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Towards a Design Space for Multisensory Data Representation

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Humans have represented data in many forms for thousands of years, yet the main sensory channel we use to perceive these representations today still remains exclusive to vision. Recent developments now offer us opportunities to perceive data through different levels and combinations of sensory modalities. In this article, we survey the state-of-the-art in data representation that requires more than one sensory channel to fully interpret and understand the data. Drawing on techniques and theories adapted from Thematic Analysis and Prototype Theory, we analysed 154 examples of multisensory data representations to establish a design space along three axes: *use of modalities, representation intent* and *human–data relations*. We frame the discussion around presenting how a selection of examples, chosen from the collection, fit into the design space. This not only informs our own research but can also draw the attention of the human–computer interaction and Design Research communities to aspects of data representation that have hitherto been either ill-defined or underexplored. We conclude by discussing key research challenges, which emerged from the exploration of the design space and point out future research topics.

RESEARCH HIGHLIGHTS

- Defined the term Multisensory Data Representation.
- Surveyed the state-of-the-art in Multisensory Data Representation.
- Established and discussed a design space for Multisensory Data Representation.
- Presented five key recommendations for practical guidance on the study and design of Data Multisensory Data Representation.
- Proposed a research agenda based on research challenges and questions.

Keywords: data representation; design space; multisensory; physicalization; sensification; visualization

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1. INTRODUCTION

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 visualization. While multisensory data representations have been studied for a long time, starting from the seminal article by Miller (1956), the majority of existing data representations rely exclusively on the visual modality. Although there are some rare examples throughout the 20th century, which represent data through and beyond the visual modality, since the turn of the century we have seen a marked increase in data representations that combine at least two modalities (Fig. 1). Some examples include: a sculpted piece of wood to represent the world's distribution of wealth (Fig. 2A), a 3D printed cup whose form represents 150 years of Sydney temperature data (Fig. 2B) and the sounds and vibration emitted from a cube to represent the real-time hydrogen levels in deep space (Fig. 2C). These seek to exploit the material, aesthetic and natural qualities and affordances offered by modalities beyond vision to represent data.

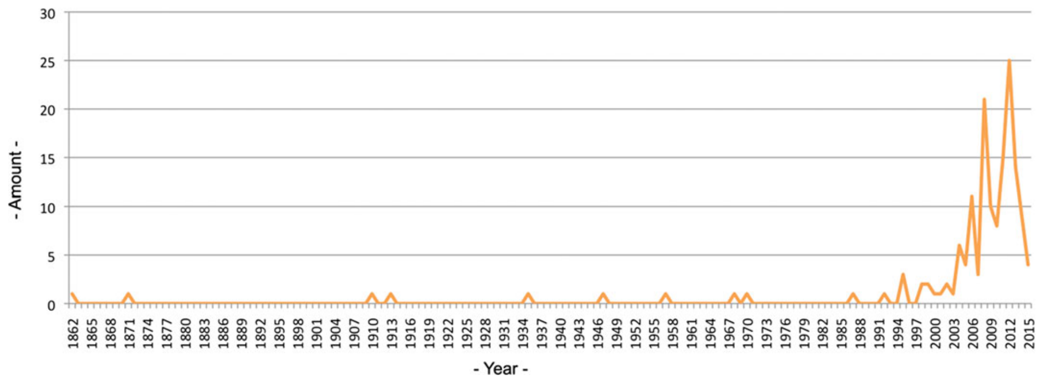

Figure 1. Year of publication/creation of the 154 examples from our survey (*x*-axis: year, *y*-axis: amount) (see Supplemental Appendix A for full list of examples).

Figure 2. (A) Fundament with permission from Andreas Nicolas Fischer (Fischer, 2007). (B) Measuring cup with permission from Mitchell Whitelaw 2010 (Whitelaw, 2010). (C) H^3 with permission from Trevor Hogan and Eva Hornecker (Hogan and Hornecker, 2013a).

The study of data represented beyond the visual modality, in particular the physical representation of data, has recently received increased attention (Alexander *et al.*, 2015; Jansen and Dragicevic, 2013; Stusak *et al.*, 2015). Reviews, such as Pousman *et al.* (2007), Swaminathan *et al.* (2014), Vande Moere (2008), Zhao and Vande Moere (2008) also provide a comprehensive overview of the state-of-the-art in these types of data representations. Notwithstanding these developments, we see limitations in the literature. First, research has tended to focus on a single modality (cf. Pan and Roberts, 2009), and few studies have surveyed research across different disciplines, for example Information Visualization (InfoVis), Human–Computer Interaction (HCI) and the Arts. Also, while research is continuing on multisensory data representation (cf. Bowen Loftin, 2003; Nesbitt, 2001; Nesbitt, 2005; Ogi and Hirose, 1996; Roberts and Walker, 2010; Search, 2015; Tak and Toet, 2013), few efforts have surveyed existing representations to identify key research and design challenges. To our knowledge, this article is the first to 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.

We believe that it is timely to explore the design space of data representations that encode data in more than one modality. We do this by first introducing the concept of *multisensory data representations*, we 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 people to interpret the data in a manner that is personally meaningful to them. This article makes several contributions to the study and design of multisensory data representations. First, we define, for the first time, *multisensory data representation*. Second, from 154 existing examples, we survey the state-of-the-art in multisensory data representations. Third, we establish and discuss a design space for multisensory data representations and finally, we propose a research agenda based on challenges and questions that are presently underexplored.

1.1. Defining multisensory data representation

The aim of this research is not to reclassify current data representations or prescribe a new domain; instead, we are 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 labelled data representation that does not rely exclusively on the visual modality as *Sonification* (Kramer and Walker, 1999), *Physicalization* (Alexander *et al.*, 2015), *Non-visual visualization* (Vande Moere, 2008) or *Cross/Multimodal displays* (Hoggan *et al.*, 2009). However, in the context of this research, these terms pose difficulties. First, the *sonification* of data typically relies on a single modality (auditory). Also, categorizing visualizations as *non-visual* is also problematic, as the visual modality often remains an integral communicative aspect of the representation, for example when physicalizations can be touched and seen. We therefore prefer the term *cross-modal* or *multimodal* display. Nevertheless, these are also problematic terms as the focus is on the output of the representation and not on the sensory channel used to perceive 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* (Ogi and Hirose, 1996), *Sensification* (Tak and Toet, 2013) or *Perceptualization* (Card, *et al.*, 1999). But as our aim is not to reclassify examples in our collection, we discuss work situated across many domains together under the umbrella term: *multisensory data representations*. We define multisensory data representation as:

> Multisensory data representation is a class of data representation that has a clear intent to reveal insight by encoding data in more than one representational modality and requires at least two sensory channels to fully interpret and understand the underlying data.

1.2. Related work

The research field that this kind of work is traditionally linked with is InfoVis (Card *et al.*, 1999). More recently, as the medium used to encode data has moved beyond the pixel toward tangible objects, sonifications and other modalities, we have seen an increased attention around the field of *HCI* (cf. Nissen and Bowers, 2015) as well as more artistic endeavours (cf. Rodgers and Bartram, 2011). Today, we continue to see related work in research fields such as *Tangible Computing* (cf. Pockson, 2014), *Data Art* (cf. Jarman and Gerhardt, 2014) and *Design* (cf. Hogan and Hornecker, 2013b).

Some attempts have already been made to address and define data representations, which fall outside the typical classification of Information Visualization. In Pousman *et al.*'s (2007) classification of *Casual Information Visualizations*, he distinguishes visualizations within this classification as: ambient, social and artistic. This definition also addresses the widening of usage of data representations, from a task-driven user to a lay audience whose motivation for engaging with visualizations is more personally meaningful rather than aiming at pure analytical discovery. Zhao and Vande Moere (2008) also proposed a domain model to establish the concept of *Data Sculpture* as a data-based physical artefact, possessing both artistic and functional qualities. Vande Moere (2008) extended this line of thinking by introducing five degrees of *'data physicality'*, which differ in the level of abstraction of how data are mapped and perceived by human senses. In recognizing the importance of design in the process of data representation, while also supporting and inspiring future designs, Vande Moere and Patel (2010) surveyed a collection of physical data representations, created within the context of education and defined a classification based on three categories—symbolic, iconic and indexical. While Vande Moere and Patel focused on the *design* of data representations, the research by Jansen and Dragicevic (2013) is more people-centred by addressing issues related to interaction. In this work, they establish an interaction model that can be used to help describe, compare and critique non-screen-based data representations.

Beyond work that attempts to categorize different types of data representation, we reviewed theoretical and empirical studies that address issues related to the representation and perception of data through more than one modality. This research is spread over a broad range of research disciplines including: *Psychology* (Freides, 1974; Heller, 1982; Miller, 1956; Warren and Rossano, 1991; Welch and Warren, 1980) *Scientific Visualization* (Ogi and Hirose, 1996), *Information Visualization* (Roberts *et al.*, 2014; Tak and Toet, 2013), *Human–Computer Interaction* (Bowen Loftin, 2003; Loftin, 2003; Reeves, *et al.*, 2004; Roberts, 2004; Search, 2015), *Geovisualization* (Faeth *et al.*, 2008; Harding, *et al.*, 2002), *Ergonomics* (Sarter, 2006), *Design* (Nesbitt, 2005), *Virtual Reality* (Basdogan and Bowen Loftin, 2009) and *Engineering* (Harding and Souleyrette, 2010). In this literature, we identified four prominent themes related to our research: *Human perception, Call for action, Previous surveys and Arts-based research.*

1.2.1. *Human perception*

A number of studies have investigated how combining representational modalities affects the capability of human perception. Warren and Rossano (1991) found that the tactile perception of transformation properties, such as tilt, size and length, in most cases, is as accurate as visual perception. Heller (1982) illustrated how the combination of modalities (i.e. touch and visual) can enhance the 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 in use. Miller (1956) refers to this as 'the span of absolute judgement'.

1.2.2. *Call for action*

A number of researchers have called for further research on multisensory data representations. For example, Roberts and

Walker (2010) encouraged 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 (2013) have argued for further systematic empirical research to develop design guidelines for multisensory data representations or as they call them, *Sensifications*. They claim that multisensory representations of complex data facilitate a more intuitive and transparent process. In particular, they suggest these help the user to: (i) acquire a wider range of detail (bandwidth expansion), (ii) fill in missing information (data completion) and (iii) gain a more holistic data experience (Gestalt forming). These aspects were also highlighted by Search (2015), 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 highlighted 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 (Sarter, 2002; Oviatt, 2002).

1.2.3. Previous surveys

Exploring the design space of multisensory data representation has been attempted before, in particular, Card and colleagues (1999) also explored this space and coined the term *Perceptualization*: a multisensory display of abstract information. This line of enquiry was subsequently extended by Nesbitt (2001). Nesbitt (2005) later categorized multisensory data representation via a multisensory taxonomy based on high-level metaphors, which he classifies as spatial, direct and temporal. The research we present in this article differs from this in regards to: approach, scope and contribution. Unlike previous attempts, we establish our 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.

1.2.4. Arts-based research

Apart from theoretical and empirical studies, other research has taken a more artistic and cultural view of non-typical data representations. Alongside the numerous articles by new media theorist Lev Manovich (cf. 2008), in which he highlights the cultural impact of data representation, Viégas and Wattenberg (2007) 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 (Stan's Café, 2011) 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.

2. DESIGN SPACE ANALYSIS

Design space analysis is a valuable approach to represent design rationale. Maclean and his colleagues (1993) 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, our 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 research, 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.

2.1. Methodology

In order to systematically understand the study and design of *multisensory data representations*, we surveyed contemporary and historical examples that fit the definition outlined above, from fields such as scientific research, design and art contexts. We identified international conferences and periodicals that publish the most articles related to this topic; these include ACM Conference on Human Factors in Computing Systems (CHI), ACM Conference on Tangible, Embedded and Embodied Interaction (TEI), IEEE Information Visualization Conference (InfoVis), ACM Transactions on Computer-Human Interactions (TOCHI) and IEEE Transactions on Visualization and Computer Graphics (TVCG). As well as journal articles and papers, we examined posters, and demos, where applicable. We also conducted a comprehensive online search for examples of work outside of academic publications, in particular for artworks. We surveyed work from online networks, such as Creative Applications,[1] research laboratories such as AVIZ,[2] archives of digital art exhibition, such as Ars Electronica[3] and personal websites of artists, designers and researchers.

[1] http://www.ca.com
[2] http://www.aviz.fr/wiki/pmwiki.php/Main/HomePage
[3] www.aec.at/

When gathering examples for our survey, we only included work that fully met our definition of multisensory data representation. We 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. Our 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 is included as additional material. We acknowledge that there may be some examples missing from our collection, mainly due to the lack of exposure surrounding the piece that is no publications or exhibitions. However, we feel that the examples in the collection are a fair representation of the state-of-the-art in multisensory data representation.

2.2. Analysis

The goal of our research was not to develop a taxonomy of multisensory data representations, instead we were more interested in analysing a large collection of representations and to establish a vocabulary to describe them. This can then be used to help shed light on the choices that designers face when creating multisensory data representations. Once we felt we had exhausted our search for examples we commenced the process of analysis. The overall goal of our analysis was to establish dimensions of the design space and categorise each example in the collection against these. The methodology used is based on Thematic Analysis (Boyatzis, 1998). 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 (Guest *et al.*, 2012). 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: (i) familiarization, (ii) thematic coding, (iii) abstraction, (iv) structuring and (v) categorization (Table 1).

2.2.1. *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 become more familiar with the data (collection). As with many qualitative 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 (Guest *et al.*, 2012).

2.2.2. *Thematic coding*

During the process of familiarization, we annotated the examples with keywords and phrases that describe the key characteristics of each representation, which included aspects such as functionality, use, context, data source, etc. Based on these annotations, we derived an initial set of thematic codes from the data (Table 2, 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 (Boyatzis, 1998). The procedure we 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, with minor adjustments being applied before the list of codes was finalized. Only codes that featured more than three times were utilized for further analysis.

Table 1. Methodological phases used to analyse the examples in the collection.

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 examples • Second 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	Categorization	• Categorize each example from the survey under the dimensions established • Confirm categorizing

2.2.3. *Abstraction and structuring*

Once we had completed coding the collection, we 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 (Braun and Clarke, 2006). An initial set of themes was produced by one researcher, which was then reviewed and refined together with the second researcher (Table 2, Column 2). These themes were then used to establish the dimensions of the design space, which are: *use of modalities, representation intent* and *human–data relations* (Table 2, Column 1).

2.2.4. *Categorization*

The final phase of analysis involved categorizing the examples in the collection against the dimension of the design space. The approach we took for this phase is adopted from Prototype Theory (Rosch, 1973). 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 our research, we applied aspects of this theory when sorting examples from the collection into the three dimensions of the design space. We specifically adhered

Table 2. 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.

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

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 our case: dimension) may be related to one another without having any properties in common that define the category (Rosch and Mervis, 1975). Second, we subscribe to the notion of *Generality*, where some members of a category (dimension) may be 'better examples' of that category than others (Lakoff, 1987). To exemplify this process, for the 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 we 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. We include this database as part of the additional material.[4]

3. THE DESIGN SPACE

We establish 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 thought of as design choices or questions that system designers must address when creating multisensory data representations. In the following, we 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.

[4]We also make an online version of this database available at http://www.tactiledata.net/mdr/database.csv

3.1. 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 and data insight through experience (Table 2, Column 2, Row 1). Hoggan and Brewster (2006) have already made a distinction between cross-modal and multimodal representation. In cross-modal interaction, different information is transmitted via different modalities, while multimodal interaction refers to the same information being transmitted by each modality. We apply the same concept to data representation. For instance, Ryoji Ikeda's installation *Data.anatomy [civic]* (Ikeda, 2012) encodes different data, derived from the latest Honda Civic car, in auditory and visual outputs, thus we consider this to be an example of cross-modal representation. However, *Tac-tile* (Wall and Brewster, 2006a) encodes the same data in sounds and vibration to allow visually impaired users to browse graphical information, thus we consider this to be a multimodal representation.

In regards to sensory modality and representation modality, we also apply a distinction between these two types of modalities. We use the term *representation modality,* when referring to representational artefact as this relates to the representational format, medium or material that encodes the data. However, when referring to sensory *modality,* from the perspective of the user/audience, we 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 we 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 Weather* (Fig. 3). Although this piece, which is a physical representation of

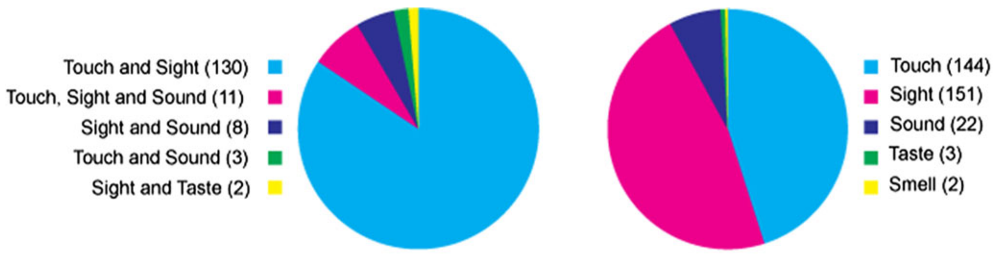

Figure 3. Inner pie chart (right): distribution of sensory modalities used in combination with other modalities. Doughnut (outer ring) (left): Combinations of sensory modalities.

weather and oceanic data, incorporates numerous modalities and materials, the viewers rely mainly on their sense of vision to interpret the representation. We do, however, acknowledge that its 3D form may affect the perception of the representation, as people can imagine what it would be like to touch. Piaget and Inhelder (1956) were the first to explain the notion 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 (2015) 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, we consider *Changing Weather*, 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, when vision interrelates with kinaesthetic experience. This may not be defined as touch, in the traditional sense, but kinaesthetic 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 2D representations such as bar graphs.

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 (Weiser *et al.* 1999), Tangible Interaction and Computational Materiality (Ishii and Ullmer, 1997), 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, we first discuss *multisensory data representation's* use of sensory modalities, following this we focus on representational modality through the lens of *materiality.* We conclude our 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.

3.1.1. Sensory modalities

We have already made the distinction between sensory and representational modality. We now focus the discussion of our analysis around sensory modalities. We do this, as we are more interested in representations that require more than one sense to perceive the data, over representations that utilize more than one representational modality. The analysis of the 154 examples shows that the predominant sensory modalities required, as part of a set, to interpret the data are sight (151) and touch (144) (Fig. 3, right). While 22 examples also require the audience to interpret the representation by listening to the representation, only 5 were found that incorporate other sensory modalities (taste and smell). Regarding the combination of senses to interpret the data, 130 required touch and sight and 11 required more than two sensory channels (see Fig. 3, left).

An example of a representation that requires more than one sensory channel to fully interpret the data is *Tac-tile* (Wall and Brewster, 2006a). While the user browses pie charts with a stylus pen, the data is transmitted to the users' 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 but we also found examples in other domains. Visual artist Ryoji Ikeda's installation *Data.anatomy [civic]* (Ikeda, 2012) 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 by mapping data points to sounds and dynamic graphics. Another example from the arts is *Perpetual (Tropical) SUNSHINE* (fabric.ch, 2012). This installation emits heat and light through a 'screen' composed of several hundred infrared light bulbs. The data driving this installation is transmitted by weather stations all around the Tropic of Capricorn measuring the real-time intensity of the sun. An example that relies on taste, smell and sight is the recent work of the design researcher Moritz Stefaner (2014). An experimental research project, *Data Cuisine* explores food as a means of data representation or as Stefaner refers to it as 'edible diagrams'.

3.1.2. Materiality

To fully appreciate the role representational modality plays in multisensory data representation, we 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 *et al.* (2013) recently asserted '*materiality of computation is best observed indirectly through the artefacts that employ it and interactions with those artefacts*' (pp. 639). Vallgårda and Redström (2007) claim that computation needs to be combined with other materials before we can consider it to be a material itself. However, Dourish and Mazmanian (2011) argue that digital information (data) is a material, in that it is only ever encountered 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's 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 (2011) disagree with Vallgårda and Redström (2007). We 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 3D form of a physicalization.

We here focus on the materiality of the objects and surfaces which the data has been encoded in. Table 3 shows a selection of materials used to represent data in the 154 examples we surveyed, sorted by the sensory channel used for interpreting the representation. However, we should note that some materials may be interpreted using several sensory channels, such as wood (sight and touch). When investigating materiality, we framed our analysis around the following question: Is the motivation for material choice metaphorically linked to the data source? From the examples we surveyed, we only found a few that use materials we consider to be metaphorically linked to the data source. One example is Perpetual (Tropical) SUNSHINE, (fabric.ch, 2012). Typically, sun intensity is translated into numerical data and represented in Fahrenheit or Celsius. However, this installation directly translates the heat and light emitted from the sun to the heat and light emitted from infrared bulbs and offers the audience who gather in front of the screen a visceral experience of the data source. Other examples include Paul May's 'From Over Here' (May, 2010) comprising numerous laser-cut paper cards, each representing a month of articles from the New York Times (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 (2009) 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 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 (Watts, 2011).

For the majority of examples surveyed, we found no evidence to show that the material choice has any metaphorical connection to the data source. To exemplify this, we return again to Nathalie Miebach's woven sculpture *Changing Weather* (Fig. 4). Although the perception of movement in

Table 3. List of materials identified in the 154 examples in the collection, these are sorted by the sensory modality used to engage with the material.

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*
Thermoception	*Infrared light*

Figure 4. Changing Weather with permission from Nathalie Miebach (Miebach, 2012).

this piece may reflect the sometimes-chaotic nature of the represented weather conditions, the material of wicker, yarn, thread and plastic is not related symbolically or metaphorically to the data source. There may be no direct link between the choice of materials in this piece and the data source; however, the materials and techniques used to assemble these certainly add interest and intrigue to the piece. This strategy is often employed by data artists who seek to offer more than just data insight, by creating aesthetic, engaging and often provocative work that sometimes facilitates the generation of meaning that goes beyond the topic of the data source.

3.1.3. *Beyond representation modality*

During our survey, we also noted nine recent examples that utilize properties beyond representation modality when encoding the data. Although the data is encoded 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' (Fig. 5A). This piece consists of a number of 3D printed spin tops, where the shape of each spintop is a translation of political, environmental, health, education, economic and quality of life data of a specific country. Once the data for a country is collated, an algorithm generates the shape of a spintop. 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 cannot be fully interpreted until the spintop is set in motion, which means the data is actually encoded in the shape as well as the behaviour of the representation. Another example that encodes data beyond traditional modalities is 'Life Don't Mean A Thing If It Ain't Got That Swing' (Fig. 5B), a usable swing installation that encodes data that represents the satisfaction levels of a country's population in its' architectural properties, that is the length of rope, the height of the seat, etc. People interpret the data through the experience and enjoyment of their ride on the swing.

In the collaborative artwork *Change Ringing* by artist Peter Shenai and composer Laurence Osborn (Fig 5C), climate data, representing changes in temperature over the last century, is encoded in the shape of six cast bronze bells. Again, the data has been translated into the physical properties of the objects. However, the audience cannot perceive or fully interpret the data until they hear the different sounds that emanate when the bells are rang. These examples illustrate a new departure for data representation, away from modalities such as visual, physical, sound, smell and taste to new ways of encoding data in the performance, behaviour, affordances and resulting experience of the data representation.

3.2. Representational Intent

During the analysis of examples in our collection, we elicited 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 (Table 2, Column 2, Row 2). They describe the motivation for creating the representation 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 design. Some seek 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 and debate about a concern related to or inspired by their creation. Traditionally, the primary purpose of data representation has been to provide people with an analytical tool that enhances human cognition about a task, and their primary value has typically been assessed along the lines of the effective and efficient discovery of information (Van Wijk, 2013). More recently, however, some have attempted to broaden the intent of visualizations to include more open-ended insight,

Figure 5. (A) The World's Best Spintop with permission from Melanie Bossert (Bossert, 2012). (B) Life Don't Mean A Thing If It Ain't Got That Swing with permission from James Pockson (Pockson, 2014). (C) Change Ringing with permission from Peter Shenai (Shenai and Osborn, 2014).

such as creating awareness and evaluating the emotional response to visualizations (cf. Vande Moere and Claes, 2015). The establishment of research fields such as *Information Aesthetics* (Lau and Vande Moere, 2007), *Artistic Visualization* (Viégas and Wattenberg, 2007) and *Data Art* (Ramirez Gaviria, 2008) has been the catalyst for extending representational intent by incorporating non-analytical intentions and evoking hedonic responses.

In our exploration of the design space, we categorize representational intent along the lines of *Utilitarian* and *Casual*, as we feel these terms capture the essence of all themes that make up this dimension. Representations whose intent we define as *Utilitarian* target a specific audience to reveal data insight related to an explicit task, such as using coloured building blocks to represent production problems within a large organization (Pastor, 2011), while *Casual* representations are intended for a much broader audience 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 (Fig. 3). In our survey, the majority of examples (115/154) were created for a casual audience. We 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 our own interpretation/experience.

3.2.1. *Utilitarian*

Returning again to the work of Wall and Brewster (2006b), *Tac-tile* provides a good example of a multisensory data representation developed primarily to serve the functional needs of its users. In explaining their motivation for *Tac-tile,* Wall and Brewster point toward the 'lack of access to data visualizations' for people with visual impairment, which hinders them from engaging in 'numerate disciplines such as maths, economics or science'. In creating *Tac-tile*, they offer people, who have a visual impairment, a platform that allows them to explore and interpret data representations using both their auditory and haptic perception. Examples from our survey that serve the utilitarian needs of a broader section of society include *Water Usage*, a prototype design by Nadeem Haidary (2010). A visible compartment within a faucet acts as a visualization of the amount of water consumed each time the faucet is used. '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 the designer 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 a *Rearrangeable 3D Bar Chart*, which was created by Janson and her colleagues to compare the efficiency of physical and virtual data representations (Jansen, *et al.*, 2013). This representation can be viewed and held when interpreting the data and is created to replicate all the features of a virtual bar graph.

3.2.2. *Casual*

At the other end of this dimension are representations that are created for a more casual user/audience and typically represent non-critical data. These types of representations may be seen as a medium for artistic expression that draws attention to an issue or 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 representation as part of their work to make statements and encourage public debate on various cultural, political or social issues. Viégas and Wattenberg (2007) discuss some of this work in detail.

We 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 effect that multisensory representations have on people, Hogan and Hornecker (2012) have determined that the meaning acquired by people when interpreting representations that use non-traditional representational modalities such as haptic and auditory is different from that generated through the visual modality. A multisensory data representation that exemplifies this is *Pulse*. Created by Berlin-based artist Markus Kison (2009), *Pulse* is a live visualization that uses social data from private weblog communities such as *blogger.com*. The piece uses concepts from Robert Plutchik's book 'Psychoevolutionary Theory of Emotion' to translate emotion-based tags found in recent blog entries 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 by lgail Reynolds in 'Mount Fear' is very explicate (Fig. 6A), and although the data source (violent crimes in East London between 2002 and 2003) would normally be associated with more utilitarian data representations (Fig 6B), we 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 or concern and to trigger debate.

The type of data insight revealed to the viewer through these examples varies, but it is clear that the data insight revealed is not intended to assist in any work-related task. However, this was never the intention of the artists, it is more about provoking the audience to interpret the work in a way that is personally meaningful to them. A key characteristic of representations that lie at this end of the 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

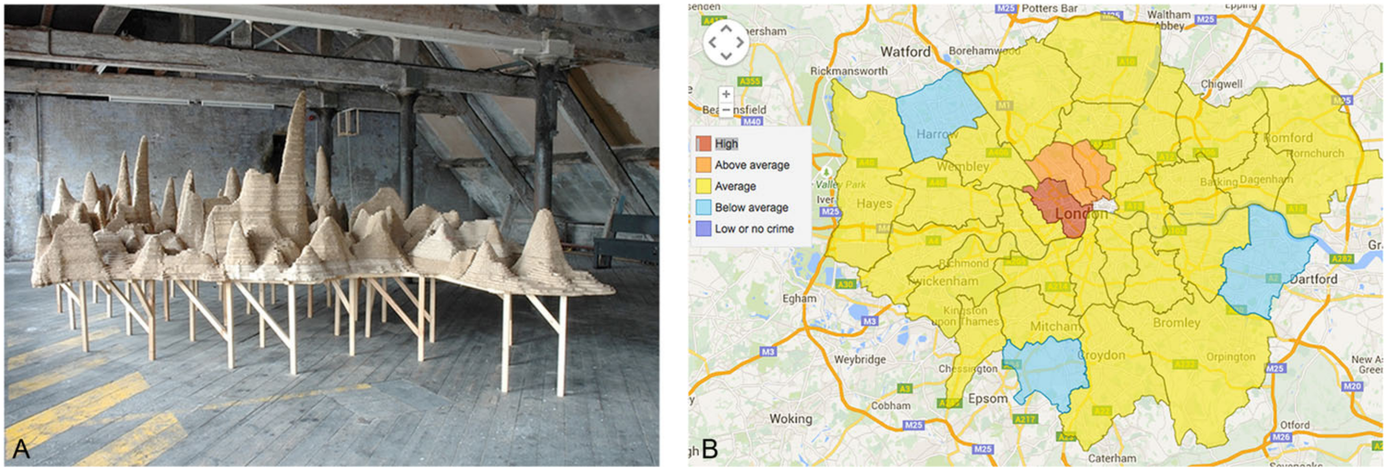

Figure 6. (A) Mount Fear with permission from Abigail Reynolds (Reynolds, 2002), (B) The distribution of London crime rates (source http://maps.met.police.uk/).

intention is to reveal similar data insight for everyone who engages with the data representation.

3.3. Human–data relations

The final dimension of our 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 (Table 2, Column 2, Row 3).

The digital age has allowed us to move beyond the printed page to bits, pixels and atoms, and opened new possibilities for designers to let people engage with data in ways that were not possible before. Digital technology also meant that live data 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. Brodbeck, *et al.*, 2009; Card, 2002), 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 (2000), who identified the concept of *asymmetry in data rates*, where more data flow 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 data input.

Our design space analysis explores the mode of interaction in terms of *active* versus *passive* engagement, these axes represent the themes: interactive systems, non-interactive systems (Table 2, Column 2, Row 3). We 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. We categorise these themes under the same dimension as they often relate. A data representation that requires interaction to fully interpret the data we define as *active*, whereas we consider representations that do not require or encourage interaction as being *passive*. While we acknowledge that all data representations (multisensory or not) require some level of engagement to form meaning from the representation, we only consider these to be *active* if they require people to intentionally manipulate the representation or data. We consider data to be *dynamic* if it is live or multidimensional, whereas data that is fixed and archived we consider *static*. When analysing the examples in our database, each could be categorised under one of four possible options: {passive/static}, {passive/dynamic}, {active/static} and {active/dynamic}. We 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} (Fig. 7).

3.3.1. *Interaction mode*

Passive. Our survey shows that the dominant mode of interaction with multisensory data representations is passive (93) (Fig. 8, right). *Datafountain* 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 and incorporates jets of water whose height is controlled by live data. In one application of this installation, the creators mapped the latest value of three international currencies to corresponding water jets (Fig. 9). 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, we 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 we also consider to be *passive* is Fundament by Andreas Nicolas Fischer (Fig. 2A), 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 our survey facilitate and encourage active engagement between the user and the data representation, and an example that exemplifying this is *Wable* (Physical Interaction Lab, 2008). Comprising a motorized physical bar chart that represents the online activity of a person logged into the system, each of the bars can be configured to link to online social network accounts, such as, for instance, Twitter or Facebook. The system monitors these accounts, and if activity increases (e.g. retweets or shared posts), the bar rises. A slider button incorporated into the physical interface allows viewing of past activity. *Wable* facilitates *active* engagement while also being using *dynamic* data. Although we acknowledge that the interaction offered by *Wable* is quite limited, the system does allow users to choose which data stream is being represented, which facilitates a sense of ownership in the user. An example that facilitates much more interaction between the data and the user is Virtual Gravity (Hilsing, 2010). Using Google Insights as the data source, this system represents the past search queries of the user. Using a tangible 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 (Fig. 10). The complex interaction of Virtual Gravity facilitates a rich and informative engagement between the user and the data source and allows for in-depth exploration of the data.

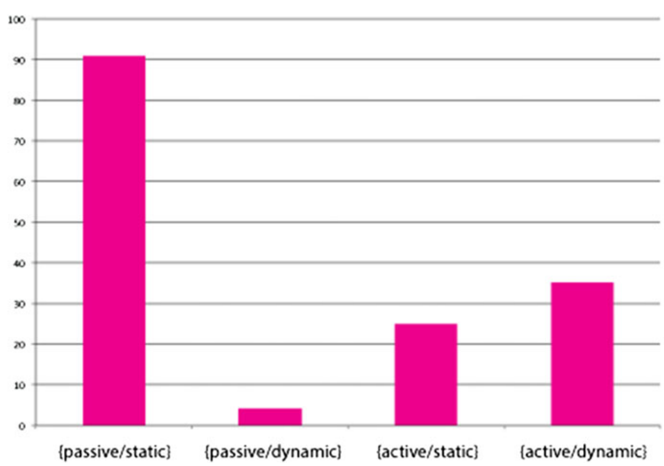

Figure 7. Design space dimension: human–data relations, showing the combination of interaction mode and nature of data: {passive/static}, {passive/dynamic}, {active/static} and {active/dynamic}.

3.3.2. *Nature of data*

When we analysed the thematic codes applied to the examples in our collection, we identified a number that related to the nature 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 we now use as the basis of our discussion on this aspect of this dimension. We could consider these data properties as polar dimensions (Fig. 8, *static*, *dynamic*); however, some data could be considered as possessing the characteristics from both poles. For instance, *data.anatomy [civic]* (Ikeda, 2012) represents a data set that, due to its size and multidimensionality, may be seen by some as dynamic, whereas in fact the data that drives this installation is retrieved from a static archived data set. An example that uses static data is From Over Here (May, 2010). 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 and continual updating of the representation. One example from our collection that is both live and multidimensional is The Rhythm of the City (Guljajeva, 2011). This art piece translates geotagged content from social media platform, such as Twitter, Flickr and Youtube, into the rhythm of

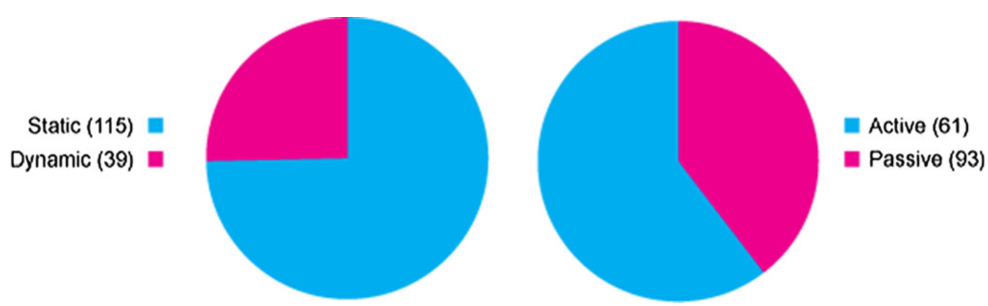

Figure 8. Design space dimension: human–data relations. Left pie chart: Nature of data. Right pie chart: Interaction mode.

Figure 9. Data Fountain with permission from Koert Van Mensvoort (Van Mensvoort, 2012).

Figure 10. Virtual Gravity with permission from Silke Hilsing (Hilsing, 2010).

a physical metronome in real time. 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.

3.4. Plotting the design space

In the previous sections, we introduced and discussed the design space for multisensory data representation. We now select 18 representations from our collection and trace their position in each dimension to present a snapshot of how the design space is populated. When selecting the 18 examples, we wanted to show a fair representation of the breadth of the design space. For instance, the majority of examples in our collection are situated at the casual end of the dimension: Representational Intent, this is also the case for the 18 examples chosen. This was similarly done for the other dimensions. The examples used represented in Fig 11 are: Illuminating Clay (Piper, *et al.*, 2002), Tactons (Brewster and Brown, 2004), Mount Fear (Reynolds, 2002), Tides and Poles (Miebach, 2006), Weather Bracelet (Whitelaw, 2009), Paper Note (Nip and Spitz, 2012), Data Cuisine (Stefaner, 2014), From Over Here (May, 2010), Underwater (Bowen, 2012), Google Eye (Boleslavský, 2012), Smell Maps (McLean, 2012), Touching Air (Posavec, 2015), Sensetable (Patten, *et al.*, 2001), Centograph (Tinker, 2009), Pulse (Kison, 2009), Data Fountain (Van Mensvoort, 2012), Season in Review (Teehan and Lax labs, 2013) and Virtual gravity (Hilsing, 2010).

Figure 11 shows the three dimensions of the design space, and each of the 18 examples are placed into a group along each. Thin 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 we inspect the graph, we see two zig-zag patterns (Fig. 11: T1&2), these patterns represent a correlation between different dimensions of the design space. First, we can see a collection of representations that use two modalities that are also (with two exceptions) casual in intent. These also utilize static data and are generally passive (Fig. 11: T1), whereas those that use three modalities tend to be utilitarian in intent, with dynamic data and offer user interaction (Fig. 11: T2). These patterns are also evident when we increase the number of examples in the parallel coordinate plot.

In Section 3.3, we highlighted the pertinacity of representations that offer interaction, to be coupled with dynamic data, whereas passive representation are more likely to use static data. This trend also appears when we populate the full design space. However, Figure 11 shows us further correlations between separate dimensions of the design space. These zig-zag patterns (Fig. 11 T1&2) raise a number of fundamental questions, including: why do casual representations, more often not utilize only two modalities, while utilitarian representations use more? Although we do not have any clear evidence that explains this trend, we 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. We 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 may be, the level of data insight generated is a reflection of the type of data and mode of interaction.

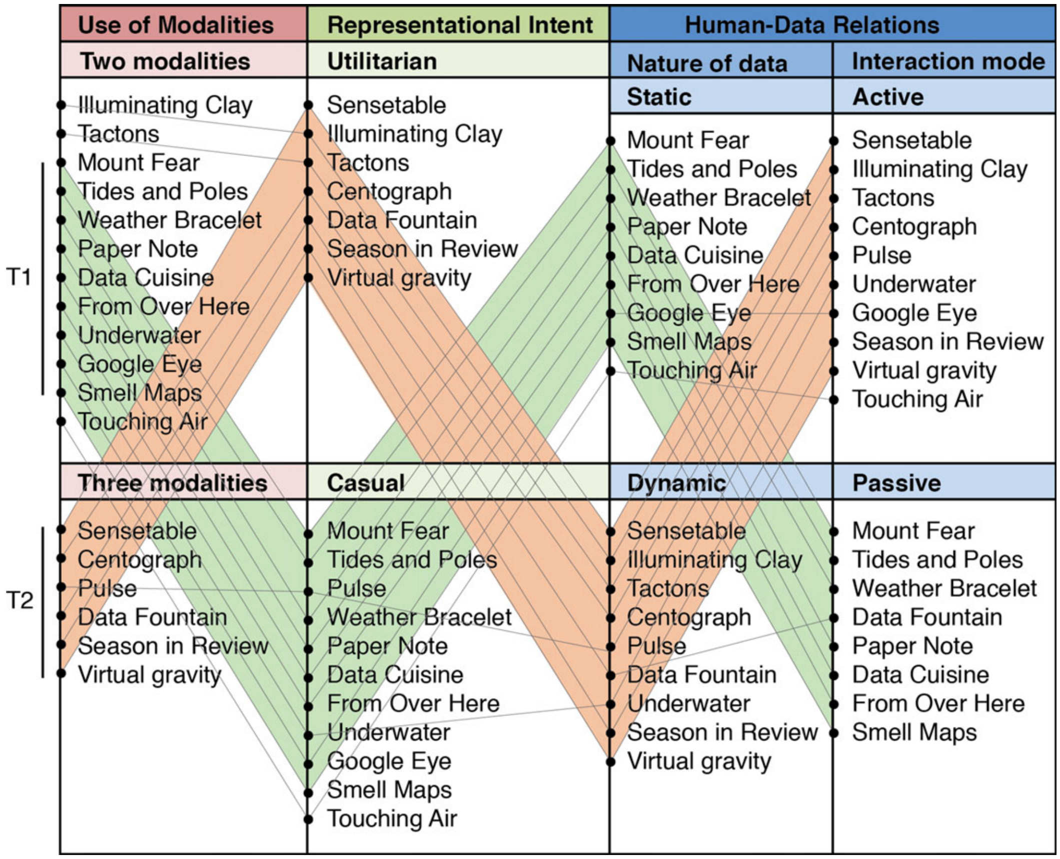

Figure 11. Parallel coordinate plot of 18 existing multisensory data representations across three design space dimensions. Lines trace each representation's position along the design space and shaded areas illustrates trends.

4. DISCUSSION

Our analysis of the design space has provoked three key research questions and challenges that have &yet to be fully addressed. These are: (i) *Does adding modalities add value?* (ii) *How do multisensory data representations affect and change the user experience?* and (iii) *When is a representation not a representation?* In the following, we discuss each of these individually. Derived from this discussion, we address research topics that are presently underexplored and list five key recommendations for addressing these issues.

4.1. Does adding modalities add value?

Once we had analysed the design space regarding the use of modalities, we questioned: *Does adding more representational modalities add further value to the representation?* It may be argued that additional modalities increase the richness of the representation by stimulating more sensory channels. However, adding modalities may also increase the cognitive demand on people to reveal data insight. Research from cognitive psychology reveals that extraneous cognitive load is caused by unnecessary cognitive processes (Kalyuga, 2011). For example, 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 may also increase the cognitive load required to interpret the representation (Soon Fook and Aldalalah, 2010). 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 (Sweller *et al*., 1998). Although work has commenced (particularly in the field of visual analytics) to investigate the cognitive and perceptual capabilities needed to explore complex information visualizations (cf. Kalyuga, 2011), 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 user experience of data representation. From an artistic perspective, expanding the sensory perception of a data representation, which may result in possible overloading of audiences' cognitive processes, could be a deliberate strategy by the artist.

When discussing the *representational intent* dimension, we categorised representations as being either *casual* or *utilitarian*. We believe that multisensory data representations at the 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* (Wall and Brewster, 2006a), 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' (Wall and Brewster, 2006a pp. 1132). At the other end of this dimension, where the purpose of a representation is not task related but to reveal or draw attention to an issue or concern, we argue that the generation of data insight is merely a part of the overall experience that the creator is hoping to achieve. 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 utilitarian task or draw attention to a concern, data representations that stimulate more than one sensory channel, we argue, facilitate a more holistic sensory experience and allow the user/audience to interpret the data in a manner that is personal to them.

4.2. Do multisensory data representations affect and change the user experience?

In our design space analysis, we distinguished representations that allow user engagement from those that do not (*active* versus *passive*). We also surveyed representations along the trajectory of representational intent from *utilitarian* to *casual*. This analysis shows not only do multisensory data representations allow for the full spectrum of human interaction but also the type of insight people gather from these varies from analytical discovery over awareness to intrigue or curiosity. We 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 (2000) 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. Hogan and Hornecker, 2012), the majority of literature evaluates the usability of data representations based on traditional measures such as *efficiency* and *effectiveness*. The InfoVis research community has recently began to acknowledge the shortfall in approaches and techniques to measure non-analytical aspects of information visualizations. Lam *et al.* (2011) point out, there is a lack of research that studies people's subjective experiences of visualizations, and Vande Moere and Claes (2015) have recently advocated incorporating qualitative and tacit aspects in future research on physicalization. Jackson and colleagues (2012) encourage the use of design processes, such as sketching, ideation and critique, which are widely used in related design fields as a form of early evaluation, while North (2009) 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 (2008) 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 we 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. Hogan and Hornecker, 2012; Wright and McCarthy, 2008). Employing methods already used in this domain 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 effect that multisensory data representations have on people's ability to generate insight.

4.3. 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 our exploration of the design space and in particular the dimension of *representational intent*. In our analysis of this dimension, we 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 user/audience. This is illustrated by Kosara (2007) who argues that the goal of artistic data representations are unlike other forms of representation, in that they are used to 'communicate a concern' rather than facilitate explicit data insight. With this in mind, we believe that designers and researchers need to be mindful when employing novel mapping techniques, where the primary aim is to 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 type of information that is being transferred to the audience. We do recognize, however, that the boundary between a data representation and a piece of art is sometimes hazy, and that it is not always the intention of the creator to define which side of the line the data artefact 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.

4.4. Underexplored areas and future challenges

We conclude our discussion by highlighting research challenges that are hitherto underexplored and warrant investigation to help this field of research to evolve and expand. Our survey showed that the predominant combination of senses needed for interpreting existing data representations is touch and vision (130 examples). Although data sonification is a vibrant field, our survey shows that combining the perceptual qualities of sound with those of vision or touch is still somewhat underexplored (11 examples). Apart from a few recent examples (Stefaner, 2014), data is very rarely interpreted using other senses: taste and smell. We 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* (fabric.ch, 2012), which relies on our ability to sense temperature, we found no examples that rely on our sense of, for example balance, pain or our kinaesthetic sense, to form meaning from a representation. We also note that the majority of examples in our survey (72%) were aimed at single users. Apart from some notable exceptions (cf. Patten *et al.*, 2001), both traditional and multisensory data representations have typically been created with the purpose of communicating to a single person. Moving representations beyond the single modality may provide an opportunity to expand the size of the audience, while also supporting collaboration. In similar terms, the size and dimension of the data typically used in our collection is small. During our review, we found only three examples 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 we 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 (Bertin, 1983). 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. Cleveland and McGill, 1986), the work of MacEachren (1995) has expanded the variables to account for the use of computer technology. His extension of Bertin's visual variables is made up of: *location, size, crispness, resolution, transparency, colour value, colour hue, colour saturation, texture, orientation, arrangement and shape*. Much like MacEachren's work, the majority of research to date on visual variables has focused on their refinement to account for new technology or different context of use (cf. Carpendale, 2003). There have also been some attempts to transfer Bertin's concept across to other modalities. Krygier (1994) explored the use of sound as a design variable for data representation. 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: location, loudness, pitch, register, timbre, duration, rate of change, order and attack/decay.* Vasconcellos (1995) also explored Bertin's graphic semiology, 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 (2016) have revisited Bertin's variables, by investigating how people interpret data encoded in the size of 3D objects. They present empirical evidence that shows physical bars achieve the same levels of perceptual accuracy as 2D bars.

Apart from the work on sound variables of Krygiers (1994), there has been no research that has attempted to systematically establish or validate design variables for modalities other than visual. We have also found no work that 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 haptic modality? We could possibly surmise that these would include pressure, vibration, temperature, texture, weight, shape or orientation; however, a concerted effort is needed to establish, confirm and validate these.

4.5. Recommendations

In this section, we outline five key recommendations that are meant to provide practical guidance to other design researchers who wish to study or design 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.

4.5.1. 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 ongoing research within the InfoVis research community to investigate how analytical discovery is made and 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 the third-wave HCI researchers (cf. Bødker, 2006). We believe that methods used in HCI are also applicable to the evaluation of multisensory data representations that have similar intent, such as, for instance, evoking hedonic responses. Another issue that can be addressed through new approaches to evaluation is the cognitive demand on users when interpreting data through more than one modality. Further fundamental research is needed to better understand how multisensory representations affect people's ability to form meaning from the representation.

4.5.2. *Beyond touch, vision and sound*

We have shown that the main representational modalities currently used in multisensory data representations are visual, haptic and sound. We 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 sensorial experience of data.

4.5.3. *Beyond visual variables*

It is almost 50 years since Jacques Bertin published his work on visual variables (Bertin, 1983). The principles that he postulated in this book are still closely adhered today by those who choose to visualize data. 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 they play in the perception and interpretation of data. Once the design variables for all modalities has been established and empirically validated, the next step would involve exploring the use of design variables from different modalities in the representation of data.

4.5.4. *Data insight through experience*

During our survey, we 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. We believe that this approach has the potential to be a key milestone in the evolution of data representation—much like how 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 we found that utilize this approach are exploratory pieces created within an art's context. However, as data representations are now commonly used in casual contexts such as libraries, museums or at home, facilitating data insight through people innate ability to perceive how something feels (experience) is worthy of further exploration. Peter Shenai, one of the creators of '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 his case a swing) serves as a reminder to the user that the data has been skewed strongly in one direction (Shenai, 4 July 2015, personal communication). This is a departure from how HCI and InfoVis researchers presently think of and address the concept of (mal)functionality. Alongside this, we 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.

4.5.5. *Multidisciplinary collaboration*

The interpretation of data through multiple channels is not exclusive to any one community. Our 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 their intentions may vary greatly, we 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 aesthetic and perceptive skills of designers and sensitivity of artists, we believe that data can be represented in a manner that is artistic, engaging, aesthetic, informative and insightful.

5. LIMITATIONS

In this article, we present a design space for multisensory data representations based on a survey of contemporary and historical examples we collected over time. However, it has several limitations. First, although we have attempted to gather as many examples as possible, we acknowledge that the list is not exhausted as work is continuously being produced, and we may also have missed some work due to their limited exposure. Second, the examples in our 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 the 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 we had to reply on a combination of third-party critiques and our own experience and interpretation to place the work within the dimensions of our design space. Finally, we acknowledge that the reader may object to the dimensions of our design space and/or the terminology used to define and describe them. However, we do not intend this research to be authoritative. We have argued in the introduction that the aim of this research is not to reclassify current data representations or prescribe a new domain. Instead, we hope that this article will promote debate, inform design and encourage future research to move towards a design space for *multisensory data representation*.

6. CONCLUSION

In this article we define, for the first time, multisensory data representation. Using this definition, we collected and surveyed 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 our design space are: *use of modalities, representation intent, human–data relations.* Derived from our analysis of the design space, we addressed key research issues, including: questioning the value added by expanding the sensory channels required to interpret a data representation. We also discussed issues from the users' perspective and explored the boundaries between representation and art. We concluded our discussion by highlighting the underexplored areas and future challenges and presented five key recommendations aimed at providing practical guidance to other researchers and practitioners who wish to study and create multisensory data representations.

We conclude our exploration of the design space by addressing a semantic dilemma that may be caused from utilizing more than one representation modality within the same representation. One could question: can a representation that utilizes modalities alongside and beyond the visual modality still be considered a visualization? New media theorist Lev Manovich (2008) defines information visualization simply as 'a mapping between discrete data and a visual representation' and 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.[5] 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 an information visualization and not *data sculpture, data art, sonification, physicalization, sensualization, sensification, perceptualization or even multisensory data representation*? We believe that by accepting this concept, while also acknowledging the broad expertise needed to meet the theoretical and practical challenges, the HCI community will play an important role in future developments of Information Visualization.

[5] http://en.oreilly.com/et2008/public/schedule/detail/1588

SUPPLEMENTARY MATERIAL

Supplementary material is available at http://iwc.oxfordjournals.org/.

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