2 (BLENDED): In a typical RepGrid study this stage is quite informal, however, as part of my proposed blending of the two methods this stage was of critical importance. Following a short introduction to the three data interfaces, all 12 participants were allowed 45 minutes to interact with them. The participants were divided into groups of four, spending fifteen minutes interacting with each interface before moving on to the next in a round-robin pattern. All groups were encouraged to openly discuss their perception and experience as well as discussing the pertinent qualities of the interfaces with each other. This session was recorded using video cameras and audio recording equipment. The transcriptions of these recordings form the central component of the subsequent analysis.

6.3.3.4 *Construct Elicitation*

STUDY 1 (TRADITIONAL): During a typical RepGrid study, following the familiarization session, the individual participants are interviewed separately to elicit their personal constructs. The method we used is the minimum-context triad form of construct elicitation. From the triad of elements each participant was asked to describe how two elements are similar (convergent pole) but different from the third (divergent pole). This continued until the participant was noticeably having difficulties in ascribing new and unique attributes to the elements. In cases where the participant found it difficult to elicit more than five constructs I would repeat some of the recorded constructs and ask them 'why' this attribute is important to them. This method, known as 'laddering', assists the participant in defining the constructs further and in many cases leads to new constructs being elicited [43]. Research has shown that the amount of constructs elicited during a RepGrid study typically ranges from 5 – 17 [71]. In the 12 sessions conducted during this study an average of 11 constructs were elicited from participants.

STUDY 2 (BLENDED): In the blended approach, instead of interviewing the participants individually, I conducted a focus group session, to elicit constructs from the group. I also used the minimum-context triad form of construct elicitation in this session. It commenced by asking all 12 participants to write down as many personal constructs as they could think of, much like the typical RepGrid study. After a few minutes participants were asked to explain their constructs aloud and the group openly discussed each of these. Although the group were in control of which constructs were discussed at length, if I felt that the discussion was not progressing the laddering technique was also used. A personal construct (or possibly now these could be called 'group construct') was only recorded if the majority of the group agreed with its inclusion. Once the group achieved consensus, I recorded the construct on a large whiteboard in the room. This process was repeated until the group could no longer think of meaningful distinctions or similarities among the triad of elements. This session was also recorded using video and audio equipment, and was subsequently transcribed for use in the analysis of the study.

6.3.3.5 *Ratings*

STUDY 1 (TRADITIONAL): Typically the third and final stage of a RepGrid study is dedicated to linking the elicited constructs to the elements under investigation. This is done by rating or ranking each element against each construct until a completed RepGrid is produced (see Table 6.4). In this study each participant was presented with a printout of their RepGrid, which consisted of their bipolar constructs displayed in the rows and the elements in the columns. The participant was then asked to rate (Likert scale 1-7) each element against the constructs so that 1 being the convergent pole (left) and 7 being the divergent pole (right). Once this had been completed the participants were asked to read over the grid and confirm that they agreed with it.

STUDY 2 (BLENDED): In the blended approach, the group of participants were not asked to rate elements. Instead, they were asked to dichotomize, meaning that each element was either one dimension of the construct or the other (George Kelly used this approach in the first RepGrid studies [135]). This process involved all participants discussing and debating whether each element belongs at the convergent or divergent pole of the dimension. Once consensus was achieved, the group decision was recorded by the researcher i.e. the visual modality is construed as comfortable but the haptic and auditory modality are construed as uncomfortable (See Table 6.5 (S2A)). Again, this part of the study was recorded, transcribed and used as part of the analysis.

6.3.3.6 *Data Processing*

The proposed adaption also extends into the analysis of the data gathered during study. During a typical RepGrid study a grid is produced for each participant, these can be analysed as individual grids or condensed into one group-grid by using various quantitative and qualitative methods. In our adapted approach only one grid is ever produced. The following sections provide a description of the procedure of processing the data gathered during both studies. First, I will present the traditional approach, this will be followed by illustrating the methods used as part of my adaption.

STUDY 1 (TRADITIONAL): The overall aim of processing the data from a traditional RepGrid study is to compress the individual grids (12 in this case) into one group-grid. During the study a total of 130 unique personal constructs were elicited by the 12 participants, these constructs were input into the software application WebGrid 5[1] , which was developed to handle data gathered during a RepGrid study. This application uses FOCUS analysis to sort the grid, which shows the highest possible correlation between constructs and elements. This is accomplished by reordering the rows (constructs) and columns (ele-

1 see http://gigi.cpsc.ucalgary.ca:2000/

		H	V	A	
S1A	*Comfortable*	4	1	7	*Uncomfortable*
S1B	*Aesthetic*	7	2	6	*Scientific*
S1C	*Stimulating*	4	1	7	*Non–stimulating*
S1D	*Physical*	1	3	7	*Virtual*
S1E	*Provocative*	2	1	6	*Non-provocative*
S1F	*Engaging*	3	2	6	*Passive*
S1G	*Impressive*	2	3	5	*Dull*
S1H	*Intriguing*	1	2	6	*Weak*
S1I	*Curious*	1	3	6	*Typical*
S1J	*Multisensory*	3	1	7	*Single Sensory*
S1K	*Calming*	5	1	7	*Intrusive*
S1L	*Multimodal*	1	6	6	*Mono modal*
S1M	*Tangible*	1	7	7	*Intangible*

Table 9: The Repertory Grid produced during traditional study, the personal constructs were collated from the 12 individual grids. H: Haptic, V: Visual, A: Auditory

ments) to produce a FOCUSed grid that places the constructs and elements that are statically similar to one another next to each other [262]. By using this FOCUSed grid I was able to identify certain clusters of constructs that were statistically similar or identical to other constructs. For the purpose of this study I applied two rules when identifying clusters: firstly, constructs must be statistically >95% similar and secondly, a cluster must include four or more constructs. My analysis identified 13 clusters, which incorporated 105 different constructs. The remaining 25 constructs were not statistically similar enough to be part of a cluster.

The next stage involves providing titles for the clusters. To exclude researcher bias, each cluster was given the title from a construct within that particular cluster, for example the cluster Comfortable – Uncomfortable includes the constructs (smooth, appealing, relaxing, comfortable) and (piercing, dull, agitated, uncomfortable). Then, the ratings of each cluster were calculated. Instead of the arithmetic mean, the median value was calculated. I used the median value as studies have shown that calculating the arithmetic mean understates extreme values, which may be at odds with the majority of participants. Following this, the repertory grid was produced that included 13 bipolar clusters (Table 6.4). The final stage of data processing involves producing a map using Principal Component Analysis (PCA). This further helps to reveal trends and clusters within the data (see Fig. 6.4) PCA is normally relied on heavily during quantitative analysis of RepGrid data [71].

STUDY 2 (BLENDED): The adapted approach requires minimal processing of the data, as the participants themselves complete this through discussion and debate during the focus group session. In all, a total of 24 constructs (group constructs) were elicited during the focus group session. To refine this list, I also input the list into WebGrid 5, which produced a repertory grid. As the elements were dichotomized against each construct and did not apply ratings, the rules we applied to reveal clusters in this grid were much more severe than in the traditional approach. These rules were as follows: the constructs must be statistically identical (100%) to each other, while also being semantically similar, i.e. the bipolar constructs engaging – non-engaging, exciting – relaxing and stimulating – non-stimulating were conflated into one cluster which we titled Stimulating – Non-Stimulating. The final repertory grid that was produced can be seen in Table 6.5.

6.3.3.7 *Comparing The Grids*

Before I present the analysis of the grids I will briefly compare the content of the two repertory grids produced. There are a number of clear similarities between the two grids (Table. 6.4 and 6.5). I have reordered both grids to highlight possible similarities. The first nine constructs (A-I) can be pared with a counterpart on the other grid, from S1A and S2A (Comfortable – Uncomfortable) to S1I and S2I (Clear-Confusing and Obvious-Abstract). From these nine pairs there are first four are almost identical, whereas the remaining five we classified as semantically similar. To verify these similarities and avoid researcher bias I used a thesaurus as well as consulting with a number of colleagues who were not part of this research. I note that there is a similarity in 65% of the elicited constructs; this however leaves 5 constructs that do not demonstrate any resemblance to constructs elicited using the other approach.

6.3.3.8 *Grid Analysis*

In presenting the analysis of both studies it is not my intention to be exhaustive; I am more concerned with highlighting the key aspects of the analysis as a means to compare my adaptation to a traditional RepGrid study. Before I describe the proposed adaption to analysing RepGrid data - which is integral to my proposed blended approach, I will first briefly illustrate a typical method of analysing the data through Principle Components Analysis.

STUDY 1 (TRADITIONAL): Principal Component Analysis (PCA) is a distance-based method of analysing RepGrid data. It produces a PCA map that illustrates the degrees of correlation between and among constructs and elements, by calculating the statistical distance between them. The first component (x-axis) of the PCA map (Fig. 6.4) accounts for 61.7% of the variance and together with the second, 38.3% (y-axis), it identifies 100% of variance in the data. Although this is extremely high, it is not unexpected as there were only 3 elements used in the study. When I examined these two components it can be interpreted as the first being related to type or level of engagement the participants thought they had with the interfaces. Constructs close to this axis include: curious, engaging, provocative and intriguing. The other component we read as being related to the material and sensory qualities of the elements, whether they felt comfortable or un-comfortable and also whether they stimulated more than one sense (multimodal) or not (mono-modal).

The PCA map also reveals three strong clusters formed close to each modality. Firstly, a dimension of the cluster (Aesthetic, Calming) is closely grouped with the visual modality. It could be inferred from this that the participants considered the visual modality not only to be highly aesthetic and extremely calming, but that the other modalities (haptic and auditory) are not seen as demonstrating these attributes. We could also surmise participants associate a sense of calming with aesthetic qualities as they are tightly clustered on the map. I also highlight a possible anomaly close to this cluster in regards to the positioning of the construct: Stimulating. From a semantic perspective, this attribute would seem to contradict the construct Calming, which is close by. In the case where we have two constructs that are statistically similar, but demonstrate very little semantic similarities, I would need to return to the participants to

		H	V	V	
S1A	*Comfortable*	>	<	>	*Uncomfortable*
S1B	*Aesthetic*	>	<	>	*Practical*
S1C	*Stimulating*	<	>	<	*Non–stimulating*
S1D	*Physical*	<	<	>	*Digital*
S1E	*Memorable*	<	<	>	*Forgetful*
S1F	*Interactive*	<	<	>	*Non-Interactive*
S1G	*Impressive*	<	<	>	*Dull*
S1H	*Different*	<	<	>	*Typical*
S1I	*Clear*	<	<	>	*Confusing*
S1J	*Variable*	<	>	<	*Constant*
S1K	*Sociable*	<	<	>	*Isolating*
S1L	*Motion*	<	>	<	*Static*
S1M	*Affective*	<	>	<	*Un-affective*
S1N	*Audible*	<	>	<	*Silent*
S1O	*Harsh*	<	<	>	*Soothing*

Table 10: The Repertory Grid produced during the focus group session. The personal constructs S2A-N were agreed by the participants during the focus group session, while S2O (Harsh - Soothing) was added to the grid after the transcripts were analysed.) H: Haptic, V: Visual, A: Auditory

question the meaning of this, as I do not have any data that can shed further light on this issue. The other clusters include (Multi-modal, Tangible) which is clustered around the haptic modality and (Abstract, Virtual, Typical), which form a cluster close to the auditory modality. The positioning and clustering of these attributes can be used to develop further understanding about how the participants construe their experience of the modalities under investigation in this study.

STUDY 2 (BLENDED): As can be seen above, a RepGrid study is typically analysed using a combination of quantitative (FOCUS and PCA) and qualitative methods (Content Analysis). In adapting this procedure, I propose taking a primarily qualitative approach. This procedure involves transcribing and analysing the familiarization and focus group sessions as examples of discourse. This discourse was treated as relating to the experience

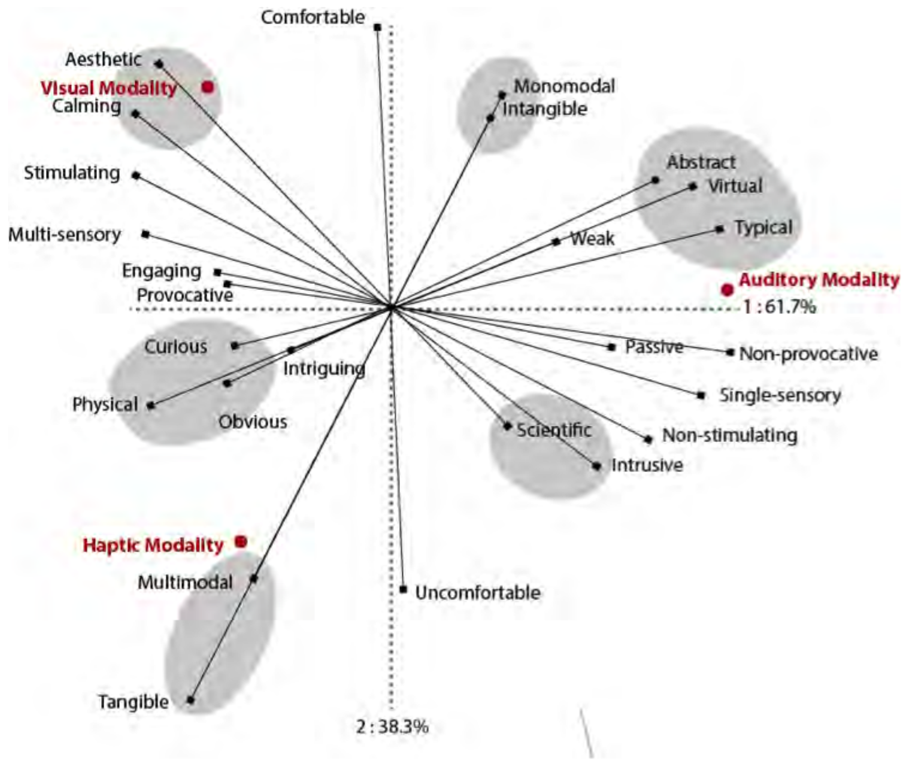


Figure 35: Principal Component Analysis of the Group Grid.

of using the three interfaces. The process I employed involves tracing the emergence of the elicited constructs through the discourse to reveal further insight related to their meaning. I will also demonstrate how this technique can be used to validate the grid and extract constructs that were not elicited during the study. The accounts are also scrutinized for the kind of discovery that might be useful in informing the design of data representations. Along with the transcripts, we also examined our field notes compiled during and after the study.

6.3.3.9 *Discussion*

In the focus group session, it was agreed that both the haptic and auditory interfaces be described as Stimulating, unlike the visual interface which they agreed was Non-Stimulating (see Table 6.5 S2C). When we examined the transcripts we found extracts that concur with this choice of construct. On one occasion, when a group were interacting with the haptic interface their discussion was as follows:

P1: *But when this one (haptic) goes from low to high you notice much more than the visual one, it makes you think more because it grabs your attention.*
P4: *...I would much prefer the sensation in my hand.*
P2: *Yeah true, but would you really know that it was at the highest.*
P4: *Does that matter, as long as it is grabbing your attention well then it works, vibration works better than lights for me...*

We can see in this extract that the participants are comparing the two modalities (haptic and visual) and negotiate the importance of stimulation, while some are willing to trade the communicative value of the modality for stimulation. Participant 4 even qualifies whether the interface works or not purely on the basis of it "grabbing your attention."

Another construct elicited during the study was Sociable – Isolating (see Table 6.5 S2K). The group described the haptic and visual modality as being Sociable while describing the auditory modality as being Isolating. The following extract provides a rationale for ascribing these constructs to the elements.

P6: *None of us have any idea what the levels are when we are not using the headphones, at least with the other we can push in beside someone else to see the colours and we all had our hands on the vibration mat at one time.*
P8: *That is not just down to the headphones, I have my own idea of what certain sounds mean, but that is not the same for colours*
P6: *You can also think about it more without some-one asking you about it...*
P8: *...This one (audio) is different from the other ones, I'd say*
P7: *Yeah, it's the only one that you have to make your own mind up about what's going on, the others you can look around a see what other people think but this one you have to explain what you feel first before can gauge what others think...*

This discourse is referencing aspects that could be construed as generating shared meaning (Sociable) within a group:

P7: *look around a see what other people think", as well as including dialogue that points toward purely independent thoughts (Isolating)*
P8: *I might perceive some-thing different from you.*

I believe these extracts highlight an important issue related to the meaning of the construct, as it rather seems to describe the (incidental) properties of the interface, and not the modalities used to represent the data. The auditory modality is the only one that cannot be experienced by more than one person at a time. The haptic modality is carried through a vibrating surface, and contrary to our design intention, which was to only support single user interaction, it did afford multiple hands to be placed on the surface at once. The visual modality was also designed to only support single user interaction. However, although the opening in the cube is quite small, the participants soon realized that by placing a hand over the opening the colour is reflected for all to see. Although all interfaces were designed for only one person, the audio interface was the only one that maintained this, leading us to believe that this is the reason why the group considered it to be isolating and not sociable like the other interfaces.

The group also agreed to describe the visual interface as aesthetic, while describing the haptic and auditory modalities as practical (see Table 6.5 S2B). During the discussions participants in one of the groups spoke about the visual interface in the following way:

P9: *I think it is really pretty, pretty colours I mean*
P12: *Yeah, it is prettier than the sound one*
P11: *That's because you can't possibly describe sounds as pretty*
P10: *Yes you can, the sound of little birds chirping can be pretty*
P8: *That is because the birds are also pretty and not just the sounds they make*
P9: *Well you surely can not say a vibration is pretty*
P12: *That's true...*

It is clear from this conversation that members of the group explicitly ascribed aesthetic qualities to the visual modality itself. They were not concerned with the physical container that the colours were being projected in. They also question whether abstract sounds and the sensation of vibration can be considered pretty.

Another group, while viewing the visual interface, discussed:

P4: *What is causing that?*
P2: *I don't know*
P3: *Neither do I*
P2: *But I don't really care what's causing it, isn't it enough just to know that something is causing it...*
P4: *What do you mean?*
P2: *It's creating these lovely colour changes and that's enough for me*
P4: *That's not all it's doing*
P2: *I know but sometimes it is nice just to look at cool things happening and not bother about why it's happening*
P4: *It's pretty cool alright...*

We see here that when the participants engaged with a modality, which they perceive as aesthetically pleasing, the communicative value of the modality becomes somewhat irrelevant. When participant 4 states that he doesn't "really care what's causing it", he is challenged by participant 2, but reaffirms his position and explains that "sometimes it is nice just to look at cool things".

These are three examples of how we trace the emergence and explore further meaning of the constructs through the dialogue recorded during the study. It not only provides us with a better understanding of the underlying meaning of the constructs, but we can also use this discourse to validate the constructs and possible even extract new constructs that were not elicited during the study. An example of the emergence of a new construct during analysis follows.

When the transcripts were examined I noticed that on a number of occasions the participants described the visual and haptic modality as being harsh and alarming, while comparing them to the soothing and smooth qualities of the auditory modality. On one occasion the group agreed when participants 4 stated "the light on your eyes is very harsh especially when it gets to red". Another example can be seen in the following extract (which was recorded while the group were interacting with the auditory modality):

P1: *It's much smoother than the lightbox*
P4: *what do you mean by smoother?*
P1: *I mean, it's more soothing*
P2: *I wouldn't say that the colours were alarming, maybe a bit harsh*

on your eyes but this was only when I look really closely at it
P4: *I find with this one is not as harsh as the other two and that makes you want to listen to it for longer...*

Following this discovery the research team agreed to add the construct harsh – soothing to the group RepGrid (see Table 6.5 S2O).

6.3.3.10 *Themes*

As well as tracing the emergence of the elicited constructs and revealing new constructs, a number of themes emerged from the transcripts. In this section I highlight three exemplar themes that are grounded in the gathered data, Referencing the *lifeworld*, Misunderstanding multimodal feedback and Visualizing non-visual modalities. This analysis is not meant to be exhaustive; it is merely presented to illustrate the potential of blending both approaches to reveal rich design relevant insight.

Referencing the *lifeworld*: When examining the transcripts I noticed, on many occasions, the participants seeking analogies with objects they encounter in their daily lives to help them describe the experience of the three interfaces. Examples include one participant describing the haptic feedback as being: "like a washing machine when it's spinning very slow". Another participant spoke about the visual feedback being "like the Photoshop spectrum from cold to hot, blue to red." while another participant disagreed "No, you should think about the colours in a rainbow, the blue is at the bottom and red at the top". When attempting to describe the auditory interface, the following participants discussed:

P1: *When you listen to it, it sometimes sounds like the sound of your engine in a car*
P2: *Yeah, I was thinking that as well, but mostly when it is low*
P3: *I think it sounds like it is accelerating and decelerating.*

These real-world analogies also incorporated other data visualizations, for instance:

P9: *So if a lot of hydrogen is hot then the hotter the colour the higher the hydrogen*
P10: *But if you think about it, the colours on a thermometer go blue,*

purple, pink and red
P11: *What kind of thermometer do you own?*
P9: *We have one at home, we use it in the oven so it must be good to stand that heat and its' labels are coloured blue, purple, pink and red so I'm guessing that this is the same.*

Misunderstanding multimodal feedback: Although the haptic interface was designed to represent the information only through vibration, the motors used in the interface also produced a sound that seemed to cause some confusion with the participants. While the interface did incorporate two sensory modalities (auditory and haptic) I do not consider it to be a multimodal interface as the sounds were generated purely as a consequence of the vibration motors and were not specifically designed to represent the data. Notwithstanding, in this case I observed that mixing two modalities within the one interface caused confusion for practically all of the participants. This is illustrated in the following exchanges:

P8: *It sounds like it should feel stronger... it feels wrong that the sound doesn't match the vibration.*
P7: *But it is the vibration that is causing the sound, isn't it?*
P8: *Yes, but I would feel better about it if loud sounds would have strong vibrations.*

This issue was further highlighted during another conversation between members of a different group:

P2: *Would you rate that sensation pretty low?*
P1: *I would rate it as low*
P2: *I think it is hard to judge the vibration on its own because the sound gets in your way.*

One participant even went so far as to say: "If you didn't have the sound it would be an entirely different experience." I observed on one occasion that a one participant asked another member of the group to put her hands over his ears so as to block out the sounds being produced by the device. When this was done he explained that the experience was completely different, stating:

P3: *I am telling you when you block the sound out the vibration feels like a lot more*

P4: *What do you mean, stronger?*
P3: *Yeah, stronger*
P1: *More intense?*
P3: *And that.*

Visualizing non-visual modalities: When I examined the transcripts I observed that the participants conversed about 'imagining' and 'visualizing' while engaging with the haptic and auditory interface, but this was not the case with the visual interface. The following extract sums this up:

P8: *I think it is harder to imagine another picture when you are looking at something*
P11: *What do you mean?*
P8: *Well, if you look at something you are seeing that thing so you don't really imagine looking at other things, but when you hear or feel something you are more inclined to make a picture in your head, aren't you?*
P12: *I get you.*

At no point, when engaging with the visual interface, did any participant use visual references to help them better understand what was being represented. Yet on many occasions when using the other interfaces, the participants used visual analogies to further elaborate on what they heard and felt. While feeling the vibrations from the haptic interface, one participant asked another:

P4: *Do you think that whatever we are feeling here can be seen out there...*
P2: *I think I have seen picture it before, do you know the ones from the Hubble telescope...*
P3: *I have one as my screensaver, is that what we are feeling? Cool!*
P4: *I didn't think about that, I know them, there are some really cool images of them, all the different colours, like nothing you have seen before...so this is actually that, wow!*

The use of visual analogies around the non-visual modalities was also observed with the audio interface. On one occasion when a group was discussing how the radio-telescope is static and its movement was caused by the Earths' rotation participant 4 remarked "You cant see the earth moving but if you think about it you can kind of hear the slow rotation of the earth, it's weird, I wouldn't of thought about that until she (P2) said it and now its all I see".

6.3.3.11 *Discussion*

The discussion that follows is divided into two parts. I first focus on issues related to the methodological adaptation of the RepGrid approach, and then discuss issues that have arisen through this work that might have implications for the future design of data representations.

METHODOLOGY To begin with, the blended approach utilizes a structured and methodologically validated approach within a focus group session, thus extending the repertoire of focus group techniques. Some commonly cited problems with focus group studies include the need for a carefully trained researcher, who must understand how to refocus conversations, and that researchers have less control over the data produced than in other quantitative studies or one-to-one interviewing [200]. I believe that incorporating the structured approach of the RepGrid helps to keep the participants focused during the study and does not require as much input from the researcher. The RepGrid technique also helps to control the data gathered during the focus group session. With a traditional focus group study, the data to be analysed is in the form of transcripts. This can be extremely daunting for a novice or even a skilled researcher. However, in my proposed adaption, the RepGrid that is produced provides the researcher with an ideal platform to commence the analysis of the transcripts. I do appreciate that the researcher must first learn to conduct and analyse a RepGrid study; despite of this I believe that the demands on the researchers during and after the study are significantly less than that of a typical focus group study.

Moreover, the blended approach can also be interpreted as an extension/adaptation of the RepGrid approach. I should first clarify that the adaptation of the RedGrid technique I present here is not meant as a replacement of the classical approach. On the contrary, I still advocate the use of the classic approach in certain circumstances. I do, however, believe that blending the RepGrid technique with focus groups affords new opportunities for researchers to expose further insight, while also validating the elicited constructs and exposing new constructs that may have been missed by the participants in the formal elicitation session. In the analysis of the discourse presented in the previous sections, I cited an example of scrutinizing the transcription for further meaning with respect to the constructs (Stimulating-Non-Stimulating). Here we saw that the transcriptions exposed further meaning that would not be possible if following the typical RepGrid approach.

I also used the example of examining the transcripts to better understand the construct (Sociable – Isolating). Here we see that the transcripts revealed important information that may not have being picked-up during a typical RepGrid study. Apart from the fact that the nature of an individual interview may not elicit constructs such as sociable or isolating, the discourse presented earlier revealed that the participants seemed to ascribe this attribute to the interface and its environment, and not to the representation modality. When designing the modal interfaces to be used in the study I purposefully created interfaces that offered only single-user interaction. However, during the study I observed the participants soon found ways of getting around the single-user interaction by squeezing more than two hands onto the haptic interface and using their hands and sheets of paper to reflect the light from the visual interface. Although on one occasion I observed participants attempting to share one headset, the predominant interaction with the audio interface was by one individual. I believe that the transcripts may have exposed a fault in the design of the interfaces and so we believe that this construct is in fact not a valid attribute of the modalities. This may have been misconstrued if this construct had been elicited during a typical RepGrid study.

The proposed blending of the methods also affords researchers an opportunity to uncover constructs that were not explicitly elicited during the study. In our analysis we presented the rationale for the inclusion of the construct (Harsh – Soothing) in the final RepGrid. It is, however, important to ask why this construct was not recorded during the group elicitation session. Initially I assumed that the group would have mentioned it, but may have felt that this construct was too similar to another i.e. (Comfortable – Uncomfortable). However, after a thorough examination of the transcript, at no point did any participant use either harsh or soothing when formalizing the constructs.

DESIGN Alongside exploring the potential of the blended approach to the RepGrid technique I also sought to expose design relevant insight about the data representations when analysing the data gathered during the studies. In the following I discuss some of the key design relevant findings that emerged during the blended approach.

Style over Function: In the analysis I presented a further exploration of the constructs (Aesthetic – Practical). The discourse indicates that the participants demonstrated less trust for the representation modality that they considered to be aesthetically pleasing, than those that they construed to be more practical or utilitarian. This may led us to question whether it is possible for a data representation to be beautiful and functional at the same time. This is an on-going concern for disciplines such as InfoVis, which is focused on balancing the communicative and aesthetic qualities of data representation.

Crossmodal Representation: I reported earlier that all groups demonstrated a sense of confusion that seemed to be caused by the mixing of modalities in the haptic interface. They perceived the strength of the vibration not to be at the same intensity as the sound it was emitting. It is clear from examining the transcripts that participant's expectations were not met when they placed their hands on the surface of the haptic interface. Although I do not classify the haptic interface as being one, this may highlight an important concern for the design of crossmodal interfaces in general. Cross-modal interfaces differ from multimodal ones in so far as they use more than one modality to represent the same data. My analysis indicates that when using more than one modality to represent the same data, these modalities must be of equal intensity, otherwise the user may misinterpret or ignore the expected data insight, as one participant pointed out "...the sound doesn't match the vibration."

6.3.3.12 *Summary of study*

In this section I validated the blending of two methods (focus group and RepGid) and compared it to a typical application of the RepGrid technique. I conducted this while investigating the role of modality in data representations. While maintaining the integrity of a classic RepGrid study, I incorporated a focus group session, which can be used to produce a multi-person

RepGrid that does not require the use of statistical measures and analysis. I demonstrated how the discourse in the focus group session, which surrounds the elicitation of the constructs could be used as a resource to reveal further meaning, to validate the inclusion of constructs, and to reveal new constructs that may have been missed by the participants during the formal elicitation session. I do however recognize some limitations to the proposed adaption. Firstly, although I state that by integrating a focus group into a RepGrid study it makes the procedure more efficient, the time saved while carrying out the study is easily lost when transcribing and analysing the obtained data. I also acknowledge and appreciate that the data collected may be more difficult to analyse than typical RepGrid data, which is normally processed using software applications. Notwithstanding these limitations, to my knowledge, since the inception of the RepGrid technique, no adaptation has been purported to produce rich qualitative data during a group session. I believe that the proposed blended approach has enough potential to equip a designer or researcher who wishes to better understand people's experience of designed artefacts while also revealing rich design relevant information.

6.4 CHAPTER SUMMARY

In this chapter, I introduced the Repertory Grid Technique as a useful method for collecting data on how people construe their experience of objects, people or events. While this method has been used by the HCI research community since the early 1980's, recently there has been a resurgence of interest in the technique. There are, however, some limitations with the traditional application of the technique, especially when following a phenomenological approach (as is my case). The main issues relate to the type of data that is gathered and the time and effort required to collect this data. To overcome these issues I presented a new approach to a RepGrid study, which involved blending it with a focus group session and analysing the data using quantitative methods. I formulated this adaptation to allow me to gather rich accounts of people's experience of representational modality. The results of this study showed clear differences between how people experienced the visual modality compared to the other two (haptic and auditory). The study also shed light on the nuances of experiencing representational modality, including the type of language used around is affected by the representational modality in use, certain modalities (visual) seem to inspire discussion about the causation, while others (haptic and auditory) relate to the affect of the data source, and certain modalities (haptic) seem to evoke more emotional responses than others (visual).

The final study presented in this chapter was conducted to valid and confirm the adaptation I tested in the first study. To accomplish this I conducted two side-by-side studies that investigated the same elements but one followed the typical RepGrid procedure, while the other utilise the blended approach. While aim of this study was also to investigate the affect of representational modality on data experience; its primary purpose was to compare the approaches (traditional verses blended). The results of this study indicate that, while the RepGrid's produced by each study are relatively similar, the blended approach is more efficient, less demanding and provides rich data (transcripts of sessions), which can be used to shed further light on the meaning of these constructs and to establish new constructs that may have been missed during the construct elicitation session.

This chapter has not only provided a first glimpse of my exploration into people's experience of representational modality, it has also laid down the foundation of my methodological approach. I the next chapter I will add another layer to this by introducing another method, before combining these approaches in Chapter 8 as I seek to establish a phenomenology of human data relations.

7 FROM PHENOMENOLOGY TO PSYCHO-PHENOMENOLOGY

If introspection is indeed a perception in the evocation of a past lived experience, then like any perception its fecundity and effectiveness will be commensurate with the categories which guide this perceptive activity.

— (Pierre Vermersch, 2009)

7.1 INTRODUCTION

In this chapter I introduce the Elicitation Interview technique as a method for gathering detailed and precise accounts of human experience. I argue that it can be applied in the context data perception to help understand how people experience and interpret representations as part of exploration and data analysis processes. In contrast to other qualitative methods the Elicitation Interview technique encourages participants to re-enact their experience while minimizing post-reasoning. This chapter describes the key characteristics of this interview technique and exemplifies how it can be applied to evaluate static data representations. This study illustrates what types of insights this technique can bring to the fore, for example, evidence for deep interpretation of visual representations, and the formation of interpretations and stories beyond the represented data. I discuss general evaluation scenarios where the Elicitation Interview technique may be beneficial and specify what needs to be considered when applying this technique[1] .

I begin this chapter by introducing the Elicitation Interview technique, which was originally designed by the psychologist Pierre Vermersch in an educational context. The Elicitation Interview is a retrospective interview technique, which was developed, in the phenomenological tradition known as psycho-phenomenology. Psycho phenomenological was conceived as a response to a perceived need for a more methodical approach to eliciting personal accounts of lived experience [294]. It focuses directly on practical ways of investigating experience through the act of reflection. Proposed as both an instrument of research as well as an approach to discovery, it is a non-inductive approach that elicits information through an in-depth interview about the experience at increased levels of "granularity". To accomplish this, the person being interviewed is guided back towards the re-enactment or re-living of the experience under investigation in order for them to provide an account, not only about the conscious acts that the interviewee is aware of but also those actions or cognitive processes that occur subconsciously. For instance, when driving a car you are completely focused on the road ahead of you but maybe not on your body position, which may be tense and uncomfortable. Known as pre-reflective consciousness, this aspect of experience is concealed by the absorption of attention in the objective or content of the experience (e.g. driving a car), and, as a result, is not instinctively described by people when recalling a past event. This human phenomenon is particularly evident when we engage in cognitive processes such as reading, writing, observing, listening, or analysing data, as we make use of processes that are precise, but which largely elude our consciousness [221].

1 Much of the content of this chapter has recently been described in [102]. In this article, co-authored by Dr. Uta Hinrichs and Prof. Dr. Eva Hornecker, we explored the potential of the technique in the context of InfoVis. In this chapter I extend this research to encompass a broader area of enquiry, including HCI. I wish to note that while this work was a collaboration, the input from the other researchers only related to incorporating an InfoVis perspective on the literature review (Dr. Hinrichs) and overseeing the findings of the study (Dr. Hinrichs and Prof. Hornecker). I contributed all other aspects of the study on my own, including learning the technique, conducting the literature review, designing the study, conducting the interviews and analysing the data.

To gain access to these concealed cognitive processes Vermersch suggested we guide the subject back to the experience through the practise of introspection [298], which is not so much a question of memory as it is a process of becoming aware of the pre-reflective dimension of the past [299]. The practise of guided introspection is a fundamental component of psycho-phenomenology as it allows researchers to "obtain descriptive verbalisations based on acts of introspection relating to a past lived experience" [299, p.22]. This is achieved through a particular style of interviewing (the Elicitation Interview technique), which includes questions about the (physical) context in which the experience took place and sensory aspects that accompanied it, the use of present tense during the interview to help the participant "re-enact" the experience, and encouraging detailed accounts of particular experiences through iterative questioning. The technique was specifically designed to capture rich and accurate accounts of people's experiences while minimizing biases introduced through post-rationalization [294].

The aim of this chapter is to demonstrate how the Elicitation Interview technique can a valuable addition to current evaluation techniques used to explore people's experience of data. Thus, I will present a study that reveals the techniques potential to capture subjective experiences with data representations. The findings show that the Elicitation Interview brings to the fore people's interpretations of individual representation aspects, and how they arrive at these interpretations by actively seeking for personal connections, rich meaning, and stories. This questions previous assumptions which claim that over- or miss-interpretation of data representations can be avoided through design [11]. While the Elicitation Interview does not provide direct design considerations, it can help to unearth problems or strengths of a design and point towards potential solutions. The key aspects that I address in this chapter are:

- *An introduction and description of the Elicitation Interview technique in the context of exploring people's experience of data.*
- *A study that exemplifies how the Elicitation Interview technique can be applied and what types of findings can be derived from it.*
- *Practical considerations of how to apply this technique to evaluate data representations.*

- *A discussion of how the technique can be applied to different evaluation scenarios and future research questions it brings to the fore.*

I wish to note that I do not propose the Elicitation Interview technique as a replacement of the existing methods described in Chapter 3. In many cases, depending on the research context, different techniques or a mixed-method approach is appropriate. However, if the objective is to gather rich accounts of experience that correspond to the actual lived experience, about the process of analysis and discovery, the Elicitation Interview can be a useful tool that allows researchers to gain access to the people's subjective experiences beyond their attitudes, judgements, and observations.

7.2 BACKGROUND

Before I introduce the Elicitation interview technique, let me digress for a moment to discuss my motivation for using it and the preparation I followed to learn how to apply the technique.

I was first introduced to the Elicitation Interview technique in the first months of my PhD. In the summer of 2011, I read Ann Light's paper "Transports of delight? What the experience of receiving (mobile) phone calls can tell us about design" [162]. This research used the Elicitation Interview technique (or the Explicitation technique, as it was known then) to form a detailed phenomenological account of people's experience of receiving telephone calls and draws on the concepts of Martin Heidegger, Andrew Feenberg, Don Ihde and Herbert Dreyfus. Reading this paper opened my eyes to a methodology that I envisaged would allow me to capture first-hand accounts of people's experience of data, which, in turn, may expose nuances that are difficult to reveal when using other commonly used methods, such as unstructured interviews or the think aloud protocol.

Shortly after reading this paper I carried out a review of all available literature on the technique, with the primary aim of learning how to use it. I soon discovered that most of the original material was only available in French (cf. [294][295][296][297] and there was little published in the English language. At this point I contacted Ann Light (author of Transports of delight? [162] to request further information on the technique. She informed me on the complex nature of the procedure and advised that I participate in a formal training programme before using it. However, she also told me that these training programmes were presently only offered in French. Two years later, in July 2013, I finally managed to enrol in a weeklong training programme in Paris, which was delivered in English by Prof. Dr. Claire Petitmengin (a onetime student of Pierre Vermersch) and one of the key proponents of the technique[2]. This training session was attended by fifteen participants, from eleven different countries, with a variety of backgrounds, including: psychotherapists, psychologists, sociologists, a meditation instructor, a social worker, a medical doctor and a textile design researcher. As part of this training we were taught about the history of the technique and the theory that underpins it. Prof. Petitmengin also provided us with practical guidance on how to conduct an Elicitation interview. Following the training session, and over a period of one-year, I conducted nearly one hundred practise interviews with colleagues, friends, family and students, before returning to Paris in 2014 to participate in another training session that was focused on analysing Elicitation interview data. In my experience, learning the procedure of the technique was invaluable, however, once I began to carry out formal interviews, the process of practising the technique (over and over again) proved to be vitally important. In the following sections I introduce the Elicitation interview technique, the knowledge I present here was gained through a combination of a comprehensive literature review, alongside Prof. Petitmengin's training sessions and the countless hours of conducting practise interviews.

7.3 THE ELICITATION INTERVIEW TECHNIQUE

The Elicitation Interview technique[3] is a form of retrospective interviewing that focuses on a particular experience (e.g., the experience of a data representation). In contrast to other interview techniques, it is based on iterative questioning where the participant is encouraged to describe their experience re-

2 see `http://www.microphenomenology.com` for more information on Prof. Dr. Claire Petitmengin and the Elicitation Interview technique
3 Translation from the French: "Entretien d'explicitation"

peatedly at finer levels of granularity. First conceived by Pierre Vermersch in the 1990's [294], the technique was initially used to help expert practitioners become aware of and describe the implicit part of their skills, and also to help people to work around cognitive blocks that may have impacted on their education. Since then the method has been used is a range of contexts, including pedagogy (cf. [175], management (cf. [239], medicine (cf. [222], therapy (cf. [132] and HCI (cf. [162]. Petitmengin have also used the technique to study intuitive experiences [220] and to investigate the structure of the auditory experience [223]. In the context of HCI the Elicitation Interview has been applied by Light and Wakeman [161] who used it to explore people's experience of entering text into a web interface, and, more recently, Obrist and colleagues captured accounts of people's verbalizations of a tactile experiences by conducting a series of elicitation interviews [209]. Although these examples are situated across a diverse range of disciplines, they all share a similar motivation: to elicit increasingly precise and detailed information about people's lived experience, whether this experience involves tactile perception, pedagogical tasks, listening to sounds, a moment of intuition, or interaction with technology.

In Chapter 3, I discussed commonly used evaluation techniques to investigate how people form insight and make discoveries, these included observation, diaries, questionnaires, the think-aloud protocol, and interviews. I also presented the rationale for employing these techniques and I eluded to the limitations of each. I argue that the Elicitation Interview technique can overcome some of these limitations by helping researchers to gain in-depth insights into people's approaches, processes, and subjective experiences of data analysis and interpretation of data representations while minimizing the problem of post-rationalization.

As the name suggests, the Elicitation Interview technique is a special form of interview. In the context of HCI, interviews are a common technique to gather opinions of participants after they have interacted with a system or to learn about existing work strategies to inform the design of a system. The data acquired during an interview can be rich in insights, going beyond potential pre-assumptions of the interviewer and superficial opinions of the participant. However, while interviews are frequently employed when evaluating systems, I found that the type and interview approach are rarely specified - researchers rarely explain how exactly the interview was conducted, beyond stating its duration and, sometimes, its "structured", "semi-structured", or "open-ended" character. Furthermore, when participants are recalling past events in an interview there is a risk that post-hoc rationalisation introduces details into the account that did not occur during the original experience. To counteract this, interviews can be conducted in combination with video recordings of participants' interactions [236]. Video-recall can increase the accuracy of the described experience while also reminding the interviewee of details that would have otherwise been forgotten. However, watching the event unfold on video can stimulate new thoughts that were not evident during the original experience. The Elicitation Interview technique differs from interview methods commonly applied in HCI by guiding the participant into a mental state where they come close to what they were actually thinking and feeling in-the-moment when they explored the system for the first time.

7.3.1 *Key Characteristics and Interview Phases*

Through my review of existing published literature on the Elicitation Interview technique [162] [161] [175] [209] [223] [220] and through my practical experience of using the technique, I have identified a number of characteristics of this technique that are important to consider when applying it.

An important issue to consider before using the Elicitation Interview technique is the type of experience to be investigated. It is essential that this is a singular lived experience. For instance, the technique can be used to help people describe their experience of a system or product situated precisely in space and time. However, the technique is less useful when trying to elicit a description of people's experience of systems or products in general as they tend to move away from describing the lived experience towards the expression of comments, justifications, explanations and beliefs.

Once the researcher has chosen a singular experience, the mode of questioning used throughout the interview is non-inductive and directive. Non-inductive, because the researcher/interviewer does not suggest any content, but asks "content-empty" questions such as: "*when you do this, what do you do exactly?*". This type of questioning enables the researcher to obtain precise descriptions without imposing their own presuppositions [224]. The Elicitation Interview is also directive, i.e., throughout the interview the researcher firmly maintains the participant's attention on a singular experience, and guides the exploration of these characteristics, down to the depth required [221].

Another important characteristic of the Elicitation interview is that it is based on an iterative approach, where key experiences identified in previous iterations are pursued in more depth in the next interview iteration. This stands in contrast to common interview techniques, which typically follow a linear flow of questions. Last but not least, the way the experience accounts are gathered during an Elicitation Interview aims at minimizing judgements or retrospective rationalization on the part of the participant. Asking questions starting with why encourages judgemental conditions and can change the mood of the interview. If a reason for an answer is needed, then questions for the how and what can help to clarify statements while not interrupting the recollection process or implying that a judgement is required from the participant. This is illustrated in the following extract, where the participant is being guided to speak about the moment when they finished reading the data visualization. Note that they are not being asked why they finished but rather how they knew that they were finished:

Interviewer: *Could I just ask you finally: how do you know when you have ended? How do you know that you have completed?*
Participant: *Before I closed it down and I went on to something else, I felt that if somebody was to ask me about the graph that the graph told a bit of a story and it is a story that I would try to retell.*

The Elicitation technique follows a number of phases that are conducted in order. Some of these steps are revisited iteratively to elicit more details on certain experiences mentioned by the participant. Based on a literature review as well as my own experience of conducting Elicitation interviews, I derived a diagram that illustrates these phases (see Figure 36). I describe the key phases of the Elicitation Interview in detail in the following paragraphs.

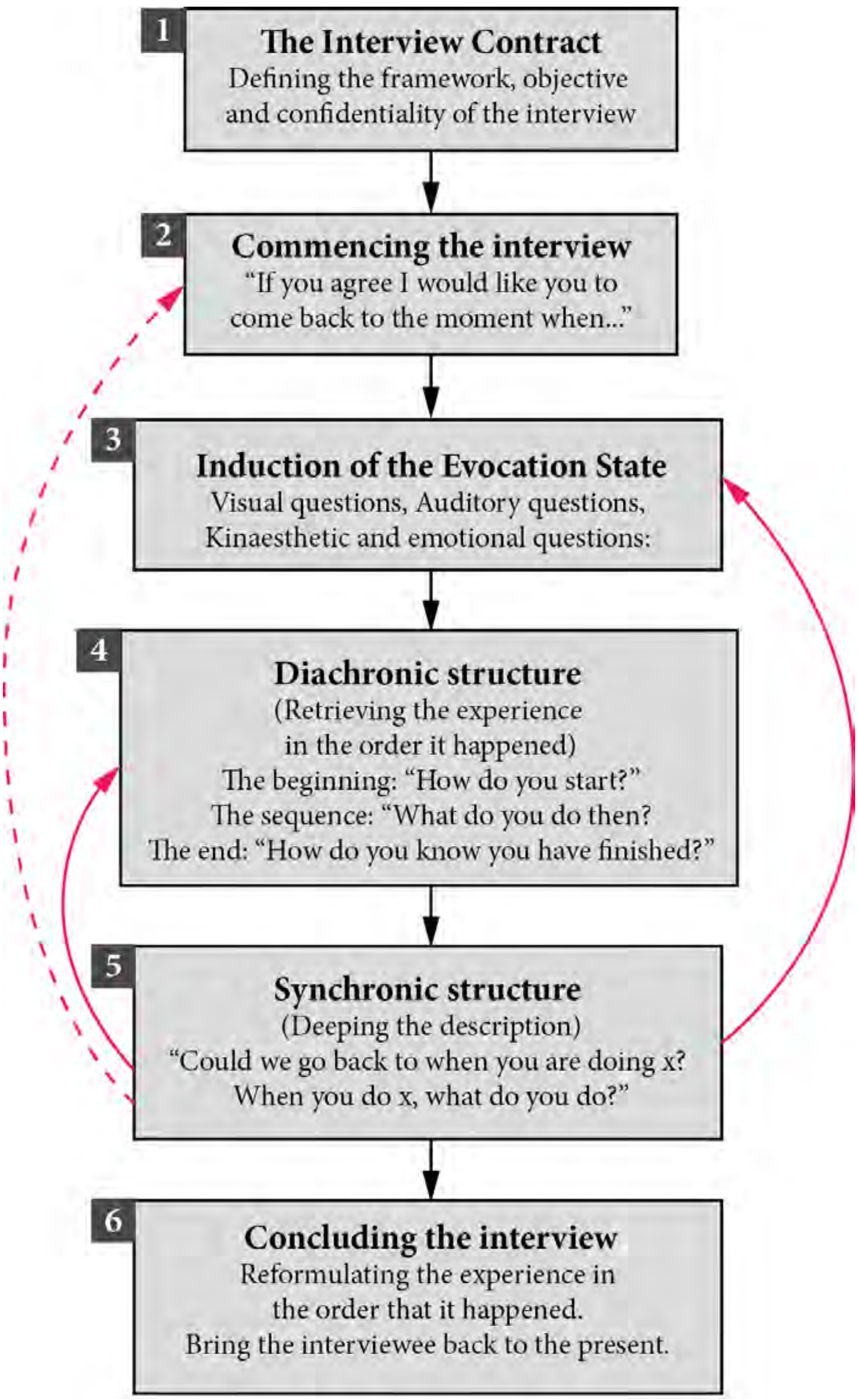


Figure 36: The phases of an Elicitation Interview typically follow in order but may require iterations between phase 3, 4, and 5. There may also be occasions when the interviewer needs to reaffirm the original contract of agreement with the interviewee.

7.3.1.1 *Agreement about Nature of Interview*

As it is common with studies and interviews in general, it is important that an agreement is established between the researcher and participant about the nature and format of the study before it starts. For an Elicitation Interview, this agreement differs from typical consent forms, in that the agreement makes the participant aware of the iterative nature of the interview that involves repeated and in-depth dwelling on certain experiences. To address this, the in-depth and iterative nature of the interview should be explained to the participant, and they should be made aware that they may withdraw from the interview at any stage if they are not fully comfortable with the nature of the interview. It may also be necessary, at certain points during the interview, for the researcher to re-iterate this agreement by requesting permission from the participant to probe a certain issue, for instance: *"If it is ok with you, I would like to return to the point when you first became aware of X. Could you tell me how you felt at this time."* Overall, questions and iterations should be performed in a gentle fashion that takes into account the probing nature of the interview.

7.3.1.2 *Induction of the Evocation State*

The goal of an Elicitation Interview is to collect a detailed account that describes the unfolding of an experience, while allowing the researcher to elicit further details about moments during this experience. To do this, the researcher guides the participant toward a state of introspection, which facilitates the (mental) re-enactment of the episode under investigation (e.g., a situation where the participant encountered a data visualization). This state is typically achieved by the researcher asking the participant to see, hear, and feel whatever was happening at the time of the original event or activity. The participant is encouraged to retrieve the episode as if it was happening now. The following example illustrates the process of guiding the participant back to the event by stimulating various sensory channels:

Interviewer: *Can we go back to that moment when you read the data visualization..., so when was this?*
Participant: *Ah... quarter past 7 this morning.*
Interviewer: *Ok and where are you?*
Participant: *At work.*

Interviewer: *At work ok, so are you at a desk?*
Participant: *I was at my desk, yeah.*
Interviewer: *Ok, and when you are at your desk, are you sitting or standing?*
Participant: *Sitting...*
Interviewer: *Are you sitting upright?*
Participant: *Yeah...*
Interviewer: *So are you very straight, is your back very straight or...?*
Participant: *It could be that I am leaning forward on the desk or I am sitting up right. [bends forward and back in the chair]*
Interviewer: *And are your hands on the table or are they on your body?*
Participant: *No, I kind of think that I have the feeling that I am leaning forward, more leaning onto my hands.*
Interviewer: *So you are leaning on your hands?*
Participant: *Yeah, underneath my chin. [mimics the pose she was in]*
Interviewer: *Ok, and you have the computer screen in front of you... Is there anything else on the desk besides the computer screen?*
Participant: *[long pause] Yeah, I have my keyboard, I have my drink bottle, I have my coffee.*
Interviewer: *Where is your coffee, on the left, or...?*
Participant: *On the left...*
Interviewer: *And is it strong coffee?*
Participant: *Yes, strong and freshly made.*
Interviewer: *Can you smell it, now?*
Participant: *Yes very much so...*

The purpose of using such evocative language is to guide the participant into a state of mind, coined by Vermersch as a state of evocation [298]. A state of evocation is recognizable by common cues familiar to most of us, for instance: when someone is recounting a past event to others, their gaze may drift off into empty space and glaze over. Alongside these non-verbal clues, there are also para-verbal clues that indicate whether a person is in a state of evocation or not, for example, the slowing of word flow and long pauses in the speech. There are also certain verbal cues that the interviewer can check for; paramount is the transition from the past to present tense. This is illustrated in the excerpt above, when the participant is asked about the contents of her desk. After a long pause she replies in the present tense: *"I have my keyboard, I have my drink bottle, I have my coffee."*

Verbal cues on their own may not confirm that a state of evocation has been reached. The researcher therefore has to be attentive to the participant demonstrating a combination of verbal, non-verbal, and para-verbal cues. To help reach this state it is advised that the participant sits in front of the researcher but slightly to the left or right. This enables them to stare into empty space without being obscured by the researcher.

To maintain a state of evocation in the participant throughout the interview, it helps to conduct the interview in the present tense. For instance, instead of asking the participant to recount their memory of the event, which may result in them replying in past tense: *"I did this...I did that..."*, the participant is invited to re-experience a situation as if they were there, for instance, by starting the interview with: *"You are in front of your computer, please tell me what you are seeing now."* This encourages the participant to be in-the-moment and to recall the experience as it was lived by them at that particular moment. In a state of evocation a participant can mentally re-enact the past experience to the point where this experience becomes highly prominent and present for them, and the experience of being interviewed fades into background [299]. The ability of the researcher to attain and maintain a state of evocation in the participant is crucial to the success of the interview. When the researcher recognizes that the participant is emerging from a state of evocation, the description of the experience can be reformulated, along with certain sensory details that may be revealed during the interview, in order to refresh the evocation of the past situation.

At the beginning of an Elicitation Interview, the participant is asked to think about a specific situation, in this case, a data visualization that they have encountered. It is this experience that forms the basis of the interview. Typically, the participant is then guided to reveal the diachronic dimension of the experience, that is, how the experience unfolded over time. For example, a participant may be asked questions such as: *"What is the first thing you do when you start reading the visualization?"*, *"What happens next?"*. The coloured blocks on the horizontal axis shown in Figure 37 illustrate the diachronic dimension of an experience where each blocks represents an individual episode of this experience. Note that such episodes differ in length and may also overlap with each other.

After the first description of the experience, which focuses on its diachronic (temporal) dimension, the participant is guided to reveal the synchronic structure, that is, the detailed characteristics and key aspects of the experience, which is made up of specific moments or episodes (see Figure 37). In this phase, the iterative nature of the interview comes into play: the participant is encouraged to repeatedly describe selected episodes of their experience at different levels of detail. In each iteration the granularity of these descriptions are refined. This phase involves questions such as: *"You already mentioned that you have done X, how do you do X?"* This iterative process of asking the participant to go back to specific moments and to reveal increasingly finer details about the experience is one of the unique characteristics of the Elicitation Interview technique, and it is what facilitates the capturing of rich accounts of experience that can then be analysed further.

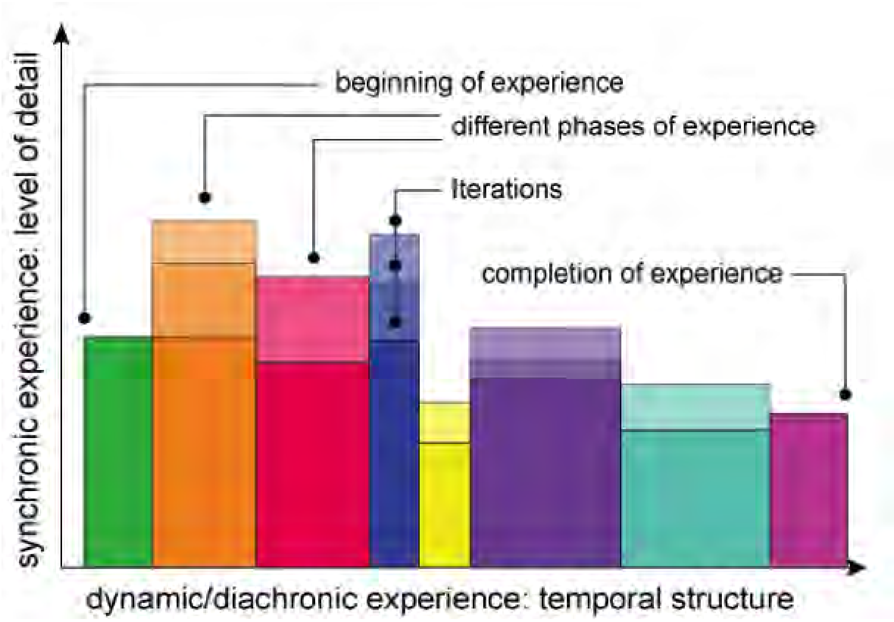


Figure 37: The iterative nature of the Elicitation Interview. The coloured blocks represent instances of a particular experience as they evolve over time (horizontal axis, diachronic dimension). These instances are re-visited during the Elicitation Interview to reveal their nature in more detail (synchronic dimension). The height of each block indicates how often an experience instance was re-visited.

Figure 36 illustrates the iterative nature of the Elicitation Interview through the height of blocks that depict the level of detail to which a certain experience episode is explored. Each transparent block of the same colour represent different interview iterations/levels of depth on an individual experience episode. The researcher may come back to certain episodes several times, focusing on the entire episodes or particular sub-episodes.

7.3.1.3 *Data Collection and Analysis*

Provided that the participant grants permission, it is recommended to both audio- and video-record the interview. Audio recordings are essential for a detailed transcription and analysis of the participant's statements. While video recordings are valuable to capture non-verbal and para-verbal cues, which can be an indicator of a participant reaching a state of evocation as described above, or bodily gestures that are used in the experience recollection.

7.3.1.4 *Reduction to Records of Pure Experience*

No matter which method is chosen for the analysis of data gathered from Elicitation Interviews, the analysis should always begin with reducing the transcripts down to records of pure experience. This is done by removing all retrospective comments, judgements and explanations by the participant. This process is illustrated in the following extract when the participant is asked to recall a moment of insight that he spoke about earlier in the interview. Note that the text in bold will be removed from the final transcript as the participant is clearly applying judgement, also you will see in this extract that the participant momentarily emerges from a state of evocation while making this judgement as he begins to stare directly at the research before returning his gaze into empty space.

Interviewer: *You mentioned already about a particular time when you had that light-bulb or 'ah ha' moment?*
Participant: *Yea.*
Interviewer: *and is there a sound associated with it, can you hear someone saying 'ah ha'?*
Participant: *yea in my head, (starting into space) I have some sort of, it's not that loud...but it would happen in my head, it would say 'ah ha' or 'there it is'... (Stares directly at researcher)* ***I think this is the same sound I hear every time I get something right or like***

that... *(Gazes into space again) I feel some sort of confirmation in my head when I realize that that is where the trend is..."*

I provide further details on the process of reduction later when I present the analysis of the data gathered during the study. Finally, once the transcripts have been reduced to pure experience they are sorted into the order in which the experience originally happened to help to identify how the experience unfolded over time (diachronic structure).

7.3.1.5 *Analysis Methods*

The method of analysing the gathered data depends on the focus of the research question. Qualitative analysis methods such as Content Analysis [145], Interpretative Phenomenological Analysis [266], and Grounded Theory [78] lend themselves well to the examination of data collected during an Elicitation Interview. Due to the richness of the collected accounts, Discourse Analysis [232] has been used widely in HCI to analyse Elicitation Interviews [162] [161] [209]. However, it is primarily concerned with scrutinizing the verbal dialogue gathered during an interview and does not address the non-verbal or para-verbal cues, which are important aspects of a participant's response during an Elicitation Interview.

In the Elicitation studies I present in this thesis, the method of analysis I use is based on Thematic Analysis–the same method I used in Chapter 5 to analyse a collection of multisensory data representations. The approach I use here involves a set of procedures designed to identify, examine, and report patterns (themes) that emerge from the interview transcripts. This method complements the non-inductive approach of the Elicitation Interview technique. Also, Thematic Analysis has a similar aim to phenomenology, in that it seeks to describe and understand the meanings that people give to their lived experiences and can help to identify patterns across qualitative data.

In the following section I describe the study I conducted to exemplify how the Elicitation Interview technique can be applied in the context investigating people's experience of data representation and what types of insights it can help reveal.

7.4 THE ELICITATION STUDY

The study described in this chapter was primarily conducted to illustrate how the Elicitation Interview technique can be used to gather accounts of people's experience with static data visualizations, and to highlight the type of insight it can provide about people's interpretation of data, how these experiences unfolded over time (diachronic structure) and how key moments manifest themselves as part of the exploration of the data representation (synchronic structure). In this example study, I sought to mainly explore (1) *how people interpret a data representation, and what thought processes are in place from the time they begin to (visually) explore it until they feel that they are finished*, and (2) *if there any similarities in the way that people describe their experience with exploring these data visualizations.*

To answer these questions I asked participants to interpret a data visualization and interviewed them about their experience using the Elicitation Interview technique. Participants were able to choose a visualization, from a collection of 18 that I made available one week before the interview was conducted (see three examples in Figure 38 and the full list is presented in Appendix A). All the visualizations included in the collection were from rebuttable sources, such as Governmental bodies, and contained topics that are relevant to a broad cross section of society. Examples include a line graph chart showing unemployment rates across the EU and in Ireland in particular (see Figure 38, A), the numbers and age distribution of emigrants coming to Ireland from 1987–2012 (see Figure 38, B), or the economic status of women in Ireland in 2011 (see Figure 38, C).

As this was the first time I used the technique in a formal study and the purpose of the was to explore and exemplify how the Elicitation Interview can be applied in the context of exploring people's experience of data representation, I choose to focus on static data visualization. Including interactivity adds a further layer of complexity that may obscure the discovery about interpretation. I do, however, acknowledge the importance of interactivity in the experience of dynamic data representations, and I explore this aspect in Chapter 8.

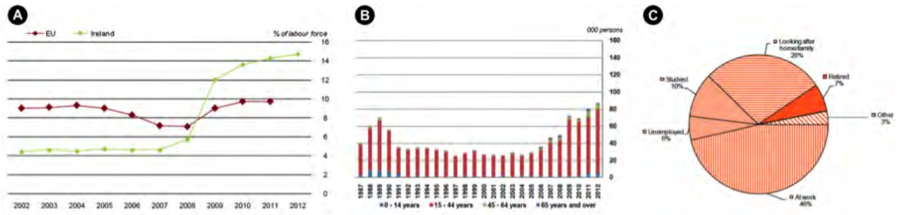


Figure 38: (A) Ireland and the EU: Unemployment rates, 2002–2012 (Central Statistics of Ireland (CSO) Ireland and Eurostat), (B) Ireland: Emigration 1987–2012 (CSO Ireland), (C) Principal economic status of Irish women, 2011 (CSO Ireland).

7.4.1 *Participants and Procedure*

Ten participants (four females) between 22 and 62 years (mean 36.7, SD 12.5) took part in the study. Participants had diverse professional backgrounds, including a business analyst, a solicitor, a retired accountant, a designer, a teacher, a web developer, a HCI researcher, a media producer, and two postgraduate media students.

Participants were first allowed to select one visualization and then given one week to look at and try to understand/analyse/interpret it until they felt that they had gathered as much information from it as they could. Following this, the interviews were conducted in a quiet location that was agreed upon between myself and the participant in the days leading up to the interview, such as, in the office space normally occupied by the participant.

I conducted all the interviews which followed the procedure described above (see Figure 36). Each interview commenced with an explanation of the purpose of the research and outlining the terms of the interview. The participants were then asked a series of questions that were aimed at guiding them back to the place and time when they first read the visualization. This included questions such as: *"When did you first read the visualization? Where were you at the time?"* The line of questioning then progressed to more sensory questions that encouraged participants to describe in detail their immediate environment when they originally read the visualization. This included questions such as: *"Are there any sounds in the room?"* or *"Please describe what else you see on your desk?"*. As mentioned earlier, the purpose of these types of questions is to guide the participant toward a state of evocation.

I then continued with questions that encouraged the participant to recall how the experience with the visualization unfolded (diachronic structure). During this phase I noted each occasion where the participant described particularly interesting experience episodes, such as when moments of new insight was discovered. Once the participant had recounted their experience in the order in which it originally occurred, I began to ask the participant to return to these moments of interest and to re-enact them in more detail, focusing on their thoughts and feelings at the time (synchronic structure).

Each interview lasted just under a half an hour on average and were video- and audio-recorded resulting in a total of just under five hours of material for transcription. To allow for further immersion in the data, I also transcribed each interview. Interview transcriptions also included gestures by the participant so that the non-verbal and para-verbal cues could be analysed alongside the verbal dialogue (see a full transcript of one interview in Appendix B).

7.4.2 *Data Analysis*

The transcribed interview recordings formed the basis for my data analysis that, as described earlier, followed the approach of Thematic Analysis [23], (Guest et al., 2012). This approach follows five discrete phases: (1) familiarization, (2) thematic coding, (3) extracting themes, (4) reviewing themes, and (5) defining and naming themes.

FAMILIARIZATION This phase involved reading the transcripts repeatedly to familiarize myself with the data even more. As with many qualitative study approaches, this is an essential phase of the data analysis as it allows the researcher to gain an overview of the data, which later enables the identification of thematic codes [14].

THEMATIC CODING I then derived an initial set of thematic codes from the data. Thematic codes can be defined as parts of the data relevant to the research questions and that capture the qualitative richness of the phenomenon [23]. This process involves line-by-line open-coding. After careful coding of all transcripts, I assigned 82 preliminary codes to 232 extracts. I then passed this analysis to my colleagues (Prof. Hornecker and Dr. Hinrichs) who validated these codes and minor adjustments were applied before the list of codes was finalized.

EXTRACTING, REVIEWING AND DEFINING THEMES The final three phases of analysis involved the extraction, review, and definition of themes that emerged from the thematic codes. Themes are broader than thematic codes in that they capture important details and meaningful patterns within the data in relation to the research question, and they apply across transcripts [24]. For reasons of rigor, all three of us sorted these codes into themes. I produced an initial set of themes, which was then reviewed and refined the second researcher (Prof. Hornecker), who then passed it on to the third researcher (Dr. Hinrichs). A total of nine core themes emerged during this phase. The final phase of the analysis involved defining and naming these themes, this involved identifying the essence of what each theme is about.

Table 11 shows these themes coupled with their definitions and the codes to which each theme corresponds. I also include illustrative quotes for each theme. The following sections describe some of these themes in more detail and illustrate the types of insights that are enabled by this interview technique.

7.4.3 *Capturing Experiences with Data Visualizations*

The themes that emerged from our analysis, as summarized in Table 11, provide examples of the types of insights that the Elicitation Interview technique can provide. These include a deep interpretation of individual visual components of the representations (Table 11: Theme A), participants trying to connect the data and topics represented in the visualization with events of their personal lives (Table 11: Theme B), participants experiencing their exploration of the visualization as a dialogue with the visualization itself and/or its creators (Table 11: Theme C), and participants contemplating about the meaning of the visualizations and the data represented on a higher level (Table 11: Theme D). In the following, I highlight four selected themes that exemplify different types of experiences that can be captured using the Elicitation Interview technique.

THEME (CODES)	DESCRIPTIONS	ILLUSTRATIVE QUOTES
(A) Interpretation Processes of Visuals Experiencing colour (9), Experiencing pattern (2), Shapes and lines (2)	Sense that the visual variables, including colour, shape, position and pattern has impacted on the interpretation and understanding of the visualization.	– *"It [the visualization] is using a different part of my brain, if I was using an excel sheet, I'd find it more boring and more serious, whereas with colours it's easier to see and to read out a pattern quickly."* [JC, Appendix A3]
(B) Active Seeking for Personal Connections Personalizing (6)	Forming a personal connection to the data source based on personal experiences, attempting to contextualize the data by placing themselves into the representation. In a way this has to do with making the visualization relevant for oneself.	– *"To make sure I understand the chart to think about my own situation and people I know in my surroundings."*[JS, Fig. 3C] – *"When I am seeing '2005', I am thinking where I was in 2005."* [JC, Appendix A3]

Continued on next page

Table 11 – continued from previous page

THEME (CODES)	DESCRIPTIONS	ILLUSTRATIVE QUOTES
(C) Presence of a Dialogue with the Data/Vis Creators Data communication (6), Use of "they" (5)	A social encounter with the data visualization? A presence of the quasi "other" referring to "it" and "they". This includes a sense of dialogue between the data and/or the creators of the visualization.	– *"It just took a couple of minutes of trying to absorb what the thing was saying and what the implications are for that personally."* [EC, Fig. 8.1B] – *"I think, I knew what they were trying to tell me. The other stuff, I had to filter out."* [VF, Appendix A4]
(D) Finding Meaning Beyond the data (3), Empathy (2), More than numbers (2)	Looking or searching for the meaning of what is being presented in the visualization. Connecting to the data on an emotional level and empathizing with the data.	– *"When I am looking at the information, the information means something more than just a graph."* [EC, Fig. 8.1B] – *"I was looking toward, or maybe, beyond at what they were trying to communicate with the graph."* [MMC, Fig. 3A]
(E) Fulfilment Fulfilment (8) Completion (2), Achievement (2)	A feeling of completion and fulfilment, which may also involve as sense of achievement.	– *"Well, I have a feeling of completion, like that I have finished it that there is nothing else that I can get out of this."* [JC, Appendix A1] – *"It was at this time that I felt satisfied and I had achieved something."* [EC, Fig. 8.1B]

Continued on next page

Table 11 – continued from previous page

THEME (CODES)	DESCRIPTIONS	ILLUSTRATIVE QUOTES
(F) Absorbing the Data Absorption (2)	Sense of absorbing as much information from the visualization as is possible.	– *"It also felt like I was hungry before, but now I have eaten something and I feel full and I don't have any more appetite to eat anymore of this, I felt that, yeah it's enough."* [VM,Appendix A5]
(G) Sense of Understanding Understanding (5) Making sense (meaning) (5)	The moment when meaning has been formed, confirming that they understand the information communicated through the visualization.	– *"I felt that I had understood the figures, there was no need for me to look back at the figures again."* [MMC, Fig. 8.1A] - *"It made sense on a number of levels."* [BD, Fig. 8.1B]
(H) Asking "Why" Questioning (3) Internal reasoning (3)	Asking questions and seeking answers. The processes involved in reasoning and rationalizing about the data.	– *"I tried to come up with a reason why could it be so low [R: eh em] and that?s what I mean I reason in my own head."* [JS, Fig. 8.1C]
(I) Personal Data Affect Feelings (1), Affect (3), Positive feeling (1), Lack of trust (1)	The personal affect of the visualization, how does it make them feel. A sense that the representation has engendered positive or negative feelings and whether they trust what is being represented.	– *"I felt that I had understood it on an intellectual level and on a level that is more deeper where there are people you know that have been affected by what you are reading."* [MMC, Fig. 8.1A]

Continued on next page

Table 11 – continued from previous page

THEME (CODES)	DESCRIPTIONS	ILLUSTRATIVE QUOTES
(J) Using Previous Knowledge Contradicting expectations (5), Surprise (3), Confirming (1)	Meeting or contradicting expectations informed by previous knowledge of the topic, which may lead to a sense of surprise.	– *"that one kind of surprised me that it was a smaller percentage of housewives than I thought."* [DH, Fig. 8.1C]

Table 11: List of themes (in bold) and codes that emerged during the analysis of the transcripts. The numbers in the themes column refer to the number of participants who the codes were applied to.

7.4.3.1 *Deep Interpretation of Visuals*

The Elicitation Interviews led to numerous instances where participants commented on their interpretation of visual elements utilized in the representations (e.g., shape or colour) (Table 11: Theme A). At various stages of the interviews all participants spoke about the importance of colour to form meaning from the visualizations. In many cases it was the first visual variable that they studied to make sense of the visualization. This is illustrated in the following extract where the participant is recounting the first thing he did when reading the visualization:

"I look at the colours first, they are the first thing that catches my eye... so after I look at the colours, I look at the colour code, what's that called again? The key, that explains what the colours mean. And after that I looked at the plain text to figure out what it was all about from then on.", [JC, Appendix A1].

This process was also echoed by other participants. Interestingly one participants' statement suggests that interpreting the colours is a separate process from reading the visualization:

"The first thing I do is check the colours and lines before I start to read what it is all about just to get at the information quickly. There are some blue lines here and green ones here... [short pause, pointing

out in space] and then I start to read it.", [VM, Appendix A5].

I also found participants interpreting visual elements such as position and texture to help them making sense of the visualization. These attempts were sometimes successful, sometimes not. For example, one participant used the path of a line to interpret any trends in the data:

"I look for, what would you call it, maybe anomalies or inconsistencies in the line movement, that stood out because they are not following a symmetric pattern.", [JC, Appendix A3].

Another participant found the use of some visual elements impeded her from understanding the underlying information:

"The first thing I notice while looking at the data visualization is the confusing [appearance]. The kind of patterns of the data visualization so even before I even read the data itself I find the way that the patterns fitted together in the circle, in the pie chart... it looks a bit dizzy.", [JS, Fig 7.3C].

These statements illustrate that the interpretation of visual variables was often the first cognitive task they engaged in when starting to read the visualizations. This raised curiosity and led to initial insights, but was often also already connected to an emotional experience (indicated by expressions such as "confusing" and the feeling of "dizziness", as highlighted in the statement above). Interviews are typically utilized to explore the utility of the visualization and the effectiveness of the use of particular variables to represent the data in focus - statements similar to the above are therefore not unusual if we ask people how they understand and interpret a visualization. However, as I illustrate in the following paragraphs, the focus of the Elicitation interview technique on *in-the-moment* experiences and its iterative character can also trigger rich perspectives on people's experiences with simple data representations that go beyond what we can gather from traditional interview strategies.

7.4.3.2 *Revealing a Process of Personal Contextualization*

Six out of the ten participants revealed that they connected the data visualization to personal situations in their lives (Table 11: Theme B). This theme was derived from explicit references to personal circumstances in relation to the represented data. It is important to highlight that I did not prompt participants to comment on these personal perspectives, but these were revealed when I asked participants to go back to the situation in which they read the visualization, and to talk about what they thought and felt like at the time. For instance, participants used their own circumstances combined with those of their family or friends to contextualize aspects of the visualization. This is illustrated in the following statement when the participant describes his process of interpreting the data visualization shown in (Figure 38, A):

"Between 2007 and 2008 it jumped, and that would have been when I started college and then my father was out of work.", [MMC, Figure 38, A].

Personal references were also used to help make sense of the visualization and to verify that the presented topics were understood correctly:

"I start looking to make sure I understand the chart to think about my own situation and people I know in my surroundings.", [JS, Figure 38, C].

Another participant contemplated how the visualization applied to her own circumstances which prompted her to critically question the suitability of the data categories presented in the visualization:

"When I am looking through it, it is putting women into different classifications, and I was like: 'Oh, where would I fall?', and I see that I fall basically into several of them so I was saying: 'Do I actually fall into none of them?", [DH, Figure 38, C].

These examples not only show that participants used references to their personal life as part of their interpretation of the visualizations, but also that this active seeking of a personal connection to the represented data was useful when (1) reaffirming an understanding of the presented information, (2) contextualizing the information, and (3) critically contemplate about presented approaches and facts. I acknowledge that it is not clear whether these aspects would have occurred if the data visualization had little or no connection to participants' personal situations and experiences. However, some participant statements suggest that they would actively seek for personal connections to the data to better understand the visualization, even when the presented topic had little relevance to them personally. For example, one participant commented on a graph that shows Ireland's dependency on imported energy from 1990-2011:

"When I am seeing 2005, I am thinking 'Where I was in 2005?' or I am thinking where I was working in that particular year or a particular film that might have been out in that year.", [JC, Appendix A, A3].

Reminiscing his circumstances in 2005 did not directly help this participant to form meaning from the visualization, but it is integral to his process of generating meaning and personal relevance and to his general subjective experience of the visualization. Along these lines, one participant summarized:

"It is the things that are important to you that lets you connect with the graph. You know, 2008 was a big year for me, but whoever created the graph, 2008 may not have been so special. These things I see but no one else sees; they let you contextualize that graph so they are 'my graph' within their [the designer's] graph." [MMC, Figure 38, A].

7.4.3.3 *Presence of a Dialogue with the Data*

Reiterating on participant's process of reading and interpreting the visualizations, and on their experiences and emotional reactions as part of this process also revealed that participants sometimes felt like engaging in a form of dialogue with the data and/or with the creator(s) of the visualization (Table 11: Theme C). The following extract illustrates such a dialogue:

"It just took a couple of minutes of trying to absorb what the thing was saying and what the implications are for that personally.", [EC, Figure 38, B].

The expression "what the thing was saying" implies a form of communication. Again, this statement also illustrates participants' attempts to extract personal meaning from the visualization.

I found some variations of this "Dialogue with Data" theme. For instance, when talking about his experience with a bar graph that represents the number of young people in Ireland with a third-level education (see Appendix A, A1), one participant described engaging in a form of communication with the data representation, but this time the visualization seemed to be doing more than just saying; to him it appeared to try to explain something:

"I noticed that there was some kind of trend which was increasing over time, so I took that as being the information that it was trying to explain to me.", [CB Appendix A, A1].

Statements by another participant implied a more complex relationship to the data visualization. This participant described a sense of mistrust in the data that was being represented. Noticing irregularities in the trend he extracted from the graph triggered this mistrust:

"I tried to look at it very critically then—is it telling me the truth or is it not telling me the truth.", [MMC, Figure 38, A].

Interestingly, this participant never mentioned a sense of mistrust toward the creators of the graph. Instead, he directed this mistrust solely at the visualization itself.

Other participants referred to the creators of the graphs as they were trying to make sense of the data representation:

"I think, I knew what they were trying to tell me. The other stuff, I had to filter out, the age thing and the pink.", [VF, Appendix A, A4].

While there were aspects in the graph that did not make sense to her, she tried to extract the basic story, which she thought was intended by the designers of the graph.

7.4.3.4 *Finding Meaning Beyond the Data*

As described earlier, participants often referred to seeking personal connections within the data representations (Table 11: Theme B). I found that these personal connections sometimes resulted in rich interpretations that went beyond the data that was actually being presented in the visualizations (Table 11:

Theme D). This is illustrated in participants talking about the implications of the represented data:

"I thought of what is happening behind the graph, you know, how many people does this affect? Like, when Ireland is at 12%... Who are those 12%? To me this is just a figure, but to them this is their livelihood. That it is not just a graph; there is a lot more going on behind it.", [MMC, Figure 38, A].

Another participant echoes this emotive response when he was talking about his experience while reading the graph shown in (Figure 38, B) :

"When I saw the trend, and I understood what it is saying... Suddenly, then, there is a phase when I am looking at the information and the information means something more than just a graph.", [EC, Figure 38, B].

This participant expanded on this point further by explaining what he took from the graph, and how he will communicate the meaning that he formed to others:

"I am surprised at the fact that there were people actually emigrating from the country in much greater numbers than I thought, so that is what I am left with now, rather than the memory of the figures [numbers]... I felt that if somebody was to ask me about the graph, that the graph told a bit of a story and it is a story that I would try to retell.", [EC, Figure 38, B].

For some participants, this revelation of meaning beyond the data manifested itself in vivid pictures. One participant described literally seeing old people and families boarding aeroplanes in front of his "inner eye" while he was reading a bar graph representing the rate of emigration from Ireland (see Figure 38, B). Another participant described seeing a clear moving image of a woman working in the kitchen that manifested in her head while she was reading a pie chart representing the economic status of Irish women in 2011 (see Figure 38, C). These examples illustrate that even plain graphs and charts, intended or not, communicate rich stories that are triggered and influenced by the personal background, experiences, and attitudes that the person interpreting the visualizations brings into the analysis process.

The themes and statements described above illustrate the variety and depth of some personal experiences and interpretation processes of the provided data representations that I was able to gather through relatively brief (30 min.) Elicitation interviews. Again, I did not prompt participants to interpret their reading activity of the data visualizations in this personal way, but these aspects naturally came up when participants were prompted to "re-enact" the situation in which they read the visualizations for the first time. Along these lines, this vignette of findings shows how an Elicitation interview can bring to the fore personal experiences as they evolve during the reading and interpretation of a data visualization. While such findings may not directly point toward implications for design, I believe they shed light into how insights develop when reading a data representation.

7.5 DISCUSSION

In this section I critically discuss the Elicitation Interview as technique for studying personal experiences and how this technique can be applied in different research areas. I also outline the types of findings the technique can support in comparison to other qualitative methods. I end with a discussion on the practical considerations that need to be observed when using the Elicitation Interview to gather precise accounts of experiences.

7.5.1 *Insights about Design and Representation Aspects*

Although the Elicitation Interview technique has been successfully applied to gather specific design recommendations for interface design [161], its strength lies in its ability to facilitate the collection of data on how people think and feel while interacting with systems. In this way it can help investigate how insight is generated and discoveries occur during this process. A better understanding of how people experience systems on a personal level can inform the design process at least indirectly. The findings I present in this chapter, for instance, revealed that colour is an important visual variable that participants usually tried to actively decipher first. Remarks about visual variables and marks were common (Table 11: Theme A). Furthermore, the fact that some participants tried to take in the visualization as a whole first, before starting to decipher its meaning and focus on individual components shows that the overall impression of a visualization already influences people's subsequent interpretation and sense-making. Although I did not compare the Elicitation technique with other methods, I argue that there is evidence to show that these deep insights on the nuances of data interpretation would be difficult to uncover using other methods.

7.5.2 *Revealing Deep Experiences and Interpretation Processes*

In Chapter 3, I discussed the inherent difficulties in capturing episodes of experience. The evaluation methods most commonly used to capture these moments all have limitations, whether it is the introduction of post-hoc rationalisation or personal biases or the difficulty in capturing people's thought processes. I argue that these limitations are reduced or not apparent at all with the Elicitation technique and it offers researchers a tool to generate deeper understanding of how people experience and interpret systems and how insights and discoveries derive. This does not only include what types of discoveries are made, but also how people arrived at these, and how these insights fit into and are influenced by people's personal background and previous experiences. For example, the study presented here suggests that people actively construct personal connections while reading static data representations - even if these do not necessarily aim at visually projecting or triggering certain emotions or contextual connotations (Table 11: Theme B and Theme D). This finding, which would be difficult to identify through common interview techniques or other qualitative research methods, suggests a new perspective on the debate around the effects of visual embellishments in visualization design [11]: even a rather plainly designed visualization, such as those used in this study, may trigger vivid connections and imaginative thought processes that, in turn, may unfold to an interpretation or message that goes beyond the depicted data.

7.5.3 *Scenarios of Use*

When illustrating the key characteristics of an Elicitation Interview I highlighted the type of experience as a fundamental element to the successful application of the technique, however, deciding upon what singular experience to investigate depends on the context and purpose of the study. The procedure I followed in the study involved creating an experience by providing the interviewees with a choice of visualizations to read before the interview took place. The reason I offered the participants this amount of time was mainly due to practical concerns, as I wanted to be assured that they would have enough time to read the visualizations. Other studies have shown that the technique can be also be applied successfully over a shorter period of time, sometimes immediately before the interview [209]. An Elicitation Interview can also be used to investigate an experience that was not seeded by the researcher. In this the technique could be used to investigate moments such as when a system or product had a significant impact on a person life, to study and better understand the affect it had on people.

7.5.4 *Understanding Environments and Work Practises*

Studies that provide an understanding of people's work practises or activities in non-work related scenarios are important to estimate the (potential) role of systems in these contexts. They can help the derivation of design considerations and requirements. However, it can be difficult for people to formulate and describe processes that they engage in on an everyday basis. Certain activities, for example, those that are performed frequently may seem trivial and remain unreported. The Elicitation Interview, with its focus on guiding participants into a mental state where they re-enact certain experiences, can help to gather details not only about the types of activities people engage in, but also how these are conducted and how participants experience them.

7.5.5 *Data Analysis and Presentation of Results*

The analysis and presentation of findings gathered from an Elicitation Interview is similar to that of common qualitative methods such as interviews or video analysis. It is key to follow a rigorous qualitative approach, and the involvement of multiple coders in this process will help to verify themes that emerge from the data. When it comes to presenting the results of an Elicitation Interview, it is important to support and illustrate the argument with direct quotes from participants. Quantitative data in the form of, for example, the number of participants who discussed a particular topic, can help to enhance results. If ethical concerns allow this, the transcribed interview data can be made publicly available to allow other researchers to better comprehend the presented results and conduct follow-up studies. However, while the data collection and analysis process can be made as transparent as possible, it will be difficult to fully reproduce an Elicitation Interview, as with all qualitative research methods the particular in-situ study context and the in-the-moment connection between participant and the interviewer may bring some insights to the fore that will not come up otherwise. This is in the nature of qualitative studies and can be considered a limitation. However, it is such types of studies, which enables rich and direct accounts of participants' experiences that cannot be collected otherwise.

7.5.6 *The Elicitation Interview in Comparison*

The study I present in this chapter is the first to apply the Elicitation Interview in the context of evaluating people's experience of data representation and was primarily conducted to explore the potential of this technique. Future studies will have to investigate in more detail its strengths and limitations, in particular in comparison to other qualitative evaluation techniques, such as think-aloud protocols, regular post-session interviews, or video-guided interviews. To this point I can only speculate that the Elicitation Interview technique can be advantageous over think-aloud protocols as it does not interfere with on-going thought processes during the activity in focus. Similarly, the themes we extracted from the Elicitation Interviews illustrate people's emotional reactions to data representations that common post-session interviews are unlikely to capture. It is the iterative character of the Elicitation Interview that enables a focus on "in-the-moment" experiences that are grounded in sensory aspects of the experience (e.g., smell, tactile, and auditory aspects) and, therefore, the collection of very personal experience accounts, such as the seeking of personal connections to reaffirm and contextualize the represented data, the experience of the data representation as a animated entity that "explains" information but may not "tell the truth", and the extraction of rich meaning and stories from charts and graphs, that go beyond the represented data, and that even manifest themselves in vivid pictures. It would be interesting to compare the Elicitation Interview to video-guided interview techniques that confront the participant with visual accounts of past activities or experiences. While I expect a higher risk of post-rationalization with such techniques, future studies will have to investigate these aspects in detail. While comparative studies of evaluation methods have been suggested previously (cf. [207], they are still rare.

7.5.7 *Practical Considerations*

The Elicitation Interview technique provides researchers with a valuable tool to capture experience and offers unique insights into cognitive processes involved. However, it should have become clear that special attention has to be paid to how the interview is conducted, and I have named a number of procedures that need to be applied (agreement with participant, interview in present tense, maintaining a state of evocation in the participant, see Figure 36). As well as the interview protocol, there are other issues that need to be considered when conducting an Elicitation interview, in the following I discuss each of these individually.

TRAINING Like all qualitative evaluation techniques, the Elicitation Interview requires training and a certain level of practise in order to apply it effectively. In particular, all interviewing requires experience to minimize the introduction of potential biases through leading questions [157]. Similarly, the nature of focus groups requires carefully trained researchers, who understand, for example, how to engage all participants in a topic and how to refocus conversations [200]. From a practise/training aspect, the Elicitation Interview is therefore not more time or resource intensive than other qualitative research methods, in some ways, it may be even be easier to gain practise. Much like most other qualitative methods, the Elicitation Interview technique rewards such efforts by producing a vast amount of rich data, which, and this, again, is a downside of all qualitative research approaches, has to be processed as part of a time consuming and, at times, qualitative analysis process.

CONTEXT While I imagine the Elicitation Interview technique to be valuable across the different research areas, including HCI, CSCW, InfoVis, and Visual Analytics, it has to be considered that the technique may not be applicable in all situations contexts. For instance, the Elicitation Interview requires time and is therefore not appropriate to gather feedback from people in an ad-hoc manner. Also, the selection of participants has to be carefully considered. Some people may feel uncomfortable with the style in which the Elicitation Interview is conducted, as it involves in-depth questions about emotional aspects of the experience. In extreme cases, such an interview can trigger unexpected or strong emotions in participants, which may require the discontinuation of the interview. For instance, during a pre-study I encountered a difficult situation where a participant became extremely distressed when recounting her experience of reading a visualization that evoked an emotional event in her life. This potential for strong emotional reactions has to be considered during the study design, in particular when recruiting participants. Also, participants have to be informed about this as a potential risk of their participation.

PHYSICAL SETTING The interview should take place in quiet location to allow the interviewee to concentrate on re-enacting the original experience. Although it is not a perquisite, it helps the process of re-enactment to conduct the interview in the same location as where the event or activity in focus took place. As mentioned already, the position of the interviewee is also an important criteria. To help the participant reach a state of evocation they should be seated at an angle to the interviewer, this allows them to gaze into space without looking straight at the interviewer.

PROPS Using the Elicitation Interview in pedagogical and therapeutic contexts has shown that using props during the interview may help to reach and maintain a state of evocation. For instance, holding an object such as a childhood toy during the interview may help a participant to re-enact a childhood event. It is not clear, however, how this practice transfers to other contexts. For example, providing the participant with the actual item under investigation, in our case the data visualization itself, may introduce bias or rationalization on the part of the interviewee. Future studies are required to investigate this aspect further.

INDIVIDUAL VS. GROUP INTERVIEWS To my knowledge the Elicitation Interview technique has only ever been used with individual participants; the in-depth and personal character of the interview technique does not seem to lend itself to group scenarios. However, in collaborative scenarios it could be interesting to explore experiences of group members individually using the Elicitation Interview technique and compare these findings with aspects that come out of regular interviews or focus groups with all members together. This points to the potential of the Elicitation Interview technique to be combined with other interview styles and evaluation methods, which, in general, is an interesting area for future research.

7.6 CHAPTER SUMMARY

In this chapter I introduced a psycho-phenomenological methodology known as the Elicitation Interview technique. This technique aims at capturing genuine accounts of people's lived experiences, including hedonistic, emotional and sensory aspects while minimizing potential biases through post-rationalization. Key characteristics include guiding the participant into a state of evocation, the capture of people's experiences at different levels of detail through iterative recall, and the use of present tense to maintain a state of evocation in the participant. I also presented a study that illustrates how the Elicitation Interview technique can be applied in different contexts and through a vignette of findings, I have shown what types of insights this technique can support. For instance, the findings illustrate how people seek for personal connections to the presented data to reaffirm and contextualize the information that is gained, and how these personal connections can also promote the critical contemplation of the presented approaches and facts. Furthermore, I have collected examples of people engaging in a personal dialogue with data representations that, evidently, can trigger rich emotions and interpretations that go beyond the presented data.

This chapter provides a first glimpse into the potential of this technique. In the next chapter I employ the technique again, this time I use it alongside the RepGrid technique to capture different levels of experience with interactive tangible data driven artefacts.

8

DELVING BELOW THE SURFACE

"I don't really feel any different, but I can hear the different"
(Participant 12)

8.1 INTRODUCTION

The purpose of this chapter is to build upon the theoretical, methodological and design knowledge and empirical findings presented in the preceding chapters. I sought to achieve this by designing an experiment that would examine a series of interactive data representations by delving deep into the experience people have with them. In Chapter 4, I showed how tangible data representations are a natural, fun and engaging way to represent scientific data for the general public. I followed this in Chapter 6 by showing how adapting and applying the Repertory Grid technique allows for the capture of rich design relevant insight. Using this method allowed me to uncover how representational modality affects the way people experience data. In Chapter 7, I introduced the Elicitation Interview technique and discussed its potential for evaluating people's experience of data representations. Using this technique to investigate people's experience with static data visualizations uncovered evidence for deep interpretation of visual representations, and the formation of interpretations and stories beyond the represented data. The aim now is to leverage the knowledge gained thus far to inform the design and evaluation of a set of tangible data representations, which will be used by participant's in their home or work life.

This chapter is divided into three phases, a design phase and two evaluation studies. The two studies I describe incorporate different methodologies (the Repertory Grid technique and the Elicitation interview technique), and were conducted consecutively. The overall rationale for employing this approach was to conduct a series of experiments that allows for the elicitation of accounts of experience at finer levels of granularity. I envisaged this approach as being like a journey down through the strata of data experience, with each level unearthing more than the previous, until I finally present holistic description of people's experience with tangible data representations. While I will discuss the findings of each of the studies separately, I conclude this chapter by collating both findings.

The first phase of this study incorporates the design and implementation of a series of data-driven prototypes that measure and represent real-time indoor air quality through different modalities (visual, auditory and haptic) . The motivation for creating these devices is twofold. First, the prototypes I designed in earlier chapters were either produced for specific public places (Chapter 4) or had limited functionality (Chapter 6). I now sought to create working prototypes that could be deployed and used in everyday scenarios, such as at home or work. I was also interested in exploring whether tangible interaction; combined with different representational modalities, affect the way people perceive data. At the same time, I wanted to provide people with a novel interface that makes them aware of their immediate environment through data representation. To achieve this, the approach I took was to create, what I term 'design probes': three objects that possess similar design features but differ in one aspect (here: representation modality). In phase two, I investigate these design probes by conducting a RepGrid study in form of a focus group session. The aim here was to gather accounts of people's immediate impression of using the prototypes and compare the differences between the three probes. The final phase comprises of a study that involves deploying the probes into the home and work life of twelve people over a period of one week. Following this, I interviewed each participant about his or her experience with the probes using the Elicitation interview technique. The purpose of this interview was to get the participant to recall a memorable episode of using the prototype. I specifically sought to focus on a moment where the participant became aware they had generated insight from the representation, and by using the elicitation technique I encouraged them to become aware of and talk about the cognitive and physical processes they used at the time of the original episode.

8.2 DESIGN APPROACH

A Design Probe approach involves creating multiple versions (in this case three) of a prototype that possess similar design features but differ in one aspect (here: representation modality). Because the representational modality is the only variation between the three prototypes, it allows me to focus the evaluation on drawing out comparisons without having other variables that may affect the findings of the study. The data source that is represented by the prototypes was also an important aspect. In the experiments I presented in earlier chapters, the data used was of little direct and immediate relevance to the participant's and included environmental, financial, economic, social and live data from deep space. For this study I sought to utilise data that would be more personally meaningful for the participant. The data I choose was real-time ambient indoor air quality (IAQ). Thus, I envisaged a series of prototypes that would provide people with a novel tool that heightens awareness of IAQ and encourages them to take action, such as opening a window to ventilate the space and improve their working or living environment without impacting on the energy consumption of the building.

When seeking to maintain a healthy lifestyle and working environment, an aspect we often overlook is the quality of the air around us. It is a common misconception that the quality of indoor air is higher than that of outdoor air. In fact, recent studies have shown that indoor levels of pollutants are two to five times higher than outdoor levels. This issue is exasperated further by the necessity to spend the majority of our daily lives indoors. One of the most important indicators of indoor air quality (IAQ) is the level of Carbon dioxide CO_2 in the ambient environment.

8.2.1 *Design Process*

In the early stages of the design process I made a number of key decisions which resulting in a design criteria for the prototypes. First, the prototypes should be portable so they can be moved within an environment and shared by people who occupy this space. Also, I did not want the prototypes to be autonomous; instead, they should require explicit user-interaction to request the data, unlike people's role with ambient or peripheral dis-

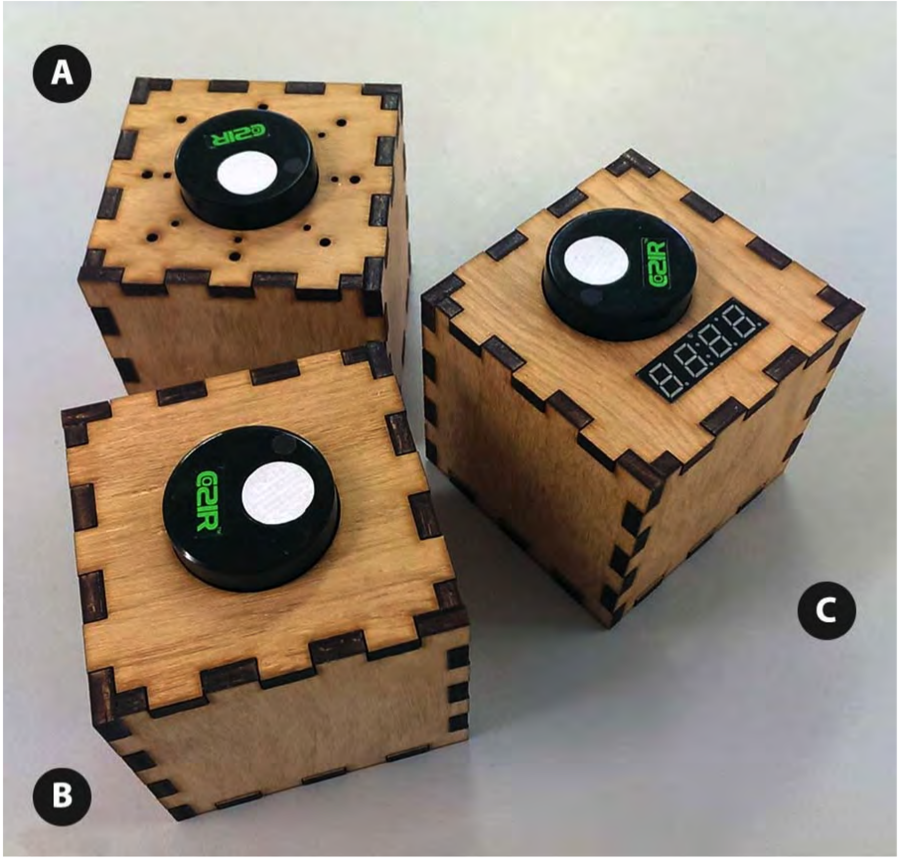


Figure 39: The three design probes (prototypes) used in the studies (A) Auditory display, (B) Haptic display, (C) Visual display.

plays [265]. I made this decision as I was interested in focusing the investigation on the specific moment people perceive the data representation. Requiring people to interact with the device to display the representation allows me to focus on the moment when people begin the process of data interpretation. Finally, I designed the physical shape of the prototypes as a cube that would fit comfortably into an adult hand and also so that they could be placed safely on a flat surface. This shape also offered us multiple surfaces to be exploited for user interaction.

A fundamental element of all data representations is the type of modality used to represent data. For reasons of consistency I choose to employ the same modalities used in the studies described in Chapter 6 – auditory, haptic, and visual. In the auditory display, I designed the data to be mapped to the frequency of a computer-generated sound, while the same data is represented through vibrations for the haptic display. In the early designs of the visual display I sought to use an equally abstract representations format, such as, for instance, colour or position. However, in the prototype I present here, I use a numerical-display, as I wanted to replicate the way IAQ is traditionally represented (numerical: PPM). The choice of wood as material for the cubes was influenced by the use of vibro–tactile feedback, since I found that natural materials evenly distribute vibrations better that synthetic materials, such as plastic. Finally, one of the most critical design aspects was the style of user-interaction employed to trigger the device to measure and represent the IAQ. I envisaged the mode of user-interaction should be natural, familiar and intuitive.

To assist the design of the interaction style I conducted an exploratory design workshop to observe how people naturally interacted with hand-held cubes. I invited 10 final year design students to participate, asking them to interact and play with the cubes in order to elicit a response from within the cube. I fitted each of the cubes with a mini-speaker, which I could remotely control. On occasions, when a participant interacted with the device I would remotely activate a sonic tone to be played through the speaker. This would signify to the user to try another form of interaction. This session lasted 30 minutes and was documented using video recording equipment. During the analysis of the tapes, I recorded numerous ways people interacted with the cubes, which included, shaking, knocking, spinning, flipping, dropping and sliding the cube onto a surface.

8.2.2 *Implementation*

Next, I produced three prototypes that require the user to shake to trigger the representation of the real-time ambient IAQ levels. I implemented the shaking gesture not only because the study showed it is a common gesture that appears familiar for most people, but I also found that it allowed the CO_2 sensor to sample air from a larger area. The actuators used to display the data are unique in each of the three prototypes. In the visual prototype (Figure 39, C) I incorporated a 4-digit, 7-segment display to represent the value in raw numerical format. In the haptic display (Figure 39, B) I used eight five-volt vibration motors fixed to the inside walls of the cube. Once triggered, the speed of the motors is mapped to the IAQ data e.g. 400PPM causes very weak vibration, while 1500PPM causes strong vibration and so on. The final display was auditory (Figure 39, A). In this cube I embedded a 50mm (diameter), 0.5W, 8–ohm speaker. The frequency played through this speaker is mapped to the value from the sensor; low value causes low frequency sounds and visa versa.

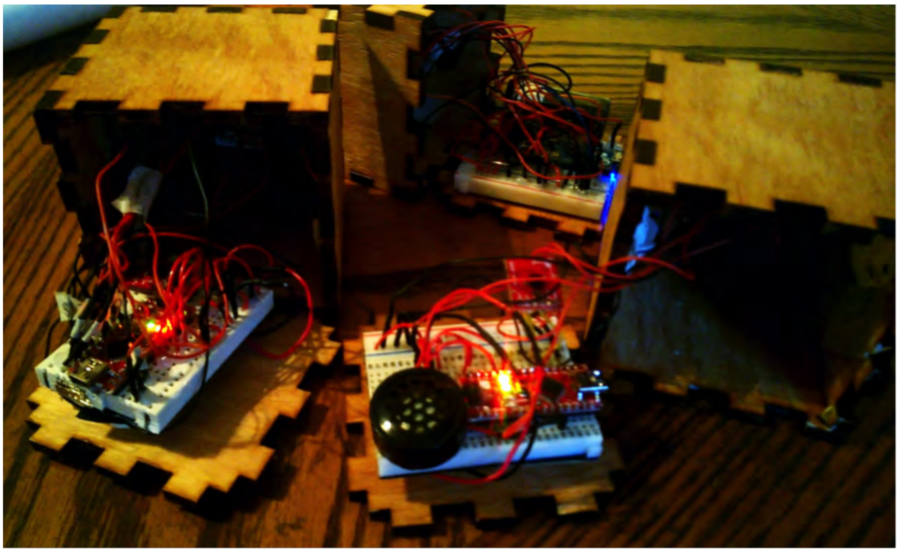


Figure 40: The working components of the design probes

Following a series of informal tests in our design lab, I observed a flaw in the system. Although people had little difficulty triggering the representation, the majority spoke about their difficulty in understanding its value. To address this issue I incorporated a legend into each prototype, so the user can map the current levels against two pre-defined levels of CO_2 (fresh air and poor indoor air quality). To trigger these values the user knocks on the side of the cube, one side for fresh air and the adjacent side for poor IAQ. I choose knocking as the design study also showed it to be a common and familiar gesture for participants. To capture the shaking gesture I used a triple-axis accelerometer, while for the knocking gesture, I fixed two 5cm circular piezo elements to inside faces of the cube. The real-time CO_2 levels are captured using a COZIR™ ambient sensor, which measures the CO_2 levels in the form of parts per million (PPM) and is suitable for battery powered applications and has a short warm-up period (1.2 seconds); other CO_2 sensors that I tested either consumed too much power or had long warm-up periods (> 5-seconds).

8.3 EVALUATION

The evaluation of the prototypes was conducted over two separate studies. The first was conducted in the lab with twelve participants, and used the Repertory Grid technique to elicit descriptions of participant's experience of each probe. The second involved a different set of 12 participants, who were asked to use one of the prototypes over the period of one week and were then interviewed using the Elicitation Technique to recall a memorable episode with the probe to provide a fine detailed account of this experience. In the following sections I describe the procedure and findings from both studies, to conclude I collate the findings and present a description of how representational modality affects people's experience of data.

8.3.1 *The RepGrid Study*

The aim of this phase is to explore people's immediate response to the probes, and to gather rich accounts about the meaning they attribute to their description of each. To accomplish this, the methodology I used is the RepGrid technique. The procedure followed is the same as described in Chapter 6, where I introduced the adaptation of the RepGrid technique to accommodate a focus group session. In the following I briefly reiterate on this procedure, before discussing the data gathered and the results of the study.

8.3.1.1 *Participants and Procedure*

Twelve participants took part in the RepGrid study (6 female) between 21 and 36 years (mean 23.2, SD 4.3). As the participants demographic and background was not critical to the outcome of the study I used a convenience sample, which was made up of final-year design students who were studying in my place of employment. I should note that I did not invite any student who I have taught as I did not want to risk bias in the results. The study was conducted in a large room where the three prototypes were placed on a table in the middle. The study commenced with a familiarization session, which involved introducing the three prototypes to the participants and then allowing time to interact with them. The participants were then divided into three groups of four, with each group spending a 20–minutes using a prototype before moving on to the next one, until all the groups had used each prototype. This session lasted just over one-hour and I was present at all times to answer any questions and to encourage the participants to openly discuss their experience of using the prototypes. The session was recorded using video- and audio-recording equipment with the transcriptions forming the principal data of the analysis.

Once the familiarization session was complete, I conducted a focus group session. The aim of this session was to establish a list of bipolar personal constructs that describe the participant's experience of the prototypes. Using the minimum-context triad technique, participants were asked to describe how two of the prototypes are similar (Convergent pole) but differ from the third (Divergent pole). Once the group reached consensus, the personal construct, as well as the position of each prototype on the bipolar dimension was recorded. In total fifteen personal constructs emerged and form the basis of the RepGrid (see Table 12). The personal constructs (PC) are presented in the order they were recorded during the focus group session, so PC 1 (Ambiguous - Precise) was the first to be established by the group. The RepGrid not only contains the list of personal constructs agreed by the group, but also includes indicators that show which end of the dimension each prototype should be placed. For example, PC 1 (Ambiguous - Precise) shows that the group agreed that the haptic and auditory prototype should be described as ambiguous, but are unlike the visual prototype, which they describe as being precise (see Table 12). In the following sections I trace the personal constructs back to the transcripts from the familiarization session, I focus on the four that were most prominently referenced in the transcripts as well as two that were not established during the focus group but were included in the final RepGrid following close examination of the transcripts. I then provide a description of the participant's experience of each modality by discussing the remaining personal constructs and presenting an extended extract from the transcripts that typifies the experience participant's had with each prototype.

		H	A	V	
PC1	Ambiguous	<	<	>	Precise
PC2	Difficult to interpret	<	<	>	Easy to interpret
PC3	Engaging	<	>	<	Non-engaging
PC4	Narrow	<	<	>	Wide
PC5	Sonic	<	<	>	Silent
PC6	Unfamiliar	<	<	>	Familiar
PC7	Passive	<	>	<	Harsh
PC8	Playful	<	<	>	Logical
PC9	Analogue	<	>	>	Digital
PC10	Tangible	<	>	>	Non-tangible
PC11	Interpretive	<	<	>	Informative
PC12	Invisible	<	<	>	Visible
PC13	Instinctual	<	<	>	Knowledgeable
***PC14**	Evocative	<	<	>	Straightforward
***PC15**	Mixes Senses	<	<	>	Single Modality

Table 12: The RepGrid produced during the focus group session, PC1-13 were agreed by the participant's, PC14&15 were added after analysis of the transcripts. The grid also includes arrows that point towards the end of the dimension each element should be placed. H: Haptic, A: Auditory, V: Visual.

8.3.1.2 *Analysis*

The aim of examining the transcripts of the familiarization session is threefold: (1) to trace the emergence of the personal constructs, (2) to examine the meaning participant's attribute to the constructs, (3) to search for further constructs that may not have been recorded in the focus group.

In the focus group session the participant's agreed that the haptic and auditory prototypes should be described as ambiguous and were unlike the visual prototype, which they described as being precise (Table 12, PC1). When I examined the transcripts I found numerous exchanges between participants that explain this decision further. For instance, in the following extract the group are using the audio prototype but are comparing it to the haptic and visual prototype:

Participant 3: *it is better than the haptic one, like when you are trying to understand where the shaky [real-time] one is*
Participant 2: *yea, but do you know that we are not getting an exact measurement, like we can not tell if it is exactly seventy or whatever in here, what if there was 3 or 4 distinct sounds, like a high sound and a low sound and then something that would be more precise in the middle*
Participant 3: *what would be more precise*
Participant 2: *I don't know, like something that you are more familiar with, like the numbers, we all know that one hundred is different from ninety, but how can you tell that in sounds.*

This exchange shows that participant's were aware that the representation of data through sound is more precise than through vibration, but neither is as clear as using numbers. However, in a further exchange participant's pointed out that while the use of numbers may be more precise than the other modalities, it might be still difficult to interpret the meaning associated with the numbers:

Participant 3: *...like so what if has changed from 100 to 90, what does that mean?*
Participant 4: *it might mean something is dangerous or you should get yourself out of the room*
Participant 2: *but if you saw it changing from 100 to 90 in numbers would that really tell you to leave the room*

There also seemed to be some confusion about the mapping of data to the sounds and vibrations. On occasions participants spoke about having difficulty generating meaning from the auditory and haptic representations. The following extract illustrates this and was captured when the group were using the auditory prototype:

Participant 7: *The shaking gives you the reading for the room so you know if it is really low or really high, or if the carbon dioxide levels are high then you know that you need to do something*
Participant 8: *but if it is low frequency then does that mean that it is low levels? and if it is high frequency then the levels are high?*
Participant 6: *do you think so?*
Participant 7: *yea it definitely is, I could hear that*
Participant 6: *but it should be the opposite way around*
Participant 5: *but it was the opposite way for me*

Participant 6: *that is really weird*

We can see here that some of the participants were unsure whether high frequency sounds represented high CO_2 levels or visa versa. This was also evident on occasions when they were using the haptic prototype, however, the transcripts did not reveal any ambiguity with the visual prototype. The words participants prominently used to describe the visual representation include: clear, precise, accurate, and exact. The following extract illustrates this point:

Participant 4: *this one is pretty much straightforward, there is no messing around with it a number is a number to me and all of us, isn't it?*
Participant 2: *yea I suppose, it is not going to confuse any of us*
Participant 1: *I am not sure, 940 isn't clear to me, I know it is pretty high but*
Participant 2: *that's all you need to know*
Participant 1: *yea I suppose*
Participant 3: *yea this one is pretty realistic*
Participant 4: *it is definitely the clearest one anyway*

It is interesting to note that Participant 1 stated "940 isn't clear to me" but also acknowledges that he is aware that it is a very high reading and when Participant 2 points out that this is all he needs to know to generate meaning or make a judgement, he quickly agrees with her.

While PC1 (*Ambiguous – Precise*) relates to participant's recognizing the representations as being inaccurate or accurate, PC2 (*Difficult to interpret - Easy to interpret*) reflects how easy, or not, the representations facilitated the generation meaning or understanding. The group agreed that the haptic and auditory prototypes were difficult to interpret, whereas the visual prototype was easy to interpret (Table 12, PC2). The following exchange was recorded when Participant 6 and 7 were using the audio prototype:

Participant 6: *but the meaning of the sounds is always hard to identify*
Participant 7: *the meaning is really important, otherwise it is just a music box*
Participant 6: *it's not much of a music box*

Participant 7: *ok a sound box*

We can see here that these participant's agreed if no meaning can be generated from a data representation (in this case a sonification) then the purpose of the prototype changes from a representation to something else. While it was evident in the transcripts that the participant's generated some level meaning from all the modalities, on many occasions participant's spoke about having difficulty in doing so with the auditory and haptic prototypes. When describing the haptic prototype participant 4 said: *"I think though if you are using this thing you would spend a lot of time saying 'is that stronger, is that weaker?"'* Participant 6 echoed this when using the auditory prototype: *"the tones are so abstract that you can't really make any sense of them"*. It was, however, quite the opposite with the visual prototype, participants had very little difficulty interpreting the data. Participant's spoke on many occasions about being immediately aware of changes in the data representation as well as being able to quickly interpret what these changes meant to them. The following extract illustrates this:

Participant 10: *it is good that you can see the difference; you know you can see the numbers*
Participant 11: *yea it is definitely more accurate, you are only guessing with the other ones [audio and haptic]*
Participant 12: *yea I found myself guessing all the time with the audio one, but with this one there is no need to guess, it is there in front of you, you don't have to work at all when you read it, 1237 is 1237 all the time, but a sound is harder to interpret, to understand, to get a grip on what it means.*

During the focus groups session the participants agreed to describe the haptic and visual modality as engaging but the auditory modality was described as non-engaging (Table 12, PC3). In regards to the haptic modality, the transcripts suggest that participants found this modality to be engaging because of the multimodal nature of the prototype. On several occasions participants spoke about the sounds emitted from the motor reinforce the sensation felt in their hands, so they were relying on two sensory channels instead of only one, which was the case with the other prototypes. On one occasion a participant remarked: *"I think the sound is reinforcing the vibration, and it is more engaging than when you just read off a screen"*. Although the visual prototype cannot be described as multimodal the participants still described it as being engaging. This time the reason for attributing this construct seems to be related to the participants' ability to perceive subtle changes in the representation. This may also be the reason why I observed participants shaking this prototype (requesting live data) more often than the other two. In the following extract the participants involved are using the visual modality, while talking about how they feel compelled to request live data:

Participant 1: *This is really addictive*
Participant 2: *Yea it is like a game, every time I shake it I get a different reading*
Participant 1: *That is because the levels are changing*
Participant 2: *But they should be changing for the others [prototypes] as well*
Participant 1: *Of course but you just can sense the changes, especially when the changes are small, with this you can see it change even if it only changes by one*
Participant 4: *It's like a compulsion, you would be constantly checking it*
Participant 1: *yea I could see myself constantly checking it*

Of the three, the auditory modality was the only one participant's described as non-engaging. I have also discussed how the haptic modality seemed to engage participants through its multimodal presentations of data and there is evidence in the transcripts to show that the heightened level of engagement with the visual modality was due to easy recognition of subtle changes. These, however, do not apply to the auditory modality as slight changes were difficult to interpret and only one sensory channel was required to perceive the data.

The participant's agreed that the auditory and haptic modality should be described as narrow, while the visual modality was experienced as being wide (Table 12, PC4). Upon inspection of the transcripts it became clear that the participant's made this determination based on their interpretation of the scope or range of data that each modality could accurately represent. The transcripts show that participant's were easily able to distinguish differences between any data point when represented through the visual modality. This, however, was not apparent when they used the haptic and auditory modality. Although there seemed to be little difficulty distinguishing large differences, for example *"you know a low tone and you know a high tone"* [Participant 2, Audio], all participants spoke about struggling with more subtle changes. The following extract highlights the difficulties two participant's had in distinguishing subtle changes when using the haptic prototype:

Participant 2: *actually yea, when you shake it does feel a bit higher, a small bit higher, I think, it is hard to tell maybe it is the way I am holding it, you tell me what you think (passes the cube to Participant 3)*
Participant 3: *hmm, I feel them very very similar, they are quite similar, maybe there is a difference but I can't tell through my hands*

In comparison to this, the following extract illustrates how the same participant's had no difficulty distinguishing subtle changes in the data when it was represented through the visual modality. Interestingly the participant's were not only aware of small changes but could also approximate the percentage of change over a given period of time.

Participant 2: *it's now 872, that has gone down, but it is hard to tell by the air, did you notice a big drop in the CO_2?*
Participant 4: *no, why would you? It hasn't changed that much, has it?*
Participant 3: *They have, the levels have dropped by 50% in the last 2 minutes and I haven't really noticed anything*
Participant 2: *maybe you have oxygenated it?*
Participant 3: *how about you raise it up in the air, is there more or less CO_2 up there*
Participant 4: *885*
Participant 2: *That's a little more, what about down on the ground?*
Participant 4: *it's 880 now.*

The personal constructs discussed already were established during the focus group session; however, the purpose of examining the transcripts is not only to add further meaning to the agreed constructs but also to extract new personal constructs that may have been missed during the focus group session. When I examined the transcripts I identified evidence of two personal constructs that were not already recorded by the participant's. These are PC 13: (Evocative – Straightforward) and

PC 14: (Mixes Senses -Single Modality).

Analysing the transcripts revealed that the participant's experience of the auditory and haptic modality evoked memories of past events and objects, whereas the visual modality did not and was much more straightforward. When perceiving the data through sound participants continuously compared it to other sounds they have heard in the past, including, an ambulance, siren, alarm, buzzing bees, dogs howling, to name but a few. The following extract not only illustrates the participant's recalling other sounds but they also use these sounds to better understand the purpose of the prototype:

Participant 6: *it sounds like Morse code*
Participant 8: *no, more like a dialup tone*
Participant 4: *yea*
Participant 6: *but Morse code is more like it cause that's a kind of communication as well, it could be words or numbers in sound*
Participant 8: *the dialup is numbers as well*
Participant 6: *is it?*
Participant 8: *well yea zeros and ones, it's the sound of data being transferred from one place to another, like this device.*

There were also numerous occasions where the participant's recalled past events that were similar to the sensation provided by the haptic modality. Sometimes this was used to help them make sense from the data, such as comparing weak vibrations to mobile phones and strong vibrations to *"travelling on a train"*; on this occasion the participant used this bi-polar dimension to judge where the real-time reading (vibration) was situated along this dimension. There were other occasions where participant's spoke more generally about communicating information through vibration. One group, when discussing how difficult it is to communicate precise information through vibration, provided the analogy of the vibrations of an alarm clock, and spoke about how it is alert you to wake up, but cannot tell you the precise time. Another group spoke more viscerally about their experience with vibrations:

Participant 4: *I hate vibration*
Participant 3: *do you?*
Participant 4: *yea there is something about it that reminds you of waking up or something*

Participant 2: *yea it does*
Participant 3: *yea you can feel the vibration telling you to wake up and get up now or even with computer games*
Participant 4: *when you get shot*
Participant 3: *yea when you get shot and the feedback when you are getting shot, that is what this reminds me of, it doesn't matter whether it is high or low, it feels bad to me, I get a bad feeling when I hear or feel it*
Participant 2: *it is never a good sign really when anything vibrates*
Participant 4: *no whenever something vibrates it is like I have to wake up or there is a phone call, well a phone call isn't always bad*
Participant 3: *yea but it only vibrates when your phone is on silent, so then you probably don't want to take a call, so it is still bad*
Participant 4: *that's true*
Participant 3: *vibration is always bad!*

These extracts show how participant's recall past events to help interpret data represented through the auditory and haptic modality. They also show how sometimes people's perception of these modalities can be unduly influenced by past experiences, such as the last extract where some of the participant's associated vibrations with a range of negative experiences. However, this was not the case with the visual modality. The transcripts show no evidence of this modality evoking past experiences, nor was there any evidence that showed participant's explicitly recalling past experience to help interpret the numbers. This is illustrated in the followed extract, which was recorded when the group were using the visual prototype:

Participant 4: *I think numbers are a good way of showing us what is going on*
Participant 2: *yea I suppose, it is the exact reading you are getting and there is no one else influencing it, you just look at the numbers and it should be clear*
Participant 3: *yea not like the sound or vibration, they are influenced by what you know already or what your feeling is about the sounds or vibration*
Participant 4: *this one is pretty much straightforward, there is no messing around with it a number is a number to me and all of us, isn't it?*
Participant 2: *yea I suppose, it is not going to confuse any of us*
Participant 1: *I am not sure, 940 isn't clear to me, I know it is pretty high but*

Participant 2: *that's all you need to know*
Participant 1: *yea I suppose*

Another personal construct that was not recorded during the focus group session, but was added to the RepGrid following an examination of the transcripts is PC 15: (*Mixes Senses - Single Modality*). There is evidence in the transcripts that shows participant's becoming aware of more than one human sense being used to perceive the haptic modality, however this was not the case with the auditory or visual modality. With regards to the haptic modality participant's spoke on occasions about focusing on the sounds emitted from the vibrations to perceive the data, this is illustrated here:

Participant 8: *I am paying more attention to the sound than the vibration, even though it was supposed to be felt, do you know what I mean?*
Participant 11: *yea*
Participant 10: *yea I wonder why that is? It's probably we are more used to sound*
Participant 8: *Yes, we are used to knowing the difference in sounds*

While there were other occasions where the multimodal characteristic of the haptic prototype interfered with participants' perception of the data, as illustrated here:

Participant 1: *try shaking it*
Participant 2: *I can hear and feel that*
Participant 1: *it feels like it is a whole different vibration, but I don't know if I can fully feel the difference by feeling it*
Participant 2: *actually yea, when you shake it, it does feel a bit higher, a pitch high speed even higher than high*
Participant 1: *Yea but the feeling and the sounds are not the same, it feels way stronger than it sounds.*

Although I did not find any evidence of participant's referring to the multimodal aspects of the other modalities, on occasions participant's spoke about wanting to augment the single modality with another to make the representation more engaging and easier to understand. For instance, when a group was talking about how the auditory prototype could incorporate numbers into the representation to make it easier to understand, participant 6 explained: *"we have the low and we have high* *and when it was just audio it is hard to understand where the real-time reading is, but if we had an accurate representation, like using numbers or colours, then we would know exactly what the middle one, 700, really means"*

REPRESENTATIONAL MODALITIES In the previous section I discussed five of the fifteen personal constructs that make up the RepGrid (Table 12). I now focus on the three representational modalities (haptic, visual and auditory), and use the constructs attributed to each modality and extended extracts from the transcripts to provide a description of the participant's experience of each.

Haptic Modality In the previous section I discussed five of these personal constructs (*Ambiguous, Engaging, Narrow, Difficult to interpret, Evocative,* and *Mixes Senses*), I now discuss the remaining dimensions attributed to the haptic modality (*Unfamiliar, Passive, Physical, Tangible, Playful, Interpretive, Sonic, Invisible* and *Instinctual*) to help provide a better understanding of the participant's experience with the haptic modality. During the focus groups session the participant's agreed that the haptic modality was unfamiliar to them. Although some spoke about other devises that use vibration, including, for instance mobile phones, these devises typically use vibration to generate an alert and the participants had little experience of it being used to communicate numerical data. The participants also choose to use passive as a word to describe their experience of the vibro–tactile feedback. While this may be due to wanting to describe the auditory modality as harsh, the transcripts revealed, on occasions, participant's describing the vibrations as being "subtle" and "not obtrusive", that it felt like a "tingle in my hand". The participant's also described the haptic modality as being physical, as they could imagine the mechanics involved in producing the vibrations and the vibrations also seemed to slightly alter depending on how they gripped the devise. Although each devise could be described as a tangible interface, the haptic modality was the only one that the participant's describe as being tangible. There were numerous occasions where participants talked about having to use their hands not only to trigger representations (shaking and knocking) but with the haptic modality they also needed their hands to perceive the data. They also spoke about grasping the devise in different ways alerted their perception of the data, for instance:

Participant 4: *I found that using only one hand doesn't work for me*
Participant 3: *yea you seem to have to use the two hands*
Participant 2: *one-handed for me worked, but it is hard to feel it with one, it feels better with two.*

The way participants grasped the prototype not only affected the perception of the vibration, but one participant spoke about his grasp influencing his understanding of the data: *"I would say that the more of your hands are against it the more you would understand it"*.

The RepGrid also shows that the participant's consider the haptic modality to be playful–a more informal way of communicating data. Some even spoke about the prototype being like a game and considered it to be *"fun to play with"*. Similarly, they agreed to describe it as being interpretive, instead of informative. The transcripts seem to show that what participant's meant by this is that the vibrations may be interpreted differently depending on the situation, such as, for instance, whether this persons has had a positive or negative experience with vibrations. The reason for describing the haptic modality as being sonic is due to the sounds being emitted from the vibration motors. Interestingly some participant's spoke about the haptic modality as being more 'sonic' than the auditory as the vibrations made the sound waves feel more "physical", "present" and "real". It is not surprising that the participant's described the haptic modality as being invisible. However, apart from occasions where participant's spoke about being able to "look around" when using the prototype, there is little evidence in the transcripts that adds further meaning to the invisibleness of this modality. The final construct used by the participants to describe their experience of the haptic modality is Instinctual. There were many occasions where participant's spoke about relying on their instinct to interpret the representational feedback. They also talked about, for instance, not being "taught this at school" and "just knowing without thinking". There is a strong sense that the participant's sometimes didn't understand or could not explain how they generated insight from the haptic representation. This is unlike the visual modality, where they could easily provide a rationale about how they know the number 400 is different from 500, on occasions they found it difficult to justify how one feeling felt different from another.

I present the following extract as an illustration of the participant's experience with the haptic modality. In this short exchange the participant's refer to the ambiguous nature of the representation, and while they also seem to struggle focusing on one modality when perceiving the data, the representation evokes memories from the past.

Participant 2: *can you feel the difference?*
Participant 3: *it is like a tiny bit weaker*
Participant 2: *it is the sound that you can feel more than the actual vibration*
Participant 1: *but if it is an object that you have to hold then the vibrations are better*
Participant 3: *the low is definitely a tiny bit weaker, I think the low is weaker, it kind of feels like a pump I have used before, like bump, bump, bump, bump*
Participant 1: *maybe you would feel it better then if it was pulsing more, like if it was high it would pump out 12 pulses*
Participant 4: *I almost feel like the low one is much stronger*
Participant 2: *that's what I thought*
Participant 1: *I find it hard to feel the difference, shake it there and see what you feel*

Auditory Modality Based on the constructs participant's attributed to each modality during the focus group session, the auditory and haptic modality are more similar than any other combination, sharing ten dimensions of the personal constructs. The auditory and visual share three while the haptic and visual share only two. Alongside those discussed already (*Ambiguous, Narrow, Difficult to interpret, Playful, Interpretive, Sonic, Evocative, Invisible, Single Modality* and *Instinctual*), the participant's agreed to describe their experience of the auditory modality as *Familiar, Non-engaging, Harsh, Digital,* and *Non-tangible*.

Although the RepGrid indicates participant's considered the auditory modality to be familiar, the transcripts seem to suggest that this only occurred when the frequency of the sounds were either very low or high. There were many other occasions where participant's suggested that the sounds between these were unfamiliar to them. For instance, when one group were having difficulty interpreting a sound, one participant spoke about *"it is not all the time we hear things like that in this way"*. On a number of other occasions participant's spoke about there wish for the sounds to be musical notes or even speech, they suggested that these familiar sounds would be easier to interpret than digitally generated tones.

The auditory modality was also the only one described as being harsh. When examining the transcripts I found many occasions where participant's were complaining about the "unpleasant" and "piercing" sounds being emitted from the prototype. This was mainly as a consequence of particularly high readings during the study, which was conducted indoors, with no natural ventilation and the room was occupied at all times by thirteen people. Although these harsh sounds did not seem to appeal to the participant's, there were occasions when they spoke about them acting as a good alert, for example:

Participant 12: *these sounds seem to alert you more than the vibration, these sounds are almost painful, something like it is trying to warm us, where the vibration was just like a sensation, it didn't really hurt me*
Participant 9: *the vibration was more subtle than this, subtle or maybe a bit boring, not boring, the numbers are boring, but the vibration didn't really alert or warn us*

Unlike the haptic modality, which was described as being physical, the auditory was described as being digital. The transcripts show that this judgement seemed to be based on the participant's perceiving the sounds as "artificial", "computer generated" and "manufactured". The reason for attributing the construct maybe due to the type of sound emitted from auditory prototype. This sound was a computer generated auditory signal, so it could be argued that this construct would not have been ascribed to the auditory modality of the sounds were more natural or organic.

They also considered this modality to be *non-tangible*. Although the transcripts show occasions where the participant's were aware of having to place the prototype close to their ear to hear the sounds, they did not consider this mode of perception to be tangible, as it did not require them to touch the prototype when perceiving the data.

The following extract typifies the participant's experience of the auditory modality. In this exchange the group are discussing the potential of augmenting the sounds with numbers, to produce and more accurate (less ambiguous) representation. They also reference how our perception of sounds maybe instinctual (for some); however, some sounds may be unpleasant to hear and could interfere with our understanding of them.

Participant 4: *but that would take away from what it is, its an auditory reading not numbers, so it would turn into a numbers thing then*
Participant 2: *but it would be an accurate representation of it then*
Participant 4: *but they are both accurate, it is just we see or hear them different*
Participant 2: *no, numbers are more accurate than sounds*
Participant 1: *what do you mean*
Participant 2: *we all know numbers, no matter where we live or what we do, but not everyone will understand the difference between two sounds*
Participant 1: *I think we would, sure don't we know that one sound is higher than another, or one sound is louder than another, we know loads about sounds*
Participant 2: *but we know more about numbers, we use them all the time to make calculations and the like, numbers are better, they are faster and more accurate*
Participant 3: *but sounds are universal, even animals would recognise the difference between 2 sounds or babies or young children who don't know how to read they all will know the difference between two sounds*
Participant 2: *yea but does a dog or a baby know that a high pitch sound means danger and a low one not*
Participant 3: *why does a high one mean danger?*
Participant 2: *well think about alarms, ambulances, fire alarms, they all are high for a reason, they alert us about danger*
Participant 4: *maybe it is because we associate them with danger, a baby may not because they haven't learned to yet*
Participant 3: *yea same as the numbers then, you have to learn how to use both of them*
Participant 2: *but not in the same way, you don't do sounds in school, well not in my school anyway, you do sounds on your own, you just pick them up along the way*

Participant 3: *but I would get sick if I heard that high pitch 12 times*
Participant 2: *but then you would know what it is then*
Participant 3: *but I think it is just like a general representation really, you know, like if it is too high it is going to sound like*
Participant 4: *yea you would notice*
Participant 3: *yea*

Visual Modality The RepGrid (Table 12) shows that ten of the fifteen dimensions of the personal constructs are unique to the visual modality. In the sections above I already discussed eleven of these (*Precise, Familiar, Engaging, Passive, Digital, Non-tangible, Wide, Easy to interpret, Informative, Straightforward* and *Single Modality*), I now discuss the remaining four (*Logical, Silent, Visible,* and *Knowledgeable*) and provide further insight into their meaning and show how they impress on the participant's experience of the visual modality.

To start with, two of these dimensions represent the participant's awareness of fundamental characteristics of this modality (*Silent* and *Visible*). Although it should be no surprise that these constructs would be used to describe the visual modality, the transcripts show that the main reason they were assigned was as a consequence of describing the other modalities as invisible and sonic. There were, however, some occasions where participants spoke about having to look at a display to perceive the data, which usually meant that more than one person could not share the experience. For instance, when one group were using the visual prototype the conversation was led by the person who was using the prototype and he was providing a commentary on the changes in the data representation:

Participant 12: *[holding the cube] It has gone up quite a bit.*
Participant 11: *What is it now?*
Participant 12: *745*
Participant 8: *what was it before*
Participant 11: *720 or maybe 710*
Participant 10: *and what's it now?*
Participant 12: *wait,... it's still 745, hold on, no it's now 749*
Participant 11: *show me, it's a pity we can't all see it*
Participant 12: *but I can tell you what it is*
Participant 9: *I'd prefer to see it myself*
Participant 12: *but that's the same as the vibrations, not all of us can*

feel it
Participant 9: *at the same time anyway*

I should note, in this extract, while the participant's seemed to be frustrated with not being able to share their direct experience of the representation, they acknowledge this occurs with the haptic modality also. Describing the visual modality as silent may be seen as obvious as considering the visual modality to be visible, and to some extent it says more about the participant's experience of the other modalities than it does about this one. Looking beyond these dimensions the two remaining (*Logical* and *Knowledgeable*) offer much more richer insight about the visual modality.

When the participant's agreed to describe their experience of the visual modality as being logical they distinguished it from the other two modalities, which they described as playful. I have already shown that participant's perceived the auditory and haptic modality to be a fun and enjoyable experience, this, however, was not the case for the visual modality. When the transcripts were examined they seemed to show that this perception related to the use of numbers instead of the visual modality in general. There were occasions where participant's described the use of numbers as being ubiquitous (*"numbers are everywhere, every gadget has them"*, [P12, Visual] and the most common form of raw data: (*"data is numbers, numbers is data, it's boring to convert them into something else"*, [P8, Visual]. There were also other occasions where participant's talked more positively about the use of numbers, for instance:

Participant 4: *I think numbers are a good way of showing us what is going on*
Participant 2: *yea I suppose it is the exact reading you are getting and there is no one else influencing it, you just look at the numbers and it should be clear*
Participant 3: *yea not like the sound or vibration, they are influenced by what you know already or what your feeling is about the sounds or vibration*

The *logical* dimension used to describe the visual modality was conceived by the participants in a positive and negative way. In some cases participant's enjoyed the easy access to information and knowledge that is offered by numbers, but this may also result in an overly familiar but underwhelming experience. Much like the auditory modality, the choice of constructs maybe related to the properties of the output and not the modality in general. For instance, it is not clear whether the participants would describe the visual modality as being logical if the representation used colours instead of numbers, as colours may require more interpretation and are less precise and logical than numbers.

In contrast to the other modalities, participants consider the visual modality to require some prior knowledge to interpret the data. They accepted that humans have an innate ability to recognise differences in sounds and vibrations, but visuals (in this case numbers) require some form of formal learning. I found numerous examples of participant's talking about how easy it is to interpret subtle differences when using the visual modality, however, on many occasions this recognition did not result is a better understanding of the data. For instance, when one of the groups were comparing the visual and auditory modality participant 11 explained: *"I like the way the last one [audio] has an alarming sense to it, but this one is just like 600, the numbers don't have any real meaning"*.

The following extract also references the logical and knowledgeable aspects of the visual modality, as well as other attributes, including, *informative*, *precise* and *familiar*:

Participant 2: *oh it is 708 now*
Participant 3: *yea I can definitely tell that that has changed*
Participant 4: *yea it is definitely the most informative one of them, or the most engaging*
Participant 1: *I think that one [audio] is the most engaging, maybe cause the sounds keep changing, where as with this you just know it when you see it you don't have to think very much, but the others you have to think more about the meaning*
Participant 3: *I think that one [vibration] is even more engaging because we had to really concentrate on what it was*
Participant 4: *I think, I guess, that if I had one of these [visual] I wouldn't find it very interesting, I think I would find it a bit too scientific, a bit boring, where those two [audio and vibration] are bit more playful*
Participant 2: *I would have though that we would like this one the best because it is the quickest one at giving you the correct informa-*

tion, like if you wanted to know quickly what the air was like
Participant 1: *yea if you wanted the information straight away*
Participant 2: *yea, like you get it instantly*

8.3.1.3 *Summary of Phase One*

In this phase I conducted a RepGrid study in form of a focus group to study participant's experience with the three design probes. The results of this echo some of the findings from Chapter 6 and show that the auditory and haptic modality produces a very similar experience, which is unlike that of the visual modality. The RepGrid produced during the focus group session contains fifteen bi-polar personal constructs, ten of whose dimensions are shared by the auditory and haptic modality. The discussion in this section first focused of five of the constructs that shows auditory and haptic representations can be ambiguous and are difficult to interpret, and while they sometimes evoke past events, they do not allow for the perception of subtle changes, the opposite in all these cases is true for the visual modality. Further discussion highlighted other aspects of the modalities, most notably: (1) the awareness of the tangible properties of the haptic modality and how grasping the interface may affect the interpretation of the data, (2) the capacity of the auditory and haptic modality to evoke memories of past events and to use these memories to interpret the data, (3) the multimodal nature of the haptic modality and how easily people switch between modalities when perceiving the data, and (4) the recognition that the visual modality requires prior knowledge but the other two modalities can be instinctively interpreted.

8.3.2 *The Elicitation Interview Study*

For the final phase of this project I invited another twelve people to participate in a study that involved giving each of them a prototype to use in their work or home life for a period of one week. At the end of the week each participant was interviewed about a memorable episode they had with the prototype. The purpose of this study was to gather accounts of this episode that would reveal fine-grained details about how they experienced the prototype. The transcripts of these interviews would then be analysed with the aim of finding patterns between people who used the same prototype as well as comparing the experience people have with the three representational modalities. In the following I first describe the procedure, before discussing the analysis of the data gathered before presenting the key findings of this study.

8.3.2.1 *Participants and Procedure*

Twelve participants (five males) between 19 and 45 years (mean 28.1, SD 9.2) agreed to take part in the study, none of who were involved in either of the two previous studies. Each participant had a diverse background, including a research assistant, a graphic designer, an accountant, a teacher, a computer technician, a multimedia producer, a professional athlete, a secretary, a university lecturer, a computer programmer, a computer science student and a stay at home parent. Before the study commenced, the participants were divided into three groups of four, and each group were assigned a different prototype (group 1: audio, group 2: visual, group 3: haptic). Over the course one week each participant was given one prototype to take home for up to one week. Before taking possession of the prototype I meet with them individually to explain the purpose of the study and also to demonstrate the use the prototype. They were also provided with my contact details if they had any difficulties with the prototypes. At the end of the week I collected the prototype from their home and I also conducted an Elicitation interview with them.

All interviews followed the same procedure outlined in Chapter 7 and started by agreeing on a memorable episode the participant had when using the prototype, once agreed this episode was used as the basis of the interview. As outlined in Chapter 7, an important aspect of the elicitation technique is to focus the interview around a singular experience that the participant has a clear memory of. The episodes chosen by the participant's were all different and varied from the first time using the prototype, a moment of insight, a moment of confusion, the last time they used the prototype etc. The interview started by asking the participant a series of questions that were aimed at guiding them back to the place and time of the agreed episode. This included questions such as:

"When did this episode happen? Where were you at the time?" The line of questioning that followed included sensory questions, similar to those described in Chapter 7, to help guide the participant toward a state of evocation.

Each of the twelve interviews lasted just under a half an hour on average and was video- and audio-recorded, resulting in a total of just less than six hours of material for transcription. The resulting transcripts included the verbal dialogue as well as non- and para-verbal cues, including, for instance: speech tempo, pauses, facial expressions, hand and body gestures and eye directions.

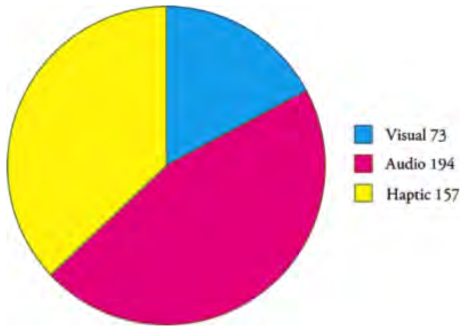


Figure 41: Distribution of codes across the three representational modalities (total number of codes: 424).

8.3.2.2 *Data Analysis*

The transcripts were analysed using Thematic Analysis, again following the same procedure described in Chapter 5 and Chapter 7. This involved five discrete phases: (1) familiarization, (2) thematic coding, (3) extracting themes, (4) reviewing themes, and (5) defining and naming themes. (Please see Chapter 7, for a detailed description of these phases). During the analysis 424 codes (72 unique) were applied to the transcripts (see Figure 41 for distribution of representational modality across these codes). Based on these codes, 16 themes emerged; Table 13 shows these themes alongside their definition, prominent codes and illustrative quotes. Before finalising the themes that would be included in further analysis I removed any theme that included 10 or less thematic codes. The reason I applied this rule was so that we could focus our enquiry on the most prominent themes that emerged from this part of the analysis.

Some themes that were removed include: Eagerness (6 codes), Talking about modalities (6), Confirming (5), Curiosity (4), Strategy (4), Focusing (3). The themes that did surpass the threshold include; demonstrating an awareness of their body during the interaction (Table 13, Theme A), the way we make sense out of data (Table 13, Theme B), the way we find meaning from the data (Table 13, Theme C), and the use of spatial and visual cues to assist sense-making and meaning-making (Table 13, Theme E & F). In the following I discuss these six themes at length as well highlighting issues that arise from the other ten themes.

THEME (CODES)	DESCRIPTION	ILLUSTRATIVE QUOTES
(A) Awareness of Body (59) Use of hands (14), Body position (10), Movement (11), Use of Body (7), Bodily Impact (5)	Demonstrating an awareness of body position during the interaction. Talking about using hands and other body parts as well as the describing the position of the data representation in relation to the body/body parts.	– *"It's the impact of your knuckle first of all, it is kind of giving you like a physical feedback to yourself, that your body had collided with something"* (Haptic) *"I put it up to my ear (mimics the pose) and I hear a high sound and when it is finished I shake the cube"* (Audio)

Continued on next page

Table 13 – continued from previous page

THEME (CODES)	DESCRIPTION	ILLUSTRATIVE QUOTES
(B) Making Sense (52) Making sense (22), Finding patterns (6), Making sense by listening (3), Processing data (5), Recording data (3), Using colour to make sense (3)	The process of making sense of the data, the different strategies employed to seek patterns in the data. This process happens prior to generating meaning from the data.	– *"I think that maybe the best air would be zero [r: ok] and 1200 would be the worst one so I didn't understand because the 762 made no sense to me"* (Visual) *"I shock it then to see what the conditions were like, so whether it was closer to the higher one or to low, but then when I did that, I realized that there was quite a different feeling between low and high"* (Haptic)
(C) Meaning Making (43) Making sense (22), Finding patterns (6), Making sense by listening (3), Processing data (5), Recording data (3), Using colour to make sense (3)	The process of making sense of the data, the different strategies employed to seek patterns in the data. This process happens prior to generating meaning from the data.	– *"I think that maybe the best air would be zero [r: ok] and 1200 would be the worst one so I didn't understand because the 762 made no sense to me"* (Visual) *"I shock it then to see what the conditions were like, so whether it was closer to the higher one or to low, but then when I did that, I realized that there was quite a different feeling between low and high"* (Haptic)

Continued on next page

Table 13 – continued from previous page

THEME (CODES)	DESCRIPTION	ILLUSTRATIVE QUOTES
(C) Meaning Making (43) Finding meaning (20), Generating insight (4), Judging (3), Understanding the data (5)	This process starts once her/she has made sense of the data. Generation of insight or understanding the data. It typically involves talking about consequence, reason or affect.	– *"yea it starts to vibrate really badly [r: ok] I remember thinking at this time that that smoke must be fair bad for you, the vibrations were so loud"* (Haptic) *"I shook it again I think it was like 520 something or 22 or maybe I was thinking that was kind of low then"* (Visual)
(D) Using Spatial Cues (35) Spatial Cues (19), Reasoning about space (6), Translating modalities (6), Spatial cues disappears (3), Using proximity (3),	Using spatial cues to help make sense or generate meaning from the data. These are always mental cues or props, which are perceived in 3D-space and may be in the form of abstract shapes, e.g. circle, cube etc. or real-world objects e.g. weighing scales, barometer etc.	– *"it is like a line, high is here (points left) and low is here (points right) and them I am saying is it up closer to high or is it closer to low (moves hands left then right)"* (Haptic) *"I have already placed them (holds two hands up (left and right)) I have already given them their positions, so I fell comfortable enough where they are and I use them as the foundations"* (Auditory)

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Table 13 – continued from previous page

THEME (CODES)	DESCRIPTION	ILLUSTRATIVE QUOTES
(E) Visual Cues (21) Use of visual cue (10), Using text (2), Swapping modalities (3) Visual Interface (2)	Using visual cues to help make sense or generate meaning from the data. A mental process that involves associating visual variables such as colour, text, 2D shapes etc. with data points	– *"I visualize, with audio feedback I am visualizing a frequency (points finger into space) so a peak, I am imagining a high peak (draws a peak with his finger) for a high sound and a lower more rounded waveform for a lower sound"* (Auditory)
(F) Comparing Data (26) Comparing (15), Comparing in mind (3), Comparing sounds (2), Comparing modalities (2)	Comparing one data with another. Recalling memories while simultaneously perceiving live data.	– *"I knocked on the low it made that high pitch sound [r: ok] and then I do it again to hear the low, I wanted to make sure I knew the difference between the two"* (Auditory) *"I was comparing with the morning time and the afternoon time"* (Visual)
(G) Aware of Technology (19) Checking operations (4), Confirming functionality (4), Exploring functionality (3), Aware of malfunction (2), Exploring the object (2)	Awareness of the technology that drives the data representation. Making reference to the functionality or being distracted by malfunction.	– *"I think I might of knocked on it too hard because it think I triggered the high feedback"* (Auditory) *"I wanted to see if it would go off without knocking"* (Auditory)

Continued on next page

Table 13 – continued from previous page

THEME (CODES)	DESCRIPTION	ILLUSTRATIVE QUOTES
(H) Confusion (25) Confusion (15), Difficulty (2)	Sense of confusion about the representation, having difficulty in making sense of the data or generating meaning.	– *"it was like a 500 when I shook it and then it was like 762 and I was just like 'I am doing this wrong' I don't know what I am doing"* (Visual)
(I) Fulfilment (17) Fulfilled (6), Satisfied (6), Complete (2)	A feeling of completion and fulfilment, which may also involve as sense of achievement.	– *"I knew then that I had got it, I knew that the readings were right and the air was bad so I left it at that"* (Haptic)
(J) Recall (16) Recalling Sounds (7), Recalling data (3), Recalling feelings (2)	Recalling memories of past data to compare the real-time values with. The process used to recall depends on the type of representational modality in use.	– *"I'm just trying to remember what high is sounding like so trying to replay that in my head (swirls finger in the air) and trying to compare it to the one that is actually playing at the same time"* (Haptic)
(K) Inner Reasoning (14) Inner thoughts (2), Voice of reason (2), Feelings (2)	Cognitive processes used to reason about making sense or meaning from the data.	– *"I have two sounds - one that is playing here (points to his ear), and the other is in my mind, I have a copy of that stored so I just recall it when I hear the new sound"* (Auditoey)
(L) Memorizing (14) Storing (6), Memory (4) Remembering (2)	Remembering or memorizing data, which may need to be recalled in the future.	– *"The next step is to take that [sound] in and give that a place in my mind, to use it to compare with the high"* (Auditory)

Continued on next page

Table 13 – continued from previous page

THEME (CODES)	DESCRIPTION	ILLUSTRATIVE QUOTES
(M) Using Previous Knowledge (13) Using past events (4), Memories (3), Recalling other objects (2), Using visualization techniques (2)	Referencing past events to help analyse the data. Meeting or contradicting expectations informed by previous knowledge of the topic, which may lead to a sense of surprise.	– *"It is kind of like a maths grid [r: ok] like one you have in primary school, when you have the little number line, where you have 400 on that end (raises left hand) and you have 1200 on that end (raise right hand)"* (Visual)
(N) Emotive Language (13) Concern (2), Annoyance (2), Emotion (2), Trust (2)	Use of emotional language when describing the representational output or meaning generated from it.	– *"It is like much stronger in my hands, I mean the sensation is much more harsh, what I feel is much harsher"* (Haptic)
(O) Aware of Surroundings (12) Conscious of noise (3), Conscious of being in a study (2), Conscious of environment (2)	Referencing events or objects in their surroundings during the interaction with the devise.	– *"It (pause 2 secs, stares into space) seemed to die a little bit, I wasn't sure if the battery was going dead or whether this was part of the experiment"* (Haptic) *"I don't know is it because of the cube or before doing it, I had already thought that the air here wasn't good at all"* (Visual)

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Table 13 – continued from previous page

THEME (CODES)	DESCRIPTION	ILLUSTRATIVE QUOTES
(P) Using Instinct (12) Instinct (5), No thinking (2), Using feelings (2)	Sense that the generation of insight happened instinctually.	– *"you just know, it's like I just know that this one (holds out hand) is much stronger that this one (points to chest) it must be a human thing but I know that it is different, I wasn't taught it I just feel it"* (Haptic)

Table 13: Themes (in bold) and codes that emerged during the analysis of the transcripts. The numbers in the themes column refer to the number of occurrences of the codes.

AN AWARENESS OF BODY Analysing the interview transcripts highlighted numerous instances where participants commented on their body or body parts when recalling their experience with the prototype (Table 13, Theme A: Awareness of Body). Although it would be quite normal for this topic to arise when interviewing people about their experience with interactive systems, especially tangible systems, I highlight specific moments of participant's becoming aware of their body when interpreting the data. Nine out of twelve participants spoke about the position and placement of their hands when using the prototypes. For obvious reasons, participants who used the haptic interface were more likely to mention their hands, but there were also some instances with the audio display. Alongside the interactions that are required to trigger the representations (knocking and shaking), participants also talked, on numerous occasions, about holding, touching, grasping, and feeling the prototypes. The following extract illustrates such a dialogue:

"I did the high value first, so I held it on the low side, with my left hand and knock with my right hand where it says high.", [MC, Audio].

There are also examples where participants talked about using their hands to perceive the data, for example, when asked how he knew there was a change in the data DM explained:

DM: *I just know*
Interviewer: *how do you know, please try to go back to that time when you know that you know and tell me how you know that you know, I am not trying to confuse you I would just like to know how you know you know.*
DM: *it is in my hands, it feels different, the sensation is much different (looks down at his hands)*
Interviewer: *how is it different?*
DM: *it is like much stronger in my hands, I mean the sensation is much more harsh, what I feel is much harsher.*

Participant's also talked about how they use their body to recall haptic sensations. On more than one occasion participants spoke about recalling these sensations from within their body, sometimes inside their head and others inside their chest or hands. When asked to explain and elaborate on this process KP said:

KP: *I feel the vibration and I think back to what it was like before*
Interviewer: *how do you think back?*
KP: *I have a feeling stored in my mind and I recall that when I want to compare it*
Interviewer: *so you recall the sensation from the morning [i: yea] so how do you recall this, how does this appear?*
KP: *it doesn't appear, I don't see it*
Interviewer: *ok so you don't see it, so how does it appear to you, if I ask you to try to recall it now could you?*
KP: *yes I am sure I can (pause 4 secs, stares into space) yea it is like it is in me (points to his chest)*
Interviewer: *in your chest? (mirrors the gesture)*
KP: *yea in, somewhere in there (points into chest again)*
Interviewer: *ok so if we go back to when you are standing with the cube in the air and you are feeling the sensation, do you feel it now?*
KP: *not at the same time, I feel the new sensation in my hands and the old one inside me.*

Another aspect of this theme is the way people talked about their body position when perceiving the data representation. There were many instances where participant's spoke about standing, sitting, walking and bending down, for example:

"I actually stood up and brought it over to the door because I wanted to see what the levels were outside, were they any different

outside." [DME, Audio].

I also found examples where participant's spoke about moving the prototype towards themselves to help with the perception of the data:

"I put it up to my ear so I could hear it better because am because the ambient noise in the room" [MC, Audio].

While the motivation here may be to block out external distractions when perceiving the data, the following extract illustrates how moving ones own body can also be a distraction when engaging in cognitive tasks, such as in this case perceiving data:

Interviewer: *ok so you shake it again*
MC: *yes I move it around a bit and I shake it*
Interviewer: *so you move it around and you are still shaking it, are you shaking it while it is vibrating?*
MC: *no I stop shaking while it is buzzing, it's hard to feel it when it is moving and I want to focus on the vibrations*
Interviewer: *so you focus on the vibrations [MC: yea] how do you focus on the vibrations*
MC: *I stay still, don't move and wait for them to finish*
Interviewer: *so you stay still*
MC: *yea and wait until I know what they mean, I mean until I get something from them*

The theme 'Awareness of Body' is made up of more codes than any other theme (59), this alone illustrates the significance participant's place on their body parts, position or posture when interpreting data. What is particularly revealing about these thematic codes is there distribution across the modalities, out of the 59 codes only 3 came from the transcripts of participant's using the visual representation, the remaining were distributed evenly across the audio (27) and haptic (29) representation. This may indicate that the auditory and haptic modality heightens people's awareness of their body when interacting with systems. In line with this, researchers in cognitive science have long since recognised the role hands play in cognitive tasks, such as thinking, remembering and perceiving [139]. Recent research in tangible computing and InfoVis also supports these theories and reports how people make extensive use of their hands to support the interpretation of data represented through physical forms [113] [123]. I believe what I have shown in this theme echoes the findings in this research, but also draws attention to other aspects, such as movement, proximity, and the internal (mental) body, all of which necessitate further investigation.

MAKING SENSE VERSES MEANING MAKING The generation of insight is one of the key objectives of data representation and it is often included in definitions of information visualization (cf. [34]). While the study of data insight is broadly covered in InfoVis (cf. [207]), there is still no agreed definition or empirical studies that have explored the conditions that support or foster data insight. A key reason for employing the Elicitation technique in this study was to shed light on the activities that surround this process, as it would allow me to gather detailed accounts by encouraging participants to focus on recalling what is commonly called an "a-ha" or "eureka" moment [169].

While many of the themes shown in Table 13 could be associated with the generation of data insight, I focus here on two in particular (Theme B: Making Sense & Theme C: Meaning Making). During the first round of coding the transcripts I used codes such as sense-making and meaning-making interchangeable. However, in subsequent iterations, after closer examination of the codes, I decided some instances should be coded as "Making Sense", while others should be "Meaning making". The reason being I identified cases where participant's recalled moments where they were attempting to interrogate or find patterns in the data and others where they were trying to contextualise the data or generate meaning from it. I delineate these themes as I consider making-sense to be a process, whereas meaning making is an outcome. They are, however, both key phases along the trajectory of generating data insight.

To elucidate this point further, let me, for a moment, focus on sense-making. All participants spoke on occasion about the processes involved in making sense of the data. Sometimes this involved trying to find patterns, for example:

"I try the shake again and move it about a few times until I find a pattern." [DM, Haptic], and *"I was trying to find a pattern, I was tying to (pause 1 sec) I was trying to find a pattern between the vibra-*

tion levels.”, [JC, Haptic].

There were also instances where participants talked about employing different strategies to compare the real-time representation with those in the legend. The following statement exemplifies this:

“after I listen to it I compare what I have listened to before, from the low and the high and then in my own mind I try to put the sound what I have just heard from the reading into a kind of graph or spectrum of where it is between the two points.” [CN, Audio].

It should be noted that CN has yet to form any meaning from the data at this point he is processing the representations before he makes any judgements. Making sense of the data can also involve checking or confirming that the readings are trustworthy, for example, here JC is not sure whether she has interpreted a false reading from the haptic prototype:

JC: *I try the shake again and move it about a few times until I find a pattern*
Interviewer: *a pattern?*
JC: *well sort of a pattern, its like I move the cube to a place where the smoke looks as bad and if the reading is pretty much the same then I know that the first reading was right. If I feel that it is different then the first reading could be wrong as well.*

What differentiates this statement from the previous is JC has already formed meaning, but she is not confirming whether the data was valid. It could be argued that the second interpretation does not yield any new meaning, instead it is used to endorse the insight that has been gathered already.

Although crossing the rubicon–from the mental processing of data to making judgements and forming meaning and knowledge–can happen very fast, there is a clear delineation between the two. This is illustrated in the following statement when JC describes a moment from her interaction with the haptic prototype:

JC: *I was trying to find a pattern, I was tying to (pause 1 sec) I was trying to find a pattern between the vibration levels*
Interviewer: *the high and the low?*

JC: *yea, between the high and the low [i: ok] and I was wondering then if am, if the room, because this room was, it was a little bit stuffy, it wouldn't have a lot of air going into it, I was wondering whether that was hampering the results that I was getting.*

We can see here that JC was seeking to find a pattern between different data streams (high and low values), and although she does not explicitly mention the moment she finds the pattern, she says *"I was wondering then if, am, if the room."* This, I believe, is the moment (the rubicon) where she has moved from making sense to making meaning from the data, as she begins to speak about external factors that may influence her judgement, as well as starting to make reference to the data source and the consequences of the readings.

I should also note that the distribution of modalities across these themes were relatively even, although the frequency of codes extracted from transcripts using the visual modality was still less than the others in Theme B: Making Sense (visual: 9, audio: 20, haptic: 23), Theme C: Meaning Making was more evenly spread (visual: 16, audio: 11, haptic: 16).

USING SPATIAL AND VISUAL CUES Seven out of the twelve participants revealed that they use mental cues to assist the processing of information, these either manifested in spatial or visual forms. While two of the participants acknowledged they were unaware of using these cues at the time of interacting with the prototypes, the others only became aware of these activities during the interview and the elicitation technique helped them to recall these cognitive activities in rich detail.

Regarding the use of spatial cues, five participants recalled the moment immediately after perceiving a data representation, where a mental marker-which represents the data would appear in front of them. Once they perceive the next data point, they then place another mental maker next to the previous one and they use the proximity between them to judge the difference between the two data representations. The following extract illustrates such a dialogue, when TH is recalling how he compares different audio representations:

TH: *I have one sound here (points his two hands out in front) and then the other one is here (moves his left hand to his left) they are on this bar and if they are the same they will be on top of each other but these are not, there is a bit of distance between them so they are different.*
Interviewer: *ok so do you see this bar?*
TH: *am (pause 2-seconds and stares into space) no I don't, it is there but I don't see it, its like I know there is something there but I don't see a picture of it but there are two sounds on it.*

It is interesting to note that TH acknowledges that he does not see the bar that he uses to place the markers on, although he is sure that it is there.

There were also similar instances with others using the haptic display, for instance, when KP spoke how he recalled and compared haptic representations:

"it is just like (2-second pauses)... its just how I placed it with my head maybe... I just place it closer to the high sound than to the low.", [KP, Audio].

MC also recalled using a similar strategy to make sense of the auditory representation:

"I see it as two sides, it is closer to the lower side or the higher side (waves his hand from left to right) and so there is a, it is like a pendulum, which way is it going towards".

It should be noted that only one participant used a similar strategy with the visual display. When recalling her experience of comparing three visual representations SH said:

"I am just thinking about (pause 3-seconds) am, where it would fall between the two on a number line, would it be closer to this end of the scale (draws line with hands and then moves both hands to the left) than it would be up here (moves right hand over to the right)".

These examples show how these participants translate the differences between the representations that they hear, feel and see into the spatial proximity of mental objects that appear (in their minds). So, for instances, the change of pitch in a sound is translated into the distance between the markers that represent the sounds. When probed further about these markers most described them as three-dimensional shapes, such as boxes, blocks or spheres. However, one participant (SH, visual) described them as being numbers, but not the same as those used on the prototype:

"they are numbers [interviewer: ok] yea they are characters (2-second pause) am actually what do you call it, I actually know (3-second pause, then draws the number in the air with her fingers) that kind of font, it was from my old maths book or something, [interviewer: ok] something like that".

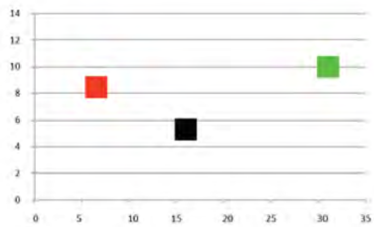
The transcripts also revealed a similar strategy that involved using visual cues to interpret the data. Unlike the previous example, which manifested in three–dimensional space, these tended to appear on a two-dimensional plane and included visual variables such as colour, pattern and shape. The following statement illustrates this:

"I visualize them, the audio feedback, I am visualizing it as a frequency (points finger into space) so a peak, I am imagining a high peak (draws a peak with his finger) for a high sound and a lower, more rounded waveform, for a lower sound". [MC, Audio].

In the following statement CN, who also used the auditory prototype, and describes a similar process but in greater detail:

CN: *so I characterise green with low and red with high*
Interviewer: *ok*
CN: *so I am seeing a square on a page, a green square (raises left hand) and a red square (raises right hand) on each side and then the reading, there is another square (points to the middle) in between those two*
Interviewer: *OK OK, and when you are comparing them, you say they are objects, they have colour, are they here in front of you or far away*
CN: *am (pause 3-seconds, stares into space) yea they are just like, I don't want to say a hallucination or like (laughs) its just like visualizing it in front of you (points to a space 20 cm away from his eyes)*
Interviewer: *ok and is it a clear image or is it fuzzy?*
CN: *(stares into space) its just am (pause 3-seconds) its just like, its just like a passive thing, its just like instant (clicks fingers) its not like something you are concentrating on, its just like a way of taking the information I have been given and just like trying to understand it.*

It should be noted that both of these participants described visuals that are similar to those used commonly in everyday data visualizations. CN incorporated simple coloured shapes, on what he implied was a printed page, and used the distance between these to gauge the differences or similarities between multiple data points. This description is very similar to the visualization technique: Scatter Plot (see Figure 42, A). MC recalled visuals that were more complex than CN's, albeit very similar to a visualization technique that is commonly used to represent audio frequencies, such as a Spectrograph (see Figure 42, B). Using this strategy may be due to the ubiquitous nature of these visualization techniques today, so even when people perceive data through an alternative modality – in this case sound – there seems to be a tendency to employ methods from traditional visualizations to make sense of the data.



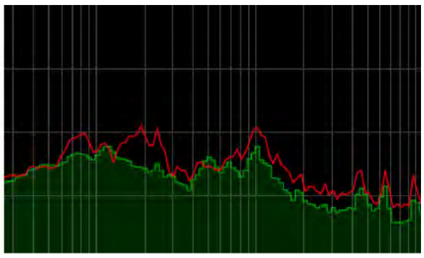


Figure 42: A: Scatter Plot technique. A: Spectrograph

8.3.2.3 *Other Thematic Observation*

The five themes discussed already represent the highest frequency of codes, incorporating nearly 50% of the total amount (210/424). There are, however, other themes that reveal interesting aspects about the participant's experience with the prototypes. Instead of reviewing these themes individually, in the following, I discuss topics that are derived from the remaining themes and then briefly address similar patterns that appear between this elicitation study and the one described in Chapter 7

COMPARING DATA The Themes B to D (see Table 12), which I discussed already, exposed aspects of insight generation, which ranged from making sense to finding meaning, and involved spatial and visual cues to help this process. The transcripts also revealed another aspect of insight generation that involved participants seeking to compare different data representations (Table 12, Theme F: Comparing Data). The codes attributed to this theme could have equally been applied to Theme B (Making Sense) or Theme C (Meaning Making); however, I decided that there were different enough to treat them independently and also this theme (Comparing Data) reveals aspects of data experience that I was unable to uncover in the previous study. In Chapter 7, I explored people's experience with static data visualizations. These visualizations did not require any interaction (apart from reading) and represented static archived data that was visible to the participants at all times. The prototypes used in this study represent real-time and archived data, however, participants could only perceive one data representation at a time. By employing this feature it required participants to recollect past representations to compare them with the present, and the elicitation technique offered me a procedure to gather detail accounts about how this was accomplished.

Earlier, I showed how participants used spatial and visual cues when comparing different data. The participants also revealed other ways of comparing data that were equally cognitive but did not involve using mental props. The following statement illustrates this:

"The next step is to take that in and give that a place in my mind, to use it to compare with the high, when I knock on the high side for the high reading.", [CN, Audio].

When probed to explain this process further and to explain how he compares the sound the is hearing with one from the past, CN stated:

"I put it to my ear (puts both hands over his ears) and I compare the two (makes swirling gesture with fingers) to try to find a medium in my head, what the difference is between the low and the high."

While this shows CN attempting to make sense of the data, there were also instances where participants compared different data in an attempt to form meaning:

"I compare the vibrations, then I know what they mean, its pretty fast really I am not even sure it lasts longer than a second, it's just

like that (clicks his fingers) then it is over.”, [DM, Haptic].

This statement not only shows DM generating meaning from comparing data, but it also demonstrates how fast this process felt. When probed to elucidate further on it DM had difficulties in recalling details about what was happening at the time and following multiple attempts he said:

“you just know, it’s like I just know that this one (holds out hand) is much stronger that this one (points to his chest) it must be a human thing but I know that it is different, I wasn’t taught it I just feel it.”

While the words he uses does not disclose much, apart from relying on instinct (see also Table 13, Theme P: Using Instinct), the hand gestures he using indicate that he is comparing an external sound (holds out hand), with a sound that is now internal (points to his chest).

DISTRIBUTION OF CODES The procedure I followed to analyse the data in this study is similar to the study described in Chapter 7, however, in this study I conducted an additional analytical phase to quantitatively explore the distribution of representational modalities across the themes. The reason for adding this phase here is that this study incorporated three prototypes and my intention was to compare people’s experience across the different modalities, whereas the primary aim of the previous study was to investigate the potential of the elicitation interview technique.

Figure 43 shows the make up of the sixteen themes, with the pie chart slices representing the proportion of thematic codes from each modality (audio, visual and haptic). Before focusing on the individual themes, it should be noted the distribution of codes across all the modalities represents a significant different between the visual modality and the other two. Figure 41 shows the visual modality accounting for less than half of the codes attributed to either of the other modalities (Visual: 73, Audio: 194, Haptic: 157). While it is difficult to provide a reason for this discrepancy, it could be surmised that the novelty of the other modalities may have simulated more in-depth recall by the participant that was not present with the relevant ubiquitous and

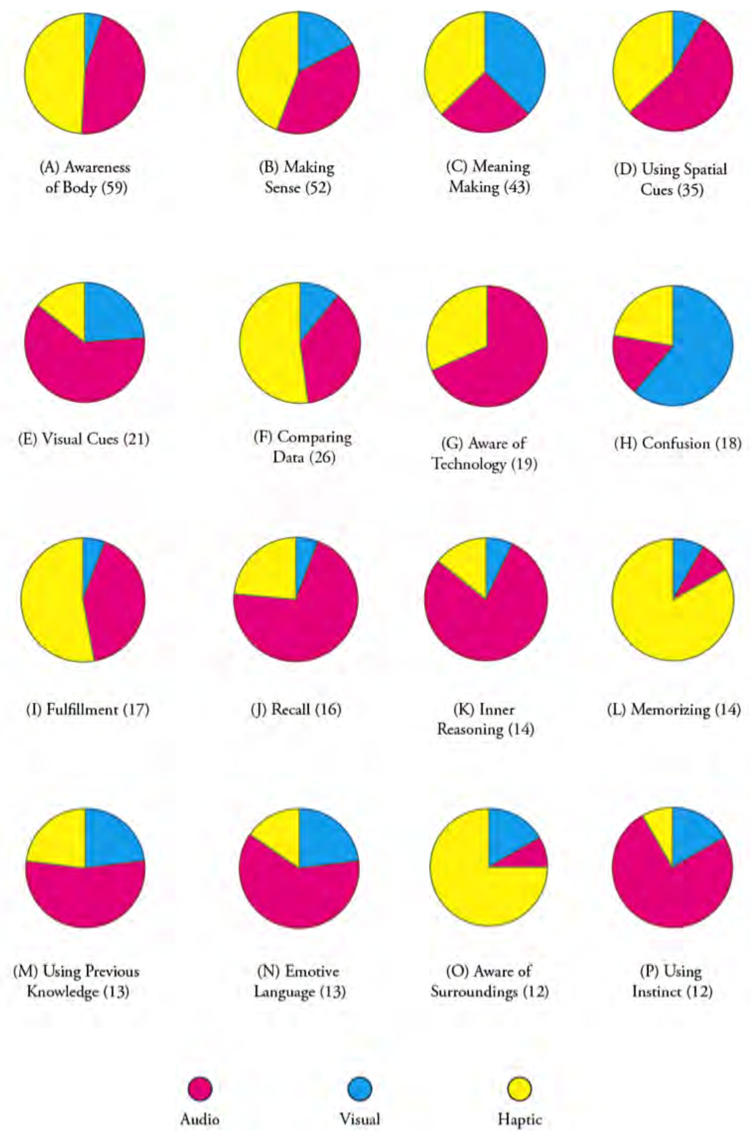


Figure 43: Distribution of representational modalities across the themes established during the analysis of the elicitation interview transcripts.

familiar nature of the visual modality.

While each pie chart represents noteworthy information about the themes, in the following I focus on specific themes that illustrate significant discrepancies. Before I focus on these individual anomalies, let me, for a brief moment, reiterate on two themes that demonstrate a relatively equal distribution of modalities. As mentioned already, Theme C (Meaning Making) and to a slightly lesser extent Theme B (Making Sense) incorporate equal amount of codes from all three modalities. These are the only two themes that display this characteristic. This may indicate that making sense and meaning is a fundamental process when interpreting data no matter what the representational modality is.

I now draw attention to certain variances that are visible in Figure 43. First is the distribution and instances of thematic codes from participants who used the visual modality. In particular, while Theme A (Awareness of Body) has only 3 from a total of 59 codes, Theme G (Awareness of Technology) does not include any. In my earlier discussion on body awareness, I described and defined this theme as demonstrating an awareness of body position during the interaction, as well as talking about using hands and other body parts as well as the describing the position of the data representation in relation to the body or body parts. The spread of modalities in this theme show these activities primarily occurred with the auditory and hapic prototype, whereas, apart from rare instances, the visual prototype does not seem to make people aware of their body when interacting with the prototype. This pattern maybe attributed to the manner in which people perceive hapic and auditory representations. While the haptic modality is perceived through direct contact with the body, to fully appreciate and perceive sounds, it is sometime required to bring the source closer to the persons ear. The following statement illustrates such a case:

"I put it up to my ear so I could hear it better because [of] the ambient noise in the room.", [MC, Audio].

Becoming aware of the technology used in the prototypes (Table 13, Theme G: Awareness of Technology) is associated primarily with experiencing auditory data representations (13 codes), however there were some instances with the haptic interface (6 codes). However, I did not observe participant's recalling such awareness when using the visual modality. Again this may be attributed to the ubiquitous nature of the visual interface. While participant's often demonstrated curiosity about the functionality of the auditory and haptic prototype, this was not evident with the visual display. Another factor that may have influence this anomaly is the way the modalities present the data to the participant's. On some occasions participants seemed to think that the haptic and audio had malfunctioned, as the sound was inaudible or the vibrations were too weak to feel. There was even occasions where participants differentiated between interacting with the prototype to gather data and interacting to check the functionality – *"I am not using it I am just checking it."*, [DM, Haptic]. This was not the case with the visual display, which displayed constant illumination at all times. These themes exemplify aspects of experiencing data that does not occur when perceiving visual representations. There is, however, one theme that is made of codes predominately retrieved from participants using the visual prototype. Throughout the transcribes there is 18 instances where participant's revealed feeling confused when interpreting the representation and 11 of these are be attributed to the visual modality. Participants also recalled becoming frustrated and annoyed with the prototype when they were unable to gain an understanding of the data. The following statement illustrates this point:

"I saw the numbers and I didn't know what they meant, I didn't even know if high was something or low was something, so I was confused all the time, does it mean that high all the time means it was too bad, I don't know." [AS, Visual].

The distribution of modalities in this theme is out of line with the rest, as it is the only one that the visual modality accounts for the majority of codes. This is compounded by the fact that it is the only theme that could be identified as being negative. By drawing attention to this issue I am not suggesting that visualizations have a higher propensity to cause confusion nor am I saying the other modalities are free from fault in this respect. The reasons for this could be explained as participant's being aware of a misunderstanding with the visual display but as the other modalities are more unusual, their confusion could be masked by their enthusiasm to interpret data through such novel interfaces.

Lastly, let me draw attention to the distribution of visual codes in Theme B: Making Sense verses Theme C: Making meaning (Table 13). Figure 43 shows that there are more occurrences of meaning-making than sense-making with the visual modality. I already discussed how the interpretation of data first starts with making sense and is followed by forming meaning from the representation. The distribution of visual codes seems to suggest that participants may skip the making sense phase and rely much less on cues (as this is the more familiar and more explicit modality).

The next representational modality that I focus on is auditory. In particular I will address themes that this modality accounts for a high majority of codes. Although the auditory modality is responsible for the highest proportion of codes in eight of the sixteen themes (D, E, G, J, K, M, N & P), I focus here of two themes (Table 13, Theme K: Inner Reasoning & Theme P: Using Instinct), as examples, and reason why this modality accounts for such a high percentage.

I found fourteen instances (codes) where participant's recounted moments that involved reasoning about the data, on these occasions they spoke about this reasoning occurring inside of them (Table 13, Theme K: Inner Reasoning). Participant's specifically recalled this occurring either in their head, chest or hands. When I examined the codes more closely I found that inner reasoning about haptic data representations was typically associated with the participants' chest or hands. While one participant recalled this happening *"behind my chest."* [DM, Haptic], another explained that reasoning about the difference between two haptic data representations happens – *"in my hands and the old one is inside me"* [KP, Haptic]. Unlike these examples, the location of inner reasoning with the auditor modality was described as being in their head. To illustrate this, TH was asked to describe the moment he realised a data representations did not match his expectation:

"it just felt not right, it felt different from what I thought would happen, I had a sound in my head and it sounded different from what I though it should be.", [TH, Audio].

Inner reasoning about auditory data representations was also, at times, accompanied by a voice. Participant's recalled this voice interjecting with comments about the data and also confirming when meaning had been gained from the data. The following statement illustrates this process:

"it is like the voice in your head, yea it is like a person, it's the voice in my head saying 'that's like the low sound'.", [DME, Audio].

DME was then probed to recall further details about the voice she was hearing at the time:

DME: *(pause 2 secs stares into space) I don't know cause I have never really, like I have never put any thought, I have never really listened to say does it sound like my voice, cause it has always been there.*
Interviewer: *OK and where is that voice in your head, could you.*
DME: *could I show you a point where it is? [interviewer: yes] yea yea, it actually sits very much here (hold back of her head) [interviewer: ok] in this section of my head. That is where it all happens.*

The analysis of the transcripts revealed twelve instances where participant's talked about using instinct or personal experiences to make sense or meaning from the data. The representational modality in use in the majority of these occasions was the auditory modality (Audio: 9, Visual: 2, Haptic: 1). When recalling these episodes it revealed participant's found it particularly difficult to describe processes of insight generation and tended to use phrases such as:

"I just know.", [DME, Audio], *"I just have to trust my instincts."*, [CN, Audio], and *"it happens so fast, it's over in a second."*, [MC, Audio].

Participant's also commenting on not feeling like they were thinking when interpreting the data representation, things just happen without them being aware of it and they described this in terms of not being in control of the judgement they make. The following statement illustrates this:

"I didn't think about it, so I just took it for granted that that was actually like the sound that I had heard before and I was accepting of that, that was it, that was like the low sound.", [DME, Audio].

Another participant echoed the sentiment of this statement when asked to describe how he knew the real-time reading was high:

"I am just gauging that it is higher, how do I gauge that it is higher? that it is towards the higher end? am I don't know, it just feels that way to me, I don't mean feel as in vibrate, I think it is just from life experience being aware of the tone.", [MC, Audio].

In this statement MC specifically acknowledges the role that life experience plays in recognizing the differences or similarities between two sounds. He also speaks about it 'feeling that way', but is quick to clarify what he means by 'feeling'. Other participant's also used the term 'feeling' as a way to describe something happening but were unsure as to why or how it happened. The following extract is DME's response to my question: what happens when you are trying to compare it to a sound that is in your memory?

"I just felt, it is kind of more of a feeling, because it is a more low level, it is more relaxing when you hear it through your senses so it didn't cause me alarm, I don't know what happens I just know, at the time, I knew it was low, I felt it was low."

Finally, let me address the distribution of codes extracted from participant's who used the haptic display. When analysing the data (see yellow slices in Figure 43), I was drawn immediately to themes that have a high proportion of hapic codes as well as those that had very few. If we look at Theme L (Memorizing), which I describe as accounts of remembering or memorizing data, participant's using the haptic modality recalled the vast majority of these moments (Audio: 1, Visual: 1, Haptic: 10). A particular interesting aspect is revealed when the codes are examined further. Although the hapic prototype represents the data using vibro–tactile feedback, on some occasions, instead of memorizing the vibrations, participant's commented on focusing on the sound being emitted from the motors. When recalling how he focuses on auditory feedback instead of vibrations from the prototype KP recalled:

"I think just because like the sound is the quickest and easiest way for me to remember it, it was harder to remember what it felt like at

high than what it sounded like at high.", [KP, Haptic].

During the interviews, it proved to be very difficult task for participants to recall how they memorize data representations. In most cases it took multiple iterations and maintaining focus on what the participant perceived to be a very short period of time to reveal details about the processes involved. The following extract exemplifies the struggle with recalling such moments:

"I make a mental record of whatever I have, whatever mental value I have is value A and then value B is the other. So whether the variable or parameter is sound or level of smell or whatever sense you are using, I make a mental note of the first one and the second and then I can recall. I then recall the first one and base the second one against the first one, because the second one is more, is more present, its more vivid in my imagination.", [JC, Haptic].

As can be seen in this statement JC reveals that he makes a *"mental record or note"* of the sound and labels it to recall it later, however, the description is not as fine as I would have wanted, so I probe JC to reiterate a number of more times to reveal further details. Following three more iterations that took just under 5-minutes JC begins to explain more about the process of memorizing haptic data representations:

"I had been drilling a wall the day before and that would have been, in terms of haptic feedback, that would be, drilling into concrete, on a scale of one to ten, it would be ten so very high. So I recall, I wasn't aware of this at the time, but now I have a mental bar chart or scale, a barometer, a haptic barometer in my mind, so I am using that as a scale of ten so I can place the data as I feel it on the barometer. So I feel a very low, I suppose, like a phone vibration and I give it 3 on the scale, so I am just memorizing the number 3 not really what I feel, just the number."

This extract provides a clearer description about how he memorizes haptic data, which is similar to the strategies, discussed the earlier section: Using Spatial and Visual Cues. What is most interesting about JC's account is the complex and multi-layered nature of the cognitive task involved in memorizing the data, which involves: reliving past experiences (drilling), using objects (barometer, scales, phone) and converting sensations into numerical data. It should also be noted that JC acknowledged that he was unaware of using such processes prior to being interviewed.

8.3.2.4 *Recurrent Themes*

I will now compare the results of this Elicitation study with those of the Elicitation study described in Chapter 7. Although the data representations used in the earlier study (Chapter 7) comprised of static printed visualizations, compared to the dynamic interactive representations presented here, the findings reveal some interesting similarities in how participant's experienced both sets of representations. Four of the themes established in this study can be easily matched to themes from the previous study. In both studies participant's recalled moments when then realised that they had formed some meaning from the data (Table 13, Theme C: Meaning Making and Theme D: Finding Meaning). Participants also spoke about having a sense of fulfilment at the conclusion of their time using the prototypes and the data visualizations (Table 13, Theme I: Fulfilment and Theme E: Fulfilment). Whether the data representations were interactive or static participant's recalled using previous knowledge to held generate insight (Table 13, Theme M: Using Previous Knowledge and Theme J: Using Previous Knowledge). Lastly both sets of participants commented on how they made sense of the data (Table 13, Theme B: Making Sense and Theme G: Sense of Understanding), these themes, however, are not as close as the previous ones. In Chapter 7 we associated making sense with gaining an understanding, however, the study we present here has shed new light on this and shows that generating insight is a iterative process that involves numerous phases with each one dependent on the previous to gain a full understanding of data.

8.4 Discussion of the Two Studies

I divide the discussion of findings into two sections. I first address issues related to the tangible nature of the prototypes and I discuss the design outcomes of the findings by pointing toward possible use scenarios for tangible data representations. I then discuss what I have learned about the affect representational modality has on people's experience of data. In doing this collate and discuss the findings of the two studies (RepGrid and Elicitation) to show what has been learned from applying a method to explore the meaning participants attribute to the their interaction with the prototypes and then using a method to probe deep into people's experience with prototypes.

8.4.1 *Tangible Interfaces*

Following the analysis of the studies there seems to be evidence to show that using tangibles to monitor and represent data stimulates debate about the data source. I provided our participant's with prototypes that can be shared within a group and it would seem that these mediated and focused the conversation around the data. While there was clear evidence of this during the focus group sessions, the Elicitation interview transcripts also support this. Although the primary aim of the Elicitation interviews was to focus on an episode when knowledge or meaning was formed from the participant's interaction with the data representation, the transcripts revealed insight about how people share their understanding of the representation with others. On occasions participants talked about being eager to tell others about the latest reading and to "warn" them that the air was unhealthy. In the following extract AS is probed about how she knows that the levels are unhealthy:

AS: *I just feel that what I am hearing is not good for me*
Interviewer: *How do you know?*
AS: *Well it is not just bad for me, it's bad for everyone*
Interviewer: *For everyone?*
AS: *Yes for the rest in the room, it is their air as well, so I should tell them about it*
Interviewer: *How do you tell them? If you go back to the time when you realised that you should "tell them", how do you realise you should tell them?*
AS: *(pause 3 seconds) I am looking at the cube, the sound is in my head and I say to myself "jezz, this is not good, let's tell Margaret (work colleague) about it"*
Interviewer: *and what do you do next?*
AS: *I go over, with the cube to talk to her about it*

In the following moments of the interview AS talked about her exchange with Margaret, explaining that she used the cube to demonstrate the present CO_2 levels. There were also occasions when participants spoke about confirming, or wanting to confirm the real-time levels with others who shared the space. I believe that portability is not the only factor here, the size of the prototypes also allowed them to be handed over and moved easily. In Hornecker and Buur's framework [111], they purport that tangible user interfaces support aspects such as social interaction. Supporting the social aspects of data representation is especially important today, as their purpose has moved beyond just assisting domain experts with analytical tasks, but are now frequently used in casual contexts such as museums, libraries or at home. I believe the findings show that tangible interaction combined with data representation can play an important role in future developments of tools for data exploration in casual contexts.

The tangible prototypes are different from how ambient data is normally monitored and represented. Typically, wall mounted sensors and displays are used to sample and represent data from a fixed point. The use of a portable device allows people to sample and represent the air space around them. I found that this creates a sense for the user that the readings are personal to them. I believe this may impact on how the user is affected by the data, which may in-turn cause them to act more quickly in a given situation, such as opening a window when the IAQ drops.

8.4.2 *Representational Modalities*

The studies presented in this chapter were conducted to gain a deep understanding of how people experience data when it is represented by tangible interfaces through three different types of representational modalities. The first study I presented used the repertory grid technique in form of a focus group session, to compare the three design probes by revealing participant's agreed description of each. The second study employed the Elicitation Interview technique to shed light on the cognitive processes people use when perceiving and interpreting the data represented by the same prototypes. The rationale for running these studies consecutively was that it allowed me to first reveal people's general impression of the different modalities before eliciting deeper insight that the participant's may or may not have been aware of at the time of using the prototypes.

I should note that the purpose of running these two studies was not to compare the methodologies, instead I was interested what these methods, conducted one–after–another, would reveal about people's experience of data representation. I should also acknowledge that the set-up of these studies was quite different, in so much as the RepGrid study only allowed participants an hour to familiarise themselves with the prototypes, while the participants of the Elicitation study had one week to use the prototypes. The discrepancy in time allowed with the prototypes may also have had an impact on the findings. For instance, the findings of Elicitation study show that the visual modality caused a high level of confusion (compared to the other modalities). However, this was not apparent in the RepGrid study, in fact, on the contrary, the participants described the visual modality as being "easy to interpret". This may indicate that confusion may start to become prominent after prolonged use of the visual modality and while the haptic and auditory modality were initially "difficult to interpret", once the participants became more familiar with them they developed personal strategies to help with the interpretation of the data, such as the use of visual and spatial cues.

In the sections above I discussed the findings of each study separately, I now zoom out to reflect on what both findings together tells us about people's experience of the three different representational modalities. When examining the results of both studies it becomes apparent that the haptic and auditory representational modalities are experienced in a very similar manner. The RepGrid reveals ten clear similarities and this is supported distribution of codes established during the Elicitation study. While these two modalities have strong connections, both are noticeably different from the visual modality. Both the RepGrid and the codes attributed to the visual modality during the Elicitation interviews show a marked contrast from the other modalities.

During the studies participants consistently spoke about their difficulty in recognising subtle changes in the haptic and auditory representation, whereas small changes were immediately noticed in the visual interface. While some confusion was caused by becoming aware of minor changes (using the visual prototype) but not understanding the implications, I believe that this reveals a characteristic of the auditory and haptic modalities that warrants further investigation. It could be argued that these modalities may be better suited to representing non-critical ambient data (such as IAQ), where minor changes have no great impact. The visual modality may, however, be more appropriate for representing critical data, such as carbon monoxide, where even small changes can be dangerous and life threatening.

An aspect of people's experience of data that was also highlighted in both studies was the role of the body. In the RepGrid study the participant recognised the importance of the hands and fingers when interpreting and forming meaning from haptic data representations. They also alluded to the body when using the auditory representation by talking about raising the prototype towards their ear to enhance the perception of the representation. The Elicitation interviews allowed me to gather further details about the body, the findings show that all the participant's spoke about their body when recalling their experience with the prototypes. Interestingly, although all the prototypes required tangible interaction to trigger the prototype to represent the data, both studies show that the haptic and auditory modality seemed to heighten this awareness, as there were very little references to the body when the participant's used the visual modality. While it would be expected that the haptic modality and to a lesser degree with the auditory modality, would increase awareness of the body, this may not be the case for the auditory modality. Nonetheless, there were many occasions where the role of the body was discussed that did not involve feeling sensations through their hands. These include being aware of their body position (standing, sitting etc.) or being aware of movement, such as walking. While these are very earlier findings and do require further investigations, they may point toward the haptic and auditory modality offering a more holistic human experience of data that is difficult to achieve when perceiving or interpreting just with our eyes.

Another aspect of people's experience with the modalities that is highlighted in the results of the studies is the complex processes involved in interpreting the data. The RepGrid revealed details about the difficulties associated with interpreting data, how some modalities struggle to represent a wide range of data points, some evoke memories of past events, some are perceived as playful while others are more serious, logical and informative. The RepGrid also shows how the visual modality is considered as being very accurate, unlike the other two, which make the perception of subtle changes very difficult. Other difficulties highlighted during the Elicitation study include (1) moments of confusion, (2) difficulties in memorising and (3) distractions caused by ambient noise. All of these issues make the process of interpreting data difficult, however, the studies also revealed the processes people employ to negate these issues. The RepGrid shows how people evoke memories of past events to help interpret the data, especially with the haptic and auditory modality. The results also show how people combine or switch between modalities when two are available i.e. haptic modality. The Elicitation study, however, offered far more insight into the process people employ during moments of data interpretation. Alongside the evocation of past events and relying on instinct, which was also evident during the RepGrid study, the interview transcripts revealed moments where participant's utilized mental cues to make sense of the data. These processes involved translating sounds and sensations into objects and images and placing these along an imagined line to judge the differences between two or more representations. In most cases the participant's were unaware of these cognitive processes until they recalled them during the interview. The Elicitation interviews also revealed details about the phases involved in interpreting data representations. They show how people first engage in a process that allows them to make sense of the data, by seeking patterns or correlations. Once these have been resolved the next phase involves attributing meaning to what they have found. The processes involved in data interpretation is vastly under-explored, and is overlooked by a series of studies that have sought to explore data insight (cf [207][255]). I believe that research is needed in this area, not just to investigate the type of insight generated by data representations but to look more closely at how people generate data insight.

8.5 CHAPTER SUMMARY

In this chapter I presented an experiment that involved the creation of three design probes (prototypes) and the evaluation of these using the RepGrid technique, followed by a series of Elicitation interviews. The aim here was to conduct a series of experiments that allows for the capture of accounts of experience at finer levels of granularity. Starting first with a RepGrid study, this enabled me to better understand how people interpret data in different modalities, by analysing the meaning structures that they apply to each prototype. I found that the auditory and haptic are generally perceived as being similar to each other, but, different from the visual modality. This study also revealed interesting insight about the modalities, such as peoples awareness of the tangible properties of the haptic modality, the capacity of the auditory and haptic modality to evoke memories of past events and the recognition that the visual modality requires prior knowledge but the other two modalities can be instinctively interpreted. The Elicitation Interview study was conducted to reveal even deeper insight about how representational modality affects people's experience of data. The results of this study revealed insight about the nuances of data interpretation that have yet to be highlighted in other studies. These include evidence that suggest the process of interpretation is a multi-step process (from making sense to making meaning), the use of metal cues (spatial and visual) to help interpret the representation, and the awareness of the body (position and proximity) when interpreting non-visual representations.

In presenting these studies I conclude the experiments I conducted during my PhD. I now move towards summarising the previous chapters, formulating my key contributions and presenting the known limitations and unanswered questions. All of this is done in the next chapter.

Part III

REFLECTION

I began this thesis with the aim of trying to better understand the way people experience data and how representational modality affects this experience. I now conclude this exploration by revisiting the major points and research questions presented in this thesis. In the following, I summarise what I have learned and what does this mean for the study and design of future data representations - in the context of HCI and neighbouring fields. I also draw together the key findings from the experiments presented in earlier chapters and reveal patterns that appear across these studies. In the introduction I presented the three connected questions that this thesis sought to answer: *How do people experience data, what influence does representation modality have on this experience, and how does it affect the way meaning is formed by the audience?* Overtime, other questions emerged from my research, and while these did not alter the focus of my research, they did exposed new areas that merited further examination and investigation. In the next chapter I discuss the manifestation of these investigations, by presenting the key contributions I claim to have made in this thesis. I divide and discuss these contributions under the following categories: theoretical, methodological, design, empirical. Before I conclude, I addressed two important aspects of my thesis, firstly the limitations of my research and the questions that remain unanswered, which I believe will be valuable inspiration for future researchers.

9 THESIS SUMMARY

9.1 SUMMARY

The main body of this thesis is divided into two parts. In part one, I laid out the theoretical and design foundations of my research, while part two was dedicated to introducing my methodological approach and presenting a series of experiments that revealed insight into peoples experience with data. In the following I summarise the previous chapters, starting first with those from Part One, before dealing with the final three chapters in Part Two.

In the beginning of this thesis, I introduced phenomenology as underpinning the philosophical and methodological approach to my work. Following an overview of the genesis of this philosophical tradition, I discussed key terminology and concepts from four phenomenologists: Edmund Husserl, Martin Heidegger, Maurice Merleau-Ponty and Don Ihde. Through this, I showed how Husserls' theory of *intentionality*, which he developed from the earlier thoughts of Franz Brentano, describes the way we experience the world as being *actional* (involves an action) and *referential* (refers to something external). I then discussed two Heideggerian ideas, including his conception of how we use equipment and how we conceive *temporality*. Heidegger argues that people encounter the equipment of our lives as either *ready-to-hand* (when we use it), or *present-at-hand* (when we stare at it but don't use it). In describing Heidegger's thoughts on *temporality*, I explained how we perceive the three phases of *temporality* in an *authentic* and an *inauthentic* mode.

In this chapter I also showed how the work of Maurice Merleau Ponty has had a pronounced influence on HCI and other fields of computer science since the 1960's, and his ideas are still highly relevant today. Specific research communities, such as TEI, regularly incorporate his ideas and concepts into contemporary research. Merleau-Ponty focused his life's work on understanding and describing the role of the human body in perception. The two key ideas that closely relate to my lines of enquiry are: The *Body Schema* and *Maximum Grip*. I showed how the body schema is the medium through which we experience the world, while maximum grip relates to the relationship between our body and the object of our intention. These objects solicit our bodies to acquire the optimal position to best perceive the object. The final concept that I introduced in Chapter 2 was Don Ihde's *Human-Technology Relations*. This concept refers to the way we technology mediates our experience of the world and it incorporates four types of relations: *Background, Embodiment, Hermeneutic,* and *Alterity*. In concluding this chapter I illustrated how phenomenology has influenced HCI research. Starting with the work of Winograd and Flores [317], I transcended the embodied turn in HCI to discuss influential contributions from notably researchers such as Dag Svanœs [276][277] [278], Paul Dourish [52], Toni Robertson [245] [246] [247] [248] [249] and others.

Once I had introduced the phenomenological tradition, I moved over to two other central aspects of my research: *data representation* and *evaluation*. In Chapter 3, I first presented a brief history of data representation, focusing at times on important milestones that have influenced the trajectory of the field. Although this review showed the primary modality used to represent data today still remains visual, I illustrated a recent surge in research on other modalities such as physical, auditory, olfactory and gustatory. As the primary focus of my research is to understand how people experience data representation, in this chapter I also reviewed approaches and methodologies that are commonly used to gather accounts of experience. I focused on outlining the strengths and limitations of methods, such as, observational studies, diary studies, questionnaires, the think-aloud protocol, and interviews. While these methods have been relatively successful at revealing issues related to the user-experience of systems, it became clear to me that I would have to incorporate other methods, some of which have rarely been applied in the context of HCI, to allow for the capture of precise accounts of experience.

In Chapter 4, I sought to bridge the gap between theory and design. To accomplish this, I conducted an experiment, which incorporated a design exercise and a user study. The artefacts introduced here were designed specifically for a public Space Observatory, with the aim of representing scientific data for casual visitors in a natural manner. Over the course of one week I deployed two prototypes in the Observatory, observed them in use and interviewed visitors about their experience of using these prototypes. Using the data gathered, I analysed the prototypes through the prism of the phenomenological concepts that I introduced in **??**. This examination not only provided me with a better understanding on how visitors experienced the prototypes but also helped me comprehend the relationship between philosophical phenomenology and the experience of data representation.

The final chapter in part one of this thesis is dedicated to surveying the state-of-the-art in data representation. In particular I focused on defining and analysing data representations that require more than one sensory channel to fully interpret the data. As part of this work I defined, for the first time, multisensory data representations as:

A class of data representation that have a clear intent to reveal insight by encoding data in more than one representational modality and require at least two sensory channels to fully interpret and understand the data.

Using this definition, I collected and analysed 154 examples, and established a design space, which incorporates three dimensions: use of modalities, representation intent, and human-data relations. Derived from the analysis of the design space, I addressed key research issues, including: questioning the value added by expanding the sensory channels required to interpret a data representation. I also discussed issues from the users perspective and explored the boundaries between representation and art. I concluded the discussion by highlighting underexplored areas and future challenges and then presented five key recommendations aimed at providing practical guidance to other researchers and practitioners who wish to study and create multi-sensory data representations.

Part Two of this thesis is focused on introducing two evaluation methodologies that I employed in this thesis while also presenting a series of experiments, which were aimed at gathering accounts of experience with data representations and comparing how representational modality affects people's experience of data. As previously stated, my review of methods commonly used to examine people's experience of systems highlighted certain limitations, including the introducing of personal bias and post-hoc rationalization, the high level of effort and commitment required by the participant and researcher, and the difficulty in obtaining in-depth and precise accounts (see Table 2, Chapter 3). To overcome these difficulties I sought to incorporate and adapt methodologies that have rarely been used in the context of HCI or for the purpose of evaluating data representations. In Chapter 6, I presented the Repertory Grid Technique (RepGrid) as a useful method for collecting data on how people construe their experience of objects, people or events. Although this method has been used in HCI since the 1980's, I discovered some limitations with the traditional application of the technique, especially when following a phenomenological approach (as is my case). The main issues relate to the type of data that is gathered and the time and effort required to collect this data. To overcome these concerns I formulated and described a new procedure for the application of the RepGrid technique, which involved blending it with a focus group session and analysing the data using a qualitative approach. In this chapter I also validated this approach by presenting a side-by-side experiment, which incorporated a traditional application of the technique, followed by a study that incorporated my adaptions. The methodological findings here show not only is the adaptions more efficient to run, but it also allows for the capture of rich data (participants remarks) that is typically overlooked or lost when employing traditional procedures. While this adaption resulted in facilitating the capture of rich design relevant information, I remained focused on gathering deeper insight and more precise accounts of people's experience. To accomplish this I introduced the Elicitation Interview technique, which apart form some notably examples (cf. [162] [209]) has rarely been used in the context of HCI and has never been used to explore people's experience of data. I dedicated Chapter 7 to introducing this technique, describing the key characteristics of the technique, illustrating how it can be applied in different contexts and describing the types of insights it can support.

As well as introducing methodologies in Chapter 6 and Chapter 7 , I also presented a series of studies, which employed these methods to explore people's experience of data representation, while also, investigating the role representation modality plays in this process. The aim of the experiment described in Chapter 8 was similar, but incorporated two studies (RepGrid and Elicitation Interviews), which were conducted consecutively, but each used the same set of prototypes to examine the phenomenon of data experience at finer levels of granularity. The findings of all these studies reveal interesting aspects about how people experience, interpret and perceive data representations. For instance, in Chapter 6, I showed how the haptic modality can be difficult to interpret but the process of interpretation happens instinctually. In Chapter 7, I discovered that when people begin to interpret data visualizations they rely heavily on visual variables to start the process, they also seek personal connections with the data source and they seek to find meaning beyond the data, which sometimes results in the manifestation of vivid (mental) images. Finally, in Chapter 8 the findings of the two studies reveal aspects such as: the haptic and auditory modality evoke memories of past experiences, the use of mental cues (spatial and visual) to help interpret the data, and there seems to be evidence that data interpretation is a two step process, which involves first making sense of the representation before meaning is formed.

These discrete findings go some way to build a picture of how we experience data; however, if we zoom out, and look at the findings from all five studies together we can get more holistic appreciation of about the structure of this experience. When I placed the findings from the studies side-by-side some similarities and patterns emerged, these relate to: (1) the body, (2) issues with interpretation, (3) relying on instinct, (4) multimodality, and (5) referencing the lifeworld.

THE BODY In Chapter 6, observations during the study revealed how participants were more active - moving from one position to another – when engaging with the auditory and haptic modality. While the same type of movement was not observed in the other studies, the findings show that there was a heightened sense of awareness of ones body position, again with the auditory and haptic modality. In Chapter 8, I showed that grasping the haptic interface in different ways affected the perception of the representation and also participants tended to speak more about their body position when recalling their experience with the auditory and haptic prototype. This insight echoes Merleau-Ponty's notion of the maximum grip (outlined in **??**), in so much as objects tend to solicit us to optimise our position to enhance our perception when interacting with. It also may encourage designers of future sonifications and physicalizations to facilitate movement and mobility around these types of representations to allow for a more holistic and natural perception of the data.

ISSUES WITH INTERPRETATION The RepGrid study represented in Chapter 6 revealed how participants had difficulty interpreting the data represented by the haptic and auditory modality. They also described the auditory modality as being abstract. The results of the RepGrid study in Chapter 8 echoed these findings. The participants who took part in this study also described these modalities as being difficult to interpret and described the representations as ambiguous. In both studies participants agreed that the visual modality was not abstract or ambiguous, instead they chose word, such as, scientific, intellectual, practical, precise, and logical to describe their experience of this modality. These findings seem to suggest the type of scenario that the various modalities are best suited to. For instance, the visual modality may be better at representing critical data and supporting work-related activities, whereas the auditory and haptic modalities may be more appropriate for non-critical data in casual scenarios, where the type of data insight revealed by the representation is more open-ended.

RELYING ON INSTINCT The findings in Chapter 6 and Chapter 8 both indicate that participant's consider the interpretation of visualizations as an intellectual activity, which requires some level of training or education to complete. Whereas, the process of interpreting haptic and auditory representations is more instinctual and relies on life experience to generate meaning from these types of representations. The Elicitation study (Chapter 8) shed some light on the cognitive processes used to form meaning from the haptic and auditory modality. These involved, for instance, the use of spatial and visual cues to help interpret the difference between two representations. A number of participants recalled seeing mental images of shapes, colours and objects and placing these on a line or graph, then using the proximity between the elements to understand the differences between the two representations, thus using their instinct of spatial awareness to interrogate the difference. Knowing that people rely on instinct over knowledge to interpret non-visual representations is something that system designers should be aware of and adds more weigh to the argument that these types of representations are better suited to casual scenarios, such as museums, public spaces, libraries etc.

MULTIMODALITY In Chapter 5, I proposed a design space for multisensory data representation, which addressed, in part, issues related to the representation of data through more than one modality. In the findings of studies presented in Chapter 6 and Chapter 8 issues related to multimodal representations also appeared. In particular these related to the experience people had with the haptic representation. When designing these prototypes, my original intention was to represent the data through vibro-tactile feedback (knocking and vibration). However, the mechanics used to generate the vibrations also resulted in sounds being emitted from the prototypes. This resulted in confusion with some participants, as the intensity of the sound was perceived as being different (stronger) to the knocking and vibration. This issue is of most concern to designers of multimodal representations, where two different modalities are used to represent the same data, whereas with cross-modal representations two modalities are used to represent different data sets in the same interface. In the case of multimodal representations it is important that the two modalities are of equal intensity so as to not cause confusion. While I acknowledge that this may be difficult to achieve, overlooking this issue may result in misinterpretation and/or confusion.

REFERENCING THE LIFEWORLD The findings of the studies presented in Chapter 6, Chapter 7, and Chapter 8 all show evidence of participants referencing events, objects, people and past experiences that were triggered during the interpretation of the data representations. In Chapter 6, I noted a tendency for participants to use real-world analogies when interpreting the representational modalities, these included, for instance, a domestic appliance (haptic modality), and a rainbow (visual modality). In the Elicitation study presented in Chapter 7, participants also referenced the lifeworld, but this time it related to finding personal connections with the data visualization. I found that they seek these connections to reaffirm their understanding of the presented information, to contextualize the information, and to critically contemplate about presented approaches and facts. This phenomenon also appeared in the studies presented in Chapter 8, however, here the haptic and auditory seemed to be the modalities that evoked memories of past events and objects, whereas the visual modality did not. While I am not entirely sure how designers can leverage this knowledge, it does reveal insight into what people think about when interpreting data representation, no matter what modalities are in use.

9.2 CONTRIBUTIONS

In this section I will present the contributions I claim to have made in this thesis. To help make sense of these, I divide them into four categories: theoretical, methodological, empirical, and design (see Figure 44). In the following I discuss each one separately.

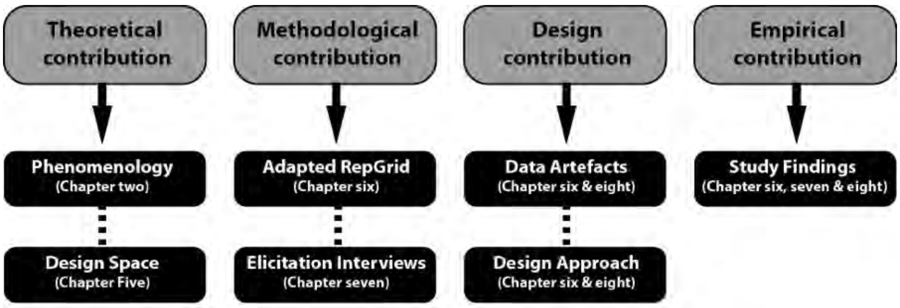


Figure 44: Thesis contributions, which includes the categories (theoretical, design, empirical, methodological), the type, and chapter where each contribution is described.

9.2.1 *Theoretical contribution*

At the commencement of my PhD I decided to take a phenomenological approach to my research. I choose this not only because I wanted to explore people's lived experience of data representation, but I also sought to bracket all of the presupposition that I have acquired about data representation over the years. When I searched the literature for related work, the only previous research I could find related to empirical studies on evaluating user-experience (cf. [37]). There had been no research conducted which attempted to describe how people experience data representation, including, how this experience unfolds over time or specific episodes during this experience i.e. formation of insight/meaning. I claim that this thesis has gone some way to fill this gap by providing the reader with rich, detailed and precise accounts of experiencing data. I have also addressed, for the first time, how representational modality affects this experience. As well as using phenomenology as a basis for my research approach, I have also incorporated concepts, notions, and ideas from philosophical phenomenology to provide a better understanding on how we experience data.

The theoretical contribution of this thesis also includes establishing the design space for multisensory data representations (see Chapter 5). The survey I conducted as part of the design space exploration is the first time that data representations from a wide range of disciplines, spread over a long period of time, have been drawn together and analysed under the same criteria and included 154 examples of publications, art installations and consumer devises from a range of domains, including the natural sciences, architecture, design, and contemporary art. I claim that this research has not only contributed to the field of HCI, but other domains that design and study data representation. It bridges the gap between theoretical concerns and the practicalities of design, and provides practitioners with an overview of the design possibilities, as well as informing to researchers about present and future research challenges when representing data with and beyond the visual paradigm.

9.2.2 *Methodological contribution*

In the early stages of my PhD I sough out methodologies that would allow me to follow a phenomenological approach by capturing rich accounts of people's lived experiences. When I commenced this search I surveyed methodologies that have been proven over the years and were commonly used in HCI. I soon discovered that all of these methods had limitations and would not be suitable in the context of my research. Thus, I extended my search to include methods that are not commonly used or wrote about in the context of HCI. From this two methods emerged: The Repertory Grid technique and The Elicitation Interview technique.

Although the Repertory Grid technique has been used in HCI since the 1980's, the contribution that I claim here relates to an adaptation I made to the typical application of the technique. In Chapter 6 I described how the Repertory Grid technique, blended with a focus group session allows for the efficient capture and analysis of rich design relevant information. There have been some sporadic attempts to conduct parts of a Repertory Grid study in groups (cf. [307] [86] [227] [187] [261] [5], however, the adaption I present in this thesis is first time that all phases of the Repertory Grid technique were conducted in a group setting. I also validated this adaption by conducting a side-by-side study that compared the traditional application against my adaption. I am not hesitant in claiming that this adaptation will increase the use of Repertory Grid studies in HCI and neighbouring fields, as some one of the most cited obstacles that hinders the use of the Repertory Grid technique is the time, effort and commitment required by the researcher and participant when carrying out a typical Repertory Grid study. The contribution that this adaption also makes relates to the type of data collected (rich qualitative data) and the method of analysis (discourse analysis).

While the Repertory Grid technique has a long tradition of use in HCI research, the use of the Elicitation Interview technique is far less common. In Chapter 7, I introduced, and for the first time in the context of HCI, described the key characteristics of this interview technique and exemplify how it can be applied to evaluate static data representations. The study I described in this chapter illustrates what types of insight this technique can bring to the fore, and also presented general evaluation scenarios where the Elicitation Interview technique may be beneficial. One of the valuable characteristics of this interview technique is that it facilitates the interviewee to re-call a past experience in high levels of detail, and it makes them aware of the pre-reflective dimension of this experience. So instead of the interviewer asking direct questions about a past event (such as with traditional interviews), the interviewer guides the participant back to the original experience to help them re-call it as if it is happening now. One of values that I see in this for HCI researchers is that instead of formulating pre-conceived questions when interviewing participants about their interaction with a system, the Elicitation technique can reveal aspects about this interaction that the participant may not have even aware of when the interaction took place.

9.2.3 *Design contribution*

The design contribution that I claim relates, in part, to the prototypes designed, developed, and presented in this thesis (see Figure 45). All of the artefacts I produced were designed for a specific purpose, in the case of H3 and the solar radiation dowsing rod (described in Chapter 4), these were created for casual visitors to a space museum to allow them to experience data that is typically only used for scientific discovery. The purpose of designing and producing a physicalization of emigration data from Ireland was to allow me to explore the practise of physical representations of data. This artefact is one from a series of ten physicalizations created to tell the story of Irelands' past through the physical representations. Each representation represents different data sets, including the economic, social and cultural, by encoding the data into the form of the object, thus allowing people to perceive the data through touch.

Figure 45: a: H_3, b: The Solar Radiation Dowsing Rod, c: CO2 cubes, d: Emigration from Ireland 1987-2013.

The contribution to design also relates to the approach I took in the studies presented in Chapter 6 and Chapter 8. I describe the artefacts created using this approach as Design Probes. Although this approach is similar to research through design, it is unique in so much as it doesn't involve an iterative process, which is integral to research through design. An iterative process involves designing a series of artefacts consecutively, where improvements are made in new designs based on the design knowledge gained from studying previous versions. I also consider it to be close in intent to Technology Probes [115], however, instead of studying the use of one artefact (which is the procedure followed with technology probes), I create design multiple artefacts that possess similar design features but differ in one aspect (e.g. representational modality). This allows researchers to focus the evaluation precisely on this design feature - in my case this was representational modality.

9.2.4 *Empirical contribution*

The easiest and most obvious way to summarize the empirical contributions of this thesis is to point to the summary of findings presented already in this chapter. In the three chapters that make up Part Two of this thesis, I presented the findings of four separate studies. Then, in this chapter, I summarised these findings and teased out patterns that appear across these studies. The findings I present in this thesis not only provide a rich account of people's conscious and pre-reflective experience of data visualizations (Chapter 7), but this is bookended with two studies that explore, in fine detail, how representational modality affects the way we perceive, interpret, analyse and experience data. I do not believe that I am over-reaching when claiming that the empirical findings, on their own, or combined with one another, go far beyond research that has been published on data experience to date.

9.3 LIMITATIONS

In this section, I acknowledge and address the limitations of this work, both in its methods, procedures and findings. While I have already acknowledged limitations in the studies carried out in proceeding chapters, in the following I describe more general limitations, which have an impact on more than one aspect of this work.

To begin with, one of the objectives of the studies presented in Chapter 6 and Chapter 8 was to explore how representational modality affects people's experience of data. In these studies I limited the modalities to three (haptic, auditory and visual). I acknowledge these modalities do not reflect the full range of possibilities, for instance, olfactory and gustatory are omitted. However, the rationale for limiting both studies to three was firstly due to technical issues related to producing and controlling odour and taste and also I sought to provide examples of the most commonly used representational modalities.

Also, in relation to the three RepGrid studies described in Chapter 6 and Chapter 8, in all cases the sample was quite a homogeneous one. All participants have extremely similar social and educational backgrounds; they are of all the same ethnicity and they fall within a relatively narrow age group (19-36 years). There are two reasons for choosing a convenience sample for these studies, firstly, as I work as a lecture in a third level institution, I had easy access to students who are, in most cases, more open to participating in studies than working professionals. Also, due to the nature of the adaptation I made to the RepGrid technique, which involved a focus group session, I sought to conduct the studies with groups who were already familiar with each other and were used to speaking aloud in the group.

In an earlier section, I claim the adaptation of the RepGrid procedure and the introduction of the Elicitation Interview technique as two key methodological contributions of this work. That being so, I also acknowledge that incorporating methodologies, which I had relatively little exposure to, or experience using, before my PhD may have limited the experiments presented in this thesis. As an example, I stated in Chapter 7 that practising using the Elicitation Interview technique is one of the most important aspects when learning to apply it correctly, and although I endeavoured to carry out as many practise interviews as possible I still believe that I am improving, even after completing two formal studies. When I compare the series of interviews completed and described in Chapter 8, I believe that they are an improvement on those described in Chapter 7. The reason for this relates to a key characteristic of the technique – the ability of the researcher to attain and maintain a state of evocation in the participant, which I found much easier to do in the second application of the technique. The experience I had with the RepGrid studies is similar. Although I had some prior experience facilitating focus group sessions, when these are combined with the procedures of the RepGrid technique it took sometime before I was entirely comfortable and pleased with the outcomes.

Another limitation that I acknowledge, which was also alluded to in the contributions of this work, relates to the data gathered when using the RepGrid and Elicitation Interview technique. In both cases this data is extremely rich and abundant, so much so that much of it ended up being removed from further analysis mainly due to time restrictions. I was also concerned with highlighting the most revealing insight gathered during these studies, which meant prioritising these over other revelations that may be seen by others as equally valuable and insightful. While this is a common occurrence when employing many qualitative methodologies, it is important to acknowledge it as being a limitation that may in some cases, if the researcher is not rigorous or objective, skew the results of a study. In my case, I relied on independent oversight from my supervisor when filtering the data down to a manageable size. Finally let me address the issue of generalizability. The question of generalizability arises in my case due to the size and homogeneity of the samples used in the studies. In this context, I do not argue for or purport to have achieved what Mason calls an "empirical generalisation of findings" [174, p.195], which is based on a generalisation or extrapolation from one population or sample to another. Instead, I sough to follow a process that would allow me gather accounts of lived experiences with data and to use these to formulated a better understanding of what happens when people interpret data representations. I do not claim to have a better understanding of one population over another, I merely present a body of work that describes the experience a collection of volunteers had when I asked to use various data representations under different conditions.

9.4 OPEN QUESTIONS

Over the course of my PhD three connected questions remained central to the focus of my research: *How do people experience data, what influence does representation modality have on this experience, and how does it affect the way meaning is formed by the audience?* When exploring answers to these questions other questions emerged, such as, for instance, *How do we study people's experience of data?* While I believe these and other pertinent questions have been answered in the proceeding chapters, some questions remain unanswered and I address these in the following paragraphs.

I already discussed the choice and range of modalities as being a limitation in this work and I provided some rationale for the decisions I made. Because of this, there are research questions related to representational modality that require further exploration. First of all, I have shown how representational modality affects the way we perceive and interpret data, but only in regards to three modalities, it remain unclear what affect other representational modalities, such as olfactory and gustatory have on the perception, interpretation and overall experience of data. Another aspect of representational modality that was not fully addressed in this work was the notion of representational variables. For instance, in the second RepGrid study described in Chapter 6, I used the colour variable to represent the data, but in other studies I used shape (BarGraph (also in Chapter 6) and numbers (Chapter 8), the same was true for the haptic modality (knocking: Chapter 6, vibration: Chapter 6 and Chapter 8). The only modality that remained consistent across all studies was the auditory modality, which used the frequency of sounds to represent the data. If time had permitted I would have liked to incorporate more than one variable for each modality, to study, not only the affect of representational modalities, but also how the variables for each modality influences people's experience of data. With this said, I believe further research needs to be completed before we can fully examine the role variables play in the experience of data. This relates to the study and formalisation of variables beyond the visual modality. I noted in Chapter 5 that visual variables have been studied and confirmed since first formulated by Jaques Bertin [13]. However, apart from some notably exceptions [146] [291] [124] very little has been achieved with the other modalities. A concerted effort is required to formulate and confirm a list of variables for the auditory, kinaesthetic, gustatory, and olfactory modalities. Until then it remains difficult for the wider research community to develop and share knowledge on the role they play when experiencing data.

On a similar note, a question that emerged from the findings of studies presented in Chapter 6 and Chapter 8 relates to the perceptual impact of different modalities. I discovered that participants were confused by perceived differences in sounds and vibrations emitted from haptic representation. It would be interesting to study the simultaneous perception of two different modalities, with the aim of finding direct relationships between the two. For instance, if a data point were represented through the visual modality using the colour 'orange', what would be the equivalent representation when using the haptic or auditory modality?

Figure 46: Life Don't Mean A Thing If It Ain't Got That Swing, with permission from James Pockson

In Chapter 5, I presented a relatively new venture in data representation that involves encoding data, not through the variables of representational modalities, but instead through the performance, affordance and experience of the representation. I presented a selection of examples that included a swing installation (see Figure 46), which encodes data in the physical properties of the swing i.e. the length of rope, the height of the seat etc. In turn, participants perceive and interpret the data through the experience of swinging on the swing. As this departure of data representation is new, there have been no studies, that I am aware of, which has investigated this form of representation. As this area grows, it seems that there may be some value to be gained in examining people's experience of experiencing data.

In the introduction of this thesis I outlined the primary design approach that I followed throughout my research. This involved designing a series of design probes, which are similar apart form one design feature. Due to the nature of this approach the type of artefacts I created were relatively simple and streamlined. A question that remains unanswered for now is how would people respond if they encountered richer data representations, which incorporated more complex interactions. Up until now, studies that have empirically examined non-traditional modalities, such as sound [183], haptics [29] and touch [124] have all used relatively simple interfaces, much like those I introduced in this thesis. However, as we gain more knowledge about representational modalities we can then begin to extend the complexity of the interface to examine the influence of other aspects, such as, for instance, interaction style and more complex design features. This, along with the other unanswered questions presented in this section may be valuable inspiration for future researchers.

9.5 A FINAL REMARK

I conclude my thesis with a call to research communities to address the unanswered question outline above, but it also my hope that further collaboration and cross-pollination will be stimulated between somewhat dispirit communities to work together on the issue we all face when representing data. While the primary audience of this thesis is the HCI community, at various stages throughout I have leveraged on theoretical and practical research produced by other communities to help shape a more holistic understanding of the state-of-the-art in data representation.

Through this journey I have encountered many different approaches, methods, definitions and terminology, which are used to define and explain various ways of studying data representation. This has led me to question: *can all representation that utilizes modalities alongside and beyond the visual modality be considered visualization?* New media theorist Lev Manovich [172] defines information visualization simply as "a mapping between discrete data and a visual representation", while Eric Rodenbeck, during his keynote address at the 2008 O'Reilly Emerging

Technology Conference spoke about information visualization as "becoming more than a set of tools and technologies and techniques to understand large data sets. It is emerging as a medium in its own right, with a wide range of expressive potential."[1] If we subscribe to the concept of defining information visualization as a medium, can we then disassociate the meaning of the word visualization from the visual modality, and propose that data represented in any modality or combination of modalities may be considered to be information visualization and not *data sculpture, data art, sonification, physicalization, sensualization, sensification, perceptualization* or even *multisensory data representation*? I believe that by accepting this concept, while also acknowledging the broad expertise needed to meet the theoretical and practical challenges, the HCI community, alongside others, such as InfoVis and the Artistic Community, can play central roles in the future developments and study of Information Visualization.

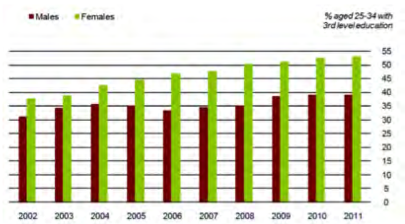
1 ETech, the O'Reilly Emerging Technology Conference, San Diego, 3–6 March 2008

Part IV

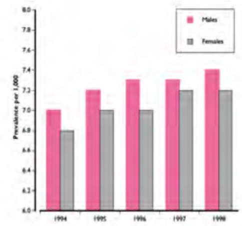
APPENDIX

A

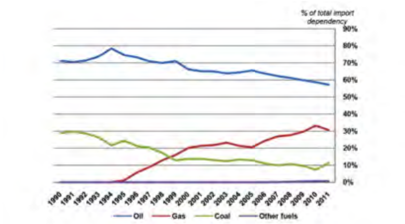
DATA VISUALIZATIONS USED IN ELICITATION STUDY



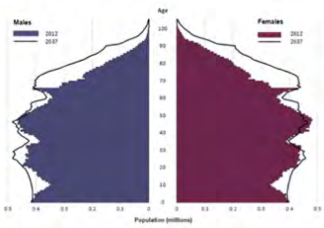
A1 Ireland: Persons aged 25-34 with third level education, 2002-2011, CB, (Source: Central Statistics Office of Ireland)



A2 Age-standardized prevalence of epilepsy per 1000 patents, by sex, 1994-1998 (UK), (Source: General Practice Research Database, UK.)

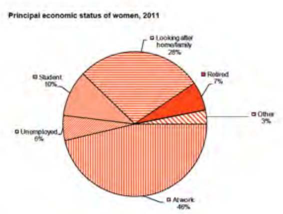


A3 Ireland: Imported energy dependency 1990-2011, (Source: Central Statistics Office of Ireland)

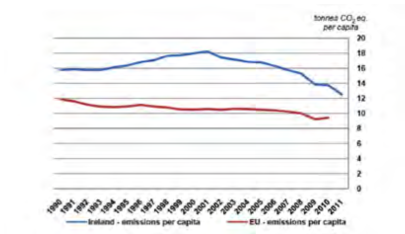


A4 Estimated and projected age structure of the United Kingdom population, mid-2012 and mid-2037 (Source: Office of National Statistics, UK)

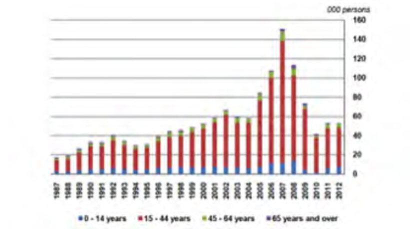
A5 Percentage of persons aged 25-34 in the EU with a third level education by country, 2009, (Source: CSO and Eurostat)



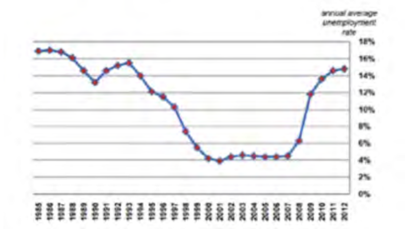
A6 Principle economic status of women in Ireland, 2011, (Source: Central Statistics Office of Ireland)



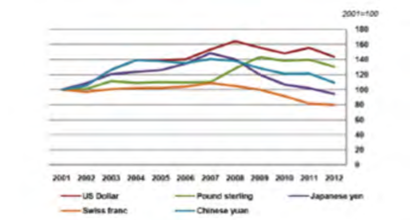
B1 Ireland and EU Greenhouse gas emissions per capita 1990–2011 (Source–EPA and EEA)



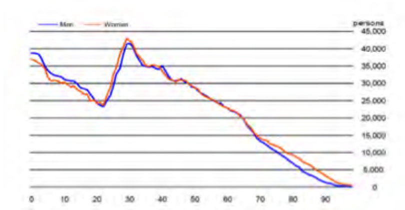
B2 Ireland Immigration 1987–2012 (Source CSO Ireland)



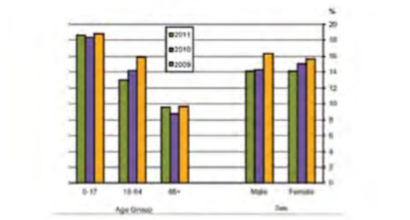
B3 Ireland Unemployment rate 1985–2012 (Source CSO Ireland)



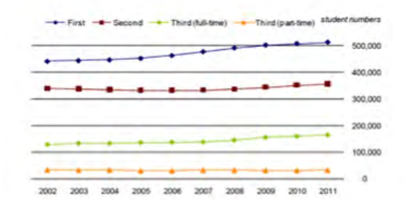
B4 Euro exchange rates 2001–2012 (Source Eurostat)



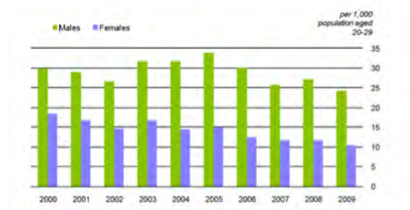
B5 Age composition of population Ireland, 2011. (Source: CSO)



B6 Ireland– at risk of poverty rate by sex, age group and year (Source CSO)



B7 Ireland– Student numbers by level, 2002–2011, (Source CSO)

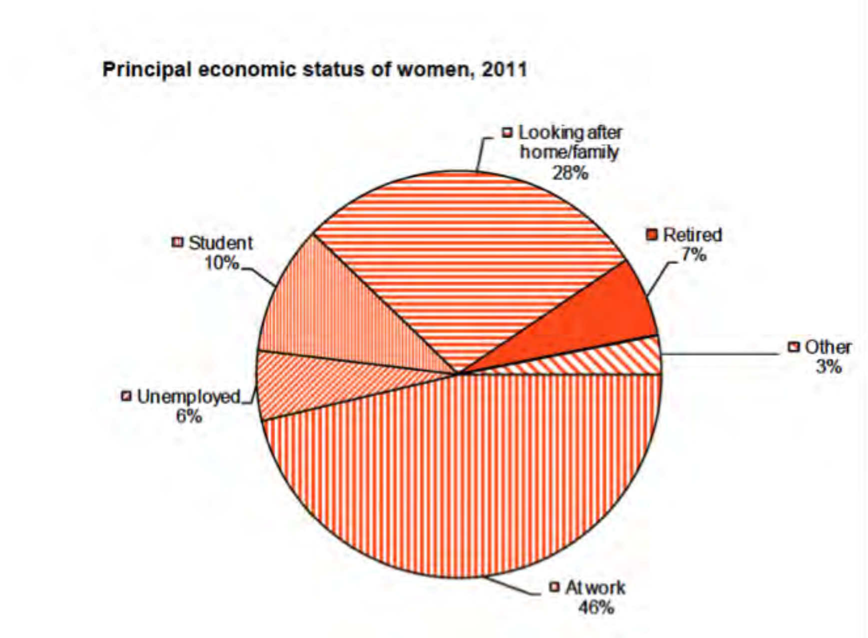


B8 Ireland– Mathematics, science and technology graduates, 2000–2009 (Source Eurostat)

B9 Live births by age group of mother, 1938–2012, England and Wales, (Source Office of National Statistics, UK)

B

SAMPLE ELICITATION INTERVIEW



Principle economic status of women in Ireland, 2011, (Source Central Statistics Office of Ireland)

JS's experience of reading the data visualization: Principle economic status of women, 2011 (see pie chart above) Researcher: Trevor Hogan Participant: (JS Female 33 year old Business Analyst)

Interviewer: Ok so what we are going to be doing here is an interview that will look at your experience of reading this data visualisation.... this approach tries to facilitate you to go back and recount an experience that you have had in the past and in this case we are looking at data visualizations and in particular we are trying to get at the moment in time when a visualization changes, for you, from a collection of abstract colours, shapes, patterns, numbers, letters into some sort of concrete knowledge on your behalf. The method we are using is the elicitation interview technique and we are trying to get you to describe the experience as it unfolded over time and then at certain points we are going to go back to specific moments during to probe these further.

JS: Ok

Interviewer:..Ok, so can we go back to that moment when you read the data visualizations, did you read it once or twice

JS: Am, twice

Interviewer: Twice, and so which occasion did you spend most time with it

JS: The first time.

Interviewer: The first time, and what was your rationale for reading it the second time?

JS: am, just going back over it, just having another look to see if I see anything more

Interviewer: Ok, was it just to confirm

JS: Yea yea

Interviewer: Ok, so we will focus in on the first time you read it

JS: em hem

Interviewer: ok, so when was this?

JS: ah, quarter past 7 this morning

Interviewer: ok and where are you?

JS: at work

Interviewer: at work ok, so are you at a desk

JS: I was at my desk yea

Interviewer: and is it printed out?

JS: no it is on my computer screen

Interviewer: ok, so is it on your computer screen in front of you?

JS: yes

Interviewer: is it the only thing that is open on the computer screen?

JS: am long pause I have a double screen and I have my outlook open on the left pointing to the left and I have the data visualization open on the right (pointing to the right)

Interviewer: ok and how far to the right is it, is it 45 degrees?

JS: ah am, I am not sure of the exact angle but from where I am sitting I am looking at the exact centre of the two screens, with one on the right and one on the left (pointing to the right and then left)

Interviewer: ok so it's on the one on the right (pointing to the right and then left)

JS: yea yes

Interviewer: and on the screen, is there anything around it

JS: No

Interviewer: Ok, are there any sounds in the environment if you go back to that time

JS: (3 second pause)...yea, because the reason I stopped looking at it was because of people arriving at work, so there is an increased level of noise, people are coming in

Interviewer: ok, so is there any particular noise that you can remember during this time

JS: No not when I started, but towards the end when I was almost close to finishing looking at it, or it was more that when the noise got louder I made the decision myself, say ok no there is no point in looking at this anymore because I will be unable to concentrate on it

Interviewer: ok, so there are some ambient noise but some were louder, some noises are louder than others

JS: yes, people talking **[Interviewer: ok]** that is the noises

Interviewer: ok, and when you are at your desk are you sitting or standing

JS: sitting

Interviewer: are you sitting upright

JS: yea

Interviewer: so are you very straight, is your back very straight or..

JS: long pauseI can't really recall, I am not 100% sure, it could be that I am leaning forward on the desk or I am sitting upright (bends forward and back in the chair)

Interviewer: and are your hands on the table or are they on your body

JS: No I kinda think that I have the feeling that I am leaning forward, more leaning onto my hand (mimics the position)

Interviewer: so leaning on your hand

JS: yea, underneath my chin (mimics the pose she was in)

Interviewer: ok ok and you have the computer screen in front of you, is there anything else on the desk besides the computer screen?

JS: am (long pause) yea, I have my keyboard, I have my drink bottle, I have my coffee

Interviewer: and where is you coffee, on the left or

JS: on the left

Interviewer: and is it strong coffee

JS: yes, strong and freshly made

Interviewer: can you smell it, now

JS: yes very much so

Interviewer: and the drink bottle is on the right?

JS: no, they are both on my left

Interviewer: Ok if you agree I would like you to go back to the time and place when you first begin to read the visualization and try to recount what you are doing as if you are doing it now...Once you are there, take your time

JS: OK (shuts eyes, pauses, then opens eyes and stares into space)

Interviewer: Please tell me how do you start to read the visualization? [I: am] what is the first thing you do

JS: the first thing I notice while looking at the data visualization is the confusing, the kind of patterns of the data visualization so even before I even read the data itself I find the way that the patterns fitted together in the circle, in the pie chart ah it looks a bit dizzy

Interviewer: Ok so is that the first thing you look at when you began to read?

JS: It is the, not necessarily specifically looking as in reading anything but it is the first impression when I opened the page

Interviewer: ok it was the first thing that grabs your attention

JS: the first thing that grabs my attention was am, it reminded me of a kind of a some kind of 3D thing, where it starts to move around that was the first thing that I saw before I even started looking at the actual data behind it

Interviewer: ok, so that grabs your attention what is it that you done next?

JS: am, the next thing I think was I kind of look at the most significant data that is there and...

Interviewer: when you say most significant?

JS: it is the biggest parts of the pie [**Interviewer:** ok] so there is one at the bottom that displays almost 50% of the data and the is one that was almost kind of a third of the data and they are the ones that I looked at first [**R:** ok] to see and am the next thing I remember, I just read what they would represent [R: eh em] and what surprises me is the large amount of women staying at home minding the house, minding people, was almost a third of women

JS: ok ok so you focus in on the two largest chunks of the pie chart first [**Interviewer:** yea] and then what came next for you after that?

JS: am long pause yea I focus on the large ones and then look, ok what are the other ones made up of and am long pause I think initially it is more just reading the numbers but then it, ah, kind of I start, ok, I look at the data to see what is it about and, ah, it's, I look at the smaller data as well so really to make sure that the economical status of women, what does that really mean, so it was what are women doing at that time or whatever that year and I kind of, am, I start looking to make sure I understand the chart to think about my own situation and people I know in my surroundings [**R:** eh em] and the surprise that I have about the large amount of women being at home which was a third and then I am surprised about the low number of women unemployed [**Interviewer**: eh em] that is a pretty small number and ah am I found that there is more women retired than unemployed [**Interviewer**: eh em] but it is kind of pretty much the same and that there is more women studying than unemployed so I kind of put the different data pieces into relation with each other to to kind of try to understand and and I think by doing that that is a way for me to memorize it, no not necessarily memorizing it but understanding it and getting to grips with it

Interviewer: Ok so when you say that you put the different parts together, how do you do this?

JS: How do I put things together is am... trying to in the environment that I am living then trying to apply what I am seeing so what I mean is, everyone knows that there is loads of unemployment in Ireland and the n you see data like this and there is a very small number that are unemployed and there are a huge number of women that are staying at home and minding the house and there are still 50% of them employed, [**Interviewer**: ok] so it is kind of putting them together as in applying the individual %'s to my own surroundings, do they make sense

Interviewer: ok, so what was it you do next, you said that you have focused in on the detail of each section [**JS**: yea] and thought about the implications of this [**JS**: yea] what do you do next after that

JS: One of the things that I do notice next is, I read the title to go back over ok is this data only representing from one year but one thing that stuck out for me in the chart and I only began to look at this towards the end of it all as well was am the source and it was not very clear am it just said source CSO so kind of is that an Irish agency or whatever so I just thought ok it would be interesting to know how the data was put together and am the other thing was well I even think before I done that there was a few things that came into my mind long pause am ok if there is only about 7% or something like that unemployed because it is such a low number I started reasoning in my head what could be the reason for such a low number and maybe the statistic means it's only women who are solely unemployed and do nothing else but maybe women who have a part-time job or are only working 5 hours a week and are still on the dole are they not considered unemployed anymore and how is that taken into account in the statistics so I think the more I looked at it the more I questioned the statistic and the more questions that came up that it would be interesting to know and to see more data behind it

Interviewer: Ok so when you say you reasoned it in-your-head, how do you reason about this in your head?

JS: what I mean with that is the low number of women in that statistic didn't seem logical to me so I tried to come up with a reason why could it be so low [R: eh em] and that's what I mean I reason in my own head, what could it be that it is so low, maybe it is that ah because a lot of women that are minding their children at home they are not considered unemployed, maybe because it is that ah people are on-the-dole that they are still employed on a part-time basis so it is kind of I try to reason how come there is such a low number or percentage of women unemployed when Ireland has such a large % of unemployment (...)

Interviewer: So if it is ok for you to go back to a particular moment when you seem to be surprised that a number was so low

JS: yea, it is more the question "how come this number is so low"

Interviewer: so so is it someone or something asking that question in-you-mind?

JS: yea I don't know if it is someone or something or whatever, it feels, I feel that it is myself asking the question "how come this number is so low"

Interviewer: and do you hear your own voice asking that question? is it your voice or is it someone else's

JS: it is my thoughts, it is my voice, it is asking me the question using my voice

Interviewer: Is that voice loud or quiet?

JS: no, it is normal

Interviewer: just normal [**JS**: ok] and is it from a distance away or is it from very close to you? if you try to go back to that time when you experienced those questions

JS: No it is not distant, it is just, it's here it is with me

Interviewer: is it behind you or in front of you [**Interviewer**: no] is it inside you?

JS: it is from inside

Interviewer: Inside your body or inside your head

JS: oh, it is inside my head

Interviewer: ok and it is just speaking in a normal voice, your normal, everyday voice [**JS**: yea yea yea] ok and do you answer that question

JS: I am trying to answer it, if that voice is asking that question well then I am trying to answer that question

Interviewer: ok, so when you have looked at these sections in detail and after you have posed these questions and attempted to answer them you mentioned that this was then close to the end your time reading the visualization, how do you know when you are finished?

JS: At no particular point did I feel that I was finished but that was when all the other colleagues arrived and there was one particular person arriving and she has an extremely loud voice and am... (...) I kind of said no I have to stop this now (...)

Interviewer: and again when you say that "I have to stop this now" is that you again saying that in-your-head?

JS: yea that is me in-my-head saying it because I can't, at that moment I have to stop this because I can't concentrate on my own thought processes that I'd need

Interviewer: Ok so how do you finish with it then?

JS: am long pause I was fairly annoyed that I had to stop because that person was annoying me so really I didn't finish by saying, it was kind of two ways now, on one way I am ok that's interesting data and I am going to close this now and on the other half was "god that person is annoying me" so as I was finishing it I was already entering another thought process with the groups and what they are talking about and my mind was occupied

Interviewer: ok good, and when you were finish do you close down the document

JS: am no I left it open, I had it opened as a separate tab on my Internet Explorer and I thought I'd leave it open in case I will just come back to it at a later stage am but I I think I got up from my desk
Interviewer: you stood up?] I stood up because at that stage the people that were right across from me were talking as well and I kind of go involved in their conversation

Interviewer: ok, so if we go, one of the things that you said at one point was that you felt a sense of surprise when you saw a large amount of women that stay at home with their family [**JS**: em] can you describe how that sense of surprise came over you? Is it something that happened over a prolonged time or..

JS: No I feel that it was at the start

Interviewer: and is it a shock surprise or was it ...

JS: no it wasn't such a shock it was more "oh I wouldn't have thought that" so it wasn't a "Oh my god" surprise it was just, it is interesting

Interviewer: ok so when you say "oh I wouldn't have thought that" again is that a voice in-your-head saying that

JS: yea (abrupt)

Interviewer: and, and when you say that "oh I wouldn't have thought that" what do you do at that point, how does that change your viewing of the chart

JS: em long pause I think that is what, I don't know if it changes it, I think it brought me onto the other parts of the data to see what are the other women doing if such a large part are staying at home and like 2 thirds of women are either working or staying at home, so what are the other ones made up of and the other thing as well is ah am that it brought thoughts into my head of women actually minding home, like mothers staying at home

Interviewer: ok and when you say it brings thoughts of mothers...

JS: I could see women working in the kitchen

Interviewer: now?

JS: now as well but I could see women working in the kitchen as I looked at the charts, it is this kind of visual of the kind of what is portrayed of women working and minding at home, so it is women minding old people or minding families members or things like that

Interviewer: Ok so when you said there that you saw images of women minding people at home, are they images of women that you know, do you recognize any of their faces?

JS: No (long pause, looks into space) they are more

Interviewer: Is it you?

JS: No

Interviewer: are they familiar to you

JS: No, I don't think so, it is more like you see them in an ad, a stereotype of a housewife

Interviewer: ok and so can you remember at that point were you looking at the pie chart or do they appear in front of you, the images I mean

JS: am, I can say that they appeared in-my-head, I can't say that they appeared in front of me, it was in my head

Interviewer: are they clear or fuzzy

JS: No they are fairly clear

Interviewer: were they moving, is it like a film or a photograph

JS: No they are moving

Interviewer: are you in it? could you see yourself looking at the film or could you just see the film

JS: just the film

Interviewer: is it a distance away

JS: No, it's close, I don't, I don't feel like watching it from a distance or like a film in a cinema, they are just in my head [**I**: ok]

(...)
Interviewer: Ok and how do you try to bring people that you know into this, if we go back to you reading the chart, how does that happen?

JS: god I don't know how it happens, it just happens

Interviewer: Do you see images of these people you know, do you hear sounds from the people that you know? [**JS**: no] Do you see any images or sounds from yourself? [**JS**: no] how do you connect sections of the chart with your own situation or of people that you know, is it just a sense?

JS: It is just a sense, it is just a thought, it's not that I see or hear them

Interviewer: so it is just a feeling

JS: yea

Interviewer: and is that a warm feeling

JS: long pause I don't know it is just a feeling
Interviewer: so it is a feeling you get when you look at a section of the chart and you associate that section with yourself or someone you know?

JS: It is not a section that is associated with me it's more how do I, my life, my surroundings fit into that data, so this is a data visualization of Irish women and how or would I feel the same data from my friends do I get a sense that what I am seeing is true to what I see in my life [**Interviewer**: ok] but I can't necessarily say that I see people that I know, it is more or less just a feeling I get

Interviewer: ok so I am now going to go through what you experienced and if I leave out anything please stop me [**JS**: ok] ok so you were at work sitting in front of your computer screen, you were sitting down your hands may have been on the table or supporting your chin, the screen was slightly to the right of you, there were some ambient sounds but some were more distractive particularly at the end [**I**: yea, really much at the end] and there was a cup of coffee and a bottle of water on the left side of the table. So when you started the first thing that grabbed your attention was the patterns, how garish and possibly how they looked like 3D images because of the use of these particular patterns

JS: Yea it was just kind of I just thought that who would represent data like that because it was very hard on the eye

Interviewer: ok so then you began to focus on the two largest sections and you felt a sense of surprise after reading one of these, then you, that triggered you to move on and look into more detail at the other small sections and you began to analyze the implications of these and at a certain point you began to connect your own situation and how you possibly would be placed into this chart and how people around you fit into this data [**I**: yes] so once you have do that then there came a point when someone in your office was particularly loud and this distracted you and you felt that you had to close the document without feeling that you had finished reading it fully

JS: What I would say is that I was in the middle of my thought process when that interruption came, so I was not satisfied that I had got my head fully around the chart and yea I was not satisfied at all

Interviewer: ok so you were distracted by someone and then finished it at that point

JS: I just made a conscious decision that at that point and with the things going on around me I couldn't concentrate...

Interviewer: but you didn't close you left it open in a separate tab so if you wanted to go back to it you could, ok so did I leave out any detail that you would like to add

JS: no

Interviewer: no, ok thanks very much the interview is now complete.

end

C

LIST OF EXAMPLES FROM THE DESIGN SPACE SURVEY

Year	Title	Credit	Source
1862	Marshall Islands Stick Charts	unknown	http://tinyurl.com/jp9ec53
1871	Thermodynamic Surfaces	James Maxwell	http://tinyurl.com/j63bq9d
1910	Pin Maps	unknown	http://tinyurl.com/zp7bgjn
1913	Frankfurt Streetcar Load	Frankfurt City Council	http://tinyurl.com/zp7bgjn
1935	Electricity consumption (Detroit)	Detroit Edison Company	http://tinyurl.com/nrq9zwb
1947	Stedman's Conic System	Dr. Don Stedman	http://tinyurl.com/jfus64h
1957	Proteine Visualizations	John Kendrew	http://tinyurl.com/m44m9d
1968	Bertin's Reorderable Matrices	Jacques Bertin	http://tinyurl.com/jhawudu
1987	All the Submarines of the United States of America	Chris Burden	http://tinyurl.com/jkhl9zt
1992	Tactile Infographics	American Printing House for the Blind	http://tinyurl.com/h3v4ws4
1995	Historical Abstract: CPI 1995	Loren Madsen	http://tinyurl.com/jjpf4fm
1995	Historical Abstract: Humdef	Loren Madsen	http://tinyurl.com/jjpf4fm

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YEAR	TITLE	CREDIT	SOURCE
1995	Live Wire (Dangling String)	Natalie Jeremijenko	http://tinyurl.com/gt3hchp
1998	Historical Abstract:L&M*	Loren Madsen	http://tinyurl.com/jjpf4fm
1998	Historical Abstract: pipes	Loren Madsen	http://tinyurl.com/jjpf4fm
1999	6,000,000,000 Monkeys	Loren Madsen	http://tinyurl.com/jjpf4fm
1999	Clockwork: 6 Billion Monkeys	Loren Madsen	http://tinyurl.com/jjpf4fm
2000	Corpse 1 & 2	Loren Madsen	http://tinyurl.com/jjpf4fm
2001	Sensetable	James Patten, Hiroshi Ishii, Jim Hines, Gian Pangaro	http://tinyurl.com/jvawh28
2002	Illuminating Clay	Ben Piper, Carlo Ratti, Hiroshi Ishii	http://tinyurl.com/prhjwoc
2002	Mount Fear	Abigail Reynolds	http://tinyurl.com/zfsg6me
2004	Gods and Demons	Loren Madsen	http://tinyurl.com/jjpf4fm
2004	Infotropism	David Holstius John KembelAmy HurstPeng-Hui WanJodi Forlizzi	http://tinyurl.com/hzmtj4a
2004	Tactons	Stephen Brewster Lorna M. Brown	http://tinyurl.com/gw66sn8

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YEAR	TITLE	CREDIT	SOURCE
2004	WaterCalls	Morten Pettersson	http://tinyurl.com/jqhnkjr
2004	World Internet Statistics	Etienne Cliquet	http://tinyurl.com/gsszpkg
2004	Worry (Prayer) Beads	Loren Madsen	http://tinyurl.com/jjpf4fm
2005	Edible Bits	Dan Maynes-Aminzade	http://tinyurl.com/zm45jqp
2005	Haptic Shoes	Xiaoyan Fu Dahai Li	http://tinyurl.com/j3u7vdg
2005	Perpetual (Tropical) SUNSHINE	fabric | ch	http://tinyurl.com/ht9qrpz
2006	3D Infographic Maps Built with Lego	Samuel Granados	http://tinyurl.com/4eb774l
2006	datamatics	Ryoji Ikeda	http://tinyurl.com/6x544th
2006	Eavesdripping	Sascha Pohflepp	http://tinyurl.com/jqdhxue
2006	Email Erosion	Ethan Ham	http://tinyurl.com/zoycrne
2006	Existing independently	Justin Stewart	http://tinyurl.com/z6pw35u
2006	GORI.Node Garden	Jee Hyun Oh	http://tinyurl.com/jl7sl4j
2006	NOWHERE Ð data landscapes	Ralf Baecker	http://tinyurl.com/jga5s9x
2006	Physical Bar Charts	Lucy Kimbell	http://tinyurl.com/hvk9osm
2006	PlantDisplay	Satoshi Kuribayashi, Akira Wakita	http://tinyurl.com/govnytr
2006	Plastic trade-off	Sylvia Eckermann	http://tinyurl.com/s6q4e

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YEAR	TITLE	CREDIT	SOURCE
2006	Tac-tile	Steven Wall, Stephen Brewster	http://tinyurl.com/hebaphp
2006	Tides and Poles (series)	Nathalie Miebach	http://tinyurl.com/zky3yrh
2007	Fundament	Andreas Nicolas Fischer	http://tinyurl.com/jfhskrp
2007	Global Cities	Richard Burdett	http://tinyurl.com/gp3etck
2007	Sound/Chair	Matthew Plummer-Fernandez	http://tinyurl.com/c9ttfuj
2008	2am-2pm	Justin Stewart	http://tinyurl.com/kg5cfss
2008	A Week in the Life	Andreas Nicolas Fischer	http://tinyurl.com/zysk8cw
2008	Changing Weather	Nathalie Miebach	http://tinyurl.com/hafzhdt
2008	Consumer Confidence, 2006-07	Joshua Callaghan	http://tinyurl.com/5wwujx
2008	Global Tobacco Production, 1950-Present	Joshua Callaghan	http://tinyurl.com/5wwujx
2008	Indizes	Andreas Nicolas	http://tinyurl.com/jd3sx7h
2008	Kinetic Sculpture BMW	Joachim Sauter	http://tinyurl.com/zfg7bnt
2008	Lego-powered time-tracking	Michael Hunger	http://tinyurl.com/24y8347
2008	Mapping Mixed Information	Justin Stewart	http://tinyurl.com/jjfd7nn
2008	Mapping mixed information	Justin Stewart	http://tinyurl.com/hdmek8p

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YEAR	TITLE	CREDIT	SOURCE
2008	Military Spending by Nation	Joshua Callaghan	http://tinyurl.com/5wwujx
2008	reflection	Andreas Nicolas Fischer	http://tinyurl.com/jr8fpwp
2008	Shade Pixel	Hyunjung Kim, Woohun Lee	http://tinyurl.com/hn2q5yd
2008	Sound memory (Oslo Rain Manifesto)	Marius Watz	http://tinyurl.com/jkbqdff
2008	Tangible Bug Tracking using LEGO bricks	Takeshi Kakeda	http://tinyurl.com/n99m8b2
2008	US Economic Growth 1997-2003	Joshua Callaghan	http://tinyurl.com/5wwujx
2008	US Poulation by Race, 2000	Joshua Callaghan	http://tinyurl.com/5wwujx
2008	Virtual gravity	Silke Hilsing	http://tinyurl.com/nro852
2008	Wable	Physical Interaction Lab	http://tinyurl.com/yo8nd6
2008	Wooden Model of a 3D MRI Scan	Neil Fraser	http://tinyurl.com/6bb8x7
2008	World Poulation, 0AD-Present	Joshua Callaghan	http://tinyurl.com/5wwujx
2009	Ask Poly	Digit	http://tinyurl.com/hzy6qg3
2009	Centograph	Tinker	http://tinyurl.com/zrc7adw
2009	Data Morphoses	Christiane Keller	http://tinyurl.com/yk57nxd
2009	Devided time 99-09	Justin Stewart	http://tinyurl.com/hbsd7nk

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YEAR	TITLE	CREDIT	SOURCE
2009	form follows data	Iohanna Pani	http://tinyurl.com/hgh87pt
2009	In-formed (series)	Nadeem Haidary	http://tinyurl.com/gtbf2c2
2009	Pulse	Markus Kison	http://tinyurl.com/93d573h
2009	Regroup (The ex-googler universe)	Justin Stewart	http://tinyurl.com/kg5cfss
2009	Regrouped (the ex-googler)	Justin Stewart	http://tinyurl.com/z47nvqa
2009	Relief	Daniel Leithinger, Adam Kumpf, Hiroshi Ishii	http://tinyurl.com/h8afdss
2009	Sculptural Musical Scores (series)	Nathalie Miebach	http://tinyurl.com/5tg8tnr
2009	Weather Bracelet	Mitchell Whitelaw	http://tinyurl.com/hwx2uhl
2010	Changing Waters (series)	Nathalie Miebach	http://tinyurl.com/go2ymbb
2010	Constraint City: The pain of everyday life	Gordan Savicic	http://tinyurl.com/jothz48
2010	Measuring Cup	Mitchell Whitelaw	http://tinyurl.com/jp74mmk
2010	Retweet Ripples	Karsten Schmidt	http://tinyurl.com/h4rh8gu
2010	The Discreet Window	Ishac Bertran	http://tinyurl.com/gwwgx9e
2010	Visualize Your Finances, Ouch!	Hampus Edstrom	http://tinyurl.com/jrp4k8g
2010	Windcuts	Miska Knapek	http://tinyurl.com/hm3r5uf
2011	Can We Keep Up?	Hal Watta	http://tinyurl.com/qxqjuuf

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YEAR	TITLE	CREDIT	SOURCE
2011	DataCoaster	Bobby Genalo	http://tinyurl.com/znh3vfc
2011	District 5 Ploice Station, Chicago, IL	Loren Madsen	http://tinyurl.com/jjpf4fm
2011	Endings	Loren Madsen	http://tinyurl.com/jjpf4fm
2011	Hypertension Singing Bowl	Stephen Barrass	http://tinyurl.com/gksct77
2011	Keyboard Frequency Sculpture	Michael Knuepfel	http://tinyurl.com/zwm29t7
2011	Laser-Cut Time Series	Miska Knapek	http://tinyurl.com/hlyxf9o
2011	Lego for visualizing production problems and health care management	Dennis Pastor	http://tinyurl.com/creoc8o
2011	Of All The People In All The World	Stan's Cafe	http://tinyurl.com/6s7fazo
2011	Paper Models of 3D Plots	Paul DeMarco	http://tinyurl.com/gus6bbh
2011	SMS to Paper Airplanes	Christian Gross	http://tinyurl.com/zw8qkmp
2011	Snow Water Equivalent Cabinet	Adrien Segal	http://tinyurl.com/gmw7vnk
2011	The Rhythm of City	Varvara Guljajeva	http://tinyurl.com/zmbln6z
2011	WorldIndexer Installation	Plan B Architecture and Urbanism	http://tinyurl.com/zb39snr

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YEAR	TITLE	CREDIT	SOURCE
2012	attracting countries	Felix Worseck	http://tinyurl.com/h35jzk5
2012	Data Cuisine	Moritz Stefan	http://tinyurl.com/zwhwbzn
2012	Data Jewelry	Meshu	http://tinyurl.com/c8debxf
2012	data.anatomy [civic]	Ryoji Ikeda	https://vimeo.com/62272296
2012	DATAFOUNTAIN	Koert Van Mensvoort	http://tinyurl.com/6hgzb
2012	From Over Here	Paul May	http://tinyurl.com/j46rbkw
2012	Google Eye	Andrej Boleslavsk_	http://tinyurl.com/h63s5cg
2012	Grand Old Party: Political Satire	Matthew Epler	http://tinyurl.com/bp8cv4r
2012	House prices in Germany	Wolf-Dieter Rase	http://tinyurl.com/hx6epvq
2012	Hypermatrix	Yeosu	http://vimeo.com/46857169
2012	Lego-compatible thesis project board	Daniel K. Schneider	http://tinyurl.com/pzyj9ok
2012	Microsonic Landscapes	Juan Manuel Escalante	http://tinyurl.com/cktcgyv
2012	Paper Note	Andrew Nip, Andrew Spitz	http://tinyurl.com/gp3dw9l
2012	PARM: Projection Augmented Relief Models	James Goulding	http://tinyurl.com/hxy4nmk
2012	Point Cloud	James Leng	https://vimeo.com/42896836
2012	Pulse	Christian Ferrara, Jon McTaggert	http://tinyurl.com/hxptnaf

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YEAR	TITLE	CREDIT	SOURCE
2012	Rearrangeable 3D Bar Chart	Yvonne Jansen, Pierre Dragicevic	http://tinyurl.com/zmsqxwp
2012	SmarterPoland	Przemyslaw Biecek	http://tinyurl.com/oxqwbu6
2012	Smell Maps	Kate McLean	http://tinyurl.com/zzkl9zf
2012	Spectral Density Estimation	Andreas Nicolas Fischer	http://tinyurl.com/h5hrrfb
2012	Taste Maps	Kate McLean	http://tinyurl.com/h8sfuz3
2012	The Persistence of Play, (series)	Nathalie Miebach	http://tinyurl.com/h884rad
2012	The world's best spintop	Melanie Bossert	http://tinyurl.com/hfk2hgw
2012	T_hoku Japanese Earthquake Sculpture	Luke Jerram	http://tinyurl.com/6znszoa
2012	Trends in Water Use	Adrien Segal	http://tinyurl.com/jhxmqs7
2012	Underwater	David Bowen	http://tinyurl.com/zz2oe83
2012	Visual Music	Christopher Barrett, Luke Taylor	http://tinyurl.com/d4bdqpu
2013	Crystalized	SOFTlab and The Creators Project	http://tinyurl.com/h3sqg6n
2013	Dressed in Data	Laura Jones Perovich	http://tinyurl.com/qgq4nao

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YEAR	TITLE	CREDIT	SOURCE
2013	emoto	Moritz Stefaner, Drew Hemment,Studio NAND	http://tinyurl.com/cppx8qn
2013	Layered 2D Plots	Simon Stusak	http://tinyurl.com/zzx2tkx
2013	Line Charts of Cortisol Levels	Nilam Ram	http://tinyurl.com/h3ocjqz
2013	Loci	Andrew Spitz	http://tinyurl.com/bcdwged
2013	Network of the German Civil Code	Oliver Bieh-Zimmert	http://tinyurl.com/hjw6ztu
2013	NYC High School Dropouts	Ben Kauffman	http://tinyurl.com/hq6atwv
2013	Punchcard Economy: Data Knitting	Sam Meech	http://tinyurl.com/hn2p7ve
2013	Season in Review	Teehan+Lax labs	http://tinyurl.com/zqa64ad
2013	Solid Statistics	Volker Schweisfurth	http://tinyurl.com/glk8h6v
2013	Synergy (series)	Nathalie Miebach	http://tinyurl.com/z5pf2xm
2013	Walkable Age Pyramid	Atelier Brockner	http://tinyurl.com/gurdqrc
2014	Cosmos	Ruth Jarman, Joe Gerhardt	http://tinyurl.com/oxv29bd
2013	H3	Trevor Hogan, Eva Hornecker	http://tinyurl.com/j98no5v
2014	DNA Jewellery	Alireza Rezaeian, Jared Donovan	http://tinyurl.com/orwswxz

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YEAR	TITLE	CREDIT	SOURCE
2014	Golden Age	Domestic Data Streamers	http://tinyurl.com/jctvvr2
2014	Lifeline	Domestic Data Streamers	https://vimeo.com/93634967
2014	Lung	Willem Kempers, Amy Whittle	http://tinyurl.com/zp7cdmm
2014	My Life Don't Mean A Thing If It Ain't Got That Swing	James Pockson, Peter Shenai,Polly O'Flynn	http://tinyurl.com/k3sym3f
2014	Nature of Data	Domestic Data Streamers	http://tinyurl.com/jctvvr2
2014	People Wood?	Something & Son	https://vimeo.com/51591994
2014	Population Density	Ewa Tuteja	http://tinyurl.com/jmofbm6
2014	Water Works	Scott Kildall	http://tinyurl.com/hgk7ngk
2015	Data Necklace of Good Night SMS	Paul Heinicker	http://tinyurl.com/hchrkqx
2015	DIY Bertin Matrix	Charles Perin, Mathieu Le Goc	http://tinyurl.com/zm4muh6
2015	Storms, Gales and Blizzards(series)	Nathalie Miebach	http://tinyurl.com/hbkpzsw
2015	Touching Air	Stefanie Posavec	http://tinyurl.com/j5hqvto

Table 14: Full list of examples from Design Space survey

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