

The Visual and Beyond: Characterizing Experiences with Auditory, Haptic and Visual Data Representations

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ABSTRACT

Research in sonification and physicalization have expanded data representation techniques to include senses beyond the visual. Yet, little is known of how people interpret and make sense of haptic and sonic compared to visual representations. We have conducted two phenomenologically oriented comparative studies (applying the Repertory Grid and the Micro-phenomenological interview technique) to gather in-depth accounts of people's interpretation and experience of different representational modalities that included auditory, haptic and visual variations. Our findings show a rich characterization of these different representational modalities: our visually oriented representations engage through their familiarity, accuracy and easy interpretation, while our representations that stimulated auditory and haptic interpretation were experienced as more ambiguous, yet stimulated an engaging interpretation of data that involved the whole body. We describe and discuss in detail participants' processes of making sense and generating meaning using the modalities' unique characteristics, individually and as a group. Our research informs future research in the area of multimodal data representations from both a design and methodological perspective.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): User Interfaces

Author Keywords

Qualitative evaluation; Sonification; Physicalisation; Phenomenology; Repertory Grid, Micro-phenomenological interview; Data interpretation; Embodiment.

INTRODUCTION

Information visualization, “*the use of computer-supported, interactive, visual representations of abstract data to amplify cognition*” [9, p.7], is arguably one of the most common ways to represent data. While originally applied mostly in professional contexts by experts, visualizations has become ubiquitous, be it as part of online news [15], in public spaces [4,

18, 59], or to depict personal data [24, 58]. This expansion of InfoVis application areas comes with new target audiences and has motivated new research questions regarding the design of visualization: “beyond the desktop” [28], for non-experts [26, 16, 40], to tell stories [25, 51], or to promote engaging (personal) experiences [18, 58]. This trend has also fueled research into alternative ways of representing data addressing haptic (cf. [22]), auditory (cf. [48]) or even gustatory (cf. [53]) senses. In parallel, recent work has started to investigate the interpretation of visualizations on a more personal level, beyond perceptual and usability questions [19]. However, little is known about how the modality of a data representation influences people's interpretation process and their overall experience of the representation. How can we characterize haptic, auditory, and visual data representations when it comes to sense making and experiences beyond perception and usability?

In this paper we start to investigate these questions by drawing from recent trends in data visualization, sonification, and physicalization on the one hand, and recent empirical approaches of capturing people's personal experiences with data representations on the other (cf. [19]). We report on two phenomenologically oriented comparative studies that capture rich accounts of people's “lived” experiences with three different representational modalities: haptic, auditory and visual—one applying the Repertory Grid technique [14] and the other based on the Micro-phenomenological interview technique [61]. Findings from our RepGrid study allow us to start characterizing people's experience with these three different representational modalities, highlighting representational challenges as well as different hedonistic responses to variations of these modalities. The micro-phenomenological interviews revealed detailed accounts of people's data interpretation processes through the different modalities, including processes of sense- and meaning making and aspects that support and hamper these. Synthesizing our findings from both studies we uncover and discuss aspects of data representation that have received little attention in past work, including: the role of the body, and the social and tangible properties of data representation.

THE MODALITIES OF DATA REPRESENTATION

Much research in the field of visualization has focused on techniques to depict data through visual elements, considering in particular their perceptual properties [10, 65]. However, as visualizations are becoming common place in everyday life, studies and (typically qualitative) evaluation methods that capture people's use and experience of visualizations have started to emerge [18, 19, 58]. Thudt et al., for example,

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have studied how spatial-temporal visualizations of people’s personal data can facilitate reminiscing and storytelling [58]. Hogan et al. have presented the Micro-phenomenological interview technique¹—a technique applied as part of our work presented here—to capture capture personal experiences of visualizations and their interpretation [19]. Their study shows that even plain graphs and charts can trigger vivid associations with past experiences which, in turn, heavily affects people’s interpretation of the presented data. Such research on how visualizations influence people’s interpretation and experience on a personal level, beyond efficiency and usability is still at its infancy. Similarly, little is known of how the experience of visual data representations compares to representations that address auditory and haptic perceptual channels, namely sonifications and physicalizations.

Sonification: Representing Data through Sound

Sonification has been defined by Kramer and colleagues as “*the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation*” [34, p.3]. However, the use of sound to represent data is by far not as widespread as the use of visual representations. Arguably, the visual system is better equipped for processing and providing an overview of large amounts of data at once; sound is perceived sequentially, and making sense of nuances in sound sequences—in particular if they are unfamiliar—is difficult [45, p.7]. Also, in contrast to the field of information visualization where design principles have been established and are in constant review (cf. [3], [8]) there are few agreed principles to designing sonifications [1, 2, 34]. However, research suggest that sonification has potential. The human hearing system is capable of discriminating small changes in pitch and tempo [44]. Auditory representations perform well when it comes to trend analysis, the estimation of data values or comparison, and pattern detection [64], and can highlight subtle or gradual value changes and emphasize anomalies and outliers [13]. Nesbitt [46] suggests temporal data to be one of the most promising use cases for sonification (e.g., rhythm can represent changes of data across time).

While previous research has highlighted the potential of sonification, little is known of how people experience, characterize and interpret sonifications, not only at a cognitive, but also at a somatic and emotional level. Aiming to close this gap, our research starts to investigate how people characterize their experiences and interpretations of sonifications in comparison to visual and haptic representations.

Physical Representations

In contrast to visualization and sonification, physical data representations focus on haptic ways of representing data. Jansen and colleagues coined the term *Physicalization* as: “*a physical artifact whose geometry or material properties encode data.*” [28, p.3228] and established a framework for visualizations to help describe, compare and critique non-screen based data representations [28]. Data physicalization is now an active research area (e.g., [42, 54, 56]). Recent research has started to explore the perceptual traits of physicalization in order to develop design guidelines. Jansen and Hornbaeck

found that size (as a visual variables) is perceived with with the same level of accuracy in 3D and 2D charts [30]. Willett et al. introduced the notion of *embedded data representations* as physicalizations and visualizations that are “*deeply integrated with the physical spaces, objects, and entities to which the data refers*” [66, p.461].

Another class of physical representation utilizes haptic or tactile feedback, instead of mapping data to physical form (e.g., [22, 57]). In *tactilization* information is conveyed through tactile stimulation [9]. In contrast to data physicalization, tactilization allows for the creation of dynamic displays supporting data-driven vibro-tactile feedback. Our work aligns with the tactilization variant of physical data representations in that the haptic design probe used in our studies presents data-driven tactile stimuli . Some work has been conducted to understand how people perceive data represented through vibro-tactile feedback. Brown et al. [7] found high recognition rates representing data through *roughness* and *rhythm*. Hoggan and Brewster [23] explored amplitude modulation, frequency, and waveform included in textures as parameters for haptic data representations and found the use of amplitude modulation to be the most successful.

Similarly to sonifications, tactilizations and physicalizations seem to have the potential to promote unique experiences with data, however, apart from some notable examples (cf. [20]), not much research has compared haptic with visual and auditory representation modalities. Hogan and Hornecker [20] found that people appear to rely more on intuition and real-world experiences when making sense of haptic and sonic, compared to visual representations, and tend to engage in more personal, emotionally-driven interpretations. In contrast, a visual representation (a bar graph) was experienced more as a pragmatic tool. We expand this work by providing a more detailed and nuanced characterization of people’s interpretation and sense-making processes and their overall experiences with variations of visual, auditory and haptic representations, based on two phenomenologically-oriented studies: one allowed participants to explore, describe, and share their experiences with such modalities ad-hoc in form of a focus group; the other was based on interviews we conducted with participants who had used a visual/haptic/auditory data representation as part of their daily activities for one week.

RESEARCH APPROACH

To gather accounts of participants’ “lived” experiences (that go beyond usability and performance issues) with visual, haptic, and auditory data representations we conducted two studies that are both structured around the use of design probes—data-driven artifacts designed specifically to be used and studied in (open-ended) scenarios. The phenomenologically-driven methods applied in the two studies (the Repertory Grid for Study 1, and Micro-phenomenological interviews for Study 2) were chosen as both are specifically designed to capture personal lived experiences with technology.

Design Probes

Our approach for designing data-driven artifacts that lend themselves for studying and contrasting experiences with alternative representation modalities is derived from Technology Probes (TP) [27]; however, instead of studying the use of one

¹Formerly known as the Elicitation Interview technique

artifact (the typical procedure with TP), we designed three artifacts that differ in their representational modality, to start a comparative characterization of these particular aspects.

Our interest in studying moments in time when people experienced and interpreted the data representations drove our process of designing the probes. We wanted to design for interactive experiences with the data that would require attention and interaction (in contrast to ambient displays [52]). Furthermore, we wanted participants to use the probes wherever they found them useful (employing Willett et al.'s notion of *embedded data representations* [66]) and to be able to pick up and handle the data devices freely. The final design probes have the shape of a cube that fits comfortably into an adult hand and that can be placed safely on a flat surface (see Fig. 1). This shape also enabled us to exploit the cube's surfaces for user interaction and to display information.

Each design probe represents the same set of data: indoor air quality (IAQ) as dynamically measured by the sensors embedded in the cubes. The probes also have the same form factor, however, each represents the data using a different modality; a particular variation of an auditory, visual, or haptic representation. The design space for each of these representation modalities is large, e.g., there are many ways of enabling the haptic experience of data, even when focusing on tactilizations. Our probes therefore can be considered as one particular example of each modality that allows a first comparative characterization of how such modalities influence people's interpretation and experience of the represented data. Our methodology and findings informs future studies to gradually form holistic insights on how representational modalities compare.

The auditory probe maps data to the frequency of a computer-generated sound using a 50mm (diameter), 0.5W, 8-ohm speaker. The data is transformed into sound by mapping each quantitative value to a particular sound frequency within a pre-defined range: a low value causes a low-frequency sound and visa versa. The haptic probe represents the data through vibrations accentuated by eight five-volt vibration motors fixed to the inside walls of the cube. Once triggered, the data is mapped to the speed of the motors. The visual probe shows this data as digits on a 4-digit, 7 segment LED display. In contrast to the auditory and haptic probe, this visual-numerical display represents the data in a highly familiar format to remind our participants of the purpose of the probes (the representation of IAQ measurements). Figure 1 shows all three probes in their final form. Real-time IAQ level readings can be triggered by shaking the probe; knocking on one side of the probe triggers the probe to display (in its particular modality) the highest current data value while knocking on the opposite side displays the lowest current IAQ value.

Study Methodologies

Working within a phenomenological tradition, studying people's experience of data requires empirical grounding in actual lived experiences. However, capturing lived experiences directly is notoriously difficult as it requires self-awareness which can be clouded in retrospect through post-hoc rationalization [61]. With the RepGrid technique and Micro-phenomenological interviews we apply two

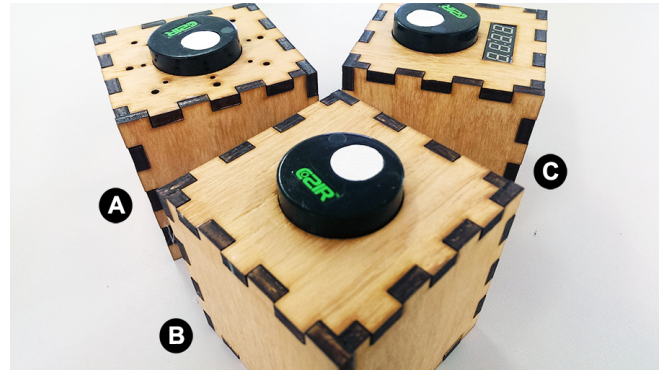


Figure 1. The three design probes: auditory probe (A), haptic probe (B), and visual probe (C).

phenomenologically-driven study methods that have been designed to capture people's lived experiences with technology while minimizing such threats. We used the RepGrid technique in Study 1 to gather participants' characterization of each probe that they agreed upon within a focus group, while Study 2 used the Micro-phenomenological interview technique to shed light on specific moments of the experience and the cognitive processes people employ when interpreting the data represented in different modalities. While findings from Study 1 shed light into participants' shared ad-hoc impression of the different modalities, Study 2 provides deeper insight into people's impression of the prototypes after more elaborate individual interactions over a week. We highlight that the purpose of running these two studies was not to compare the methodologies, but what these would reveal about people's experience of the representational modalities.

THE REPGRID STUDY

The aim of the Repgrid study was to explore immediate responses to different variations of representational modalities—as manifested in the three design probes—and to gather first-hand accounts of how people collectively characterize each probe and their interpretation of and/or interaction with it. The RepGrid is a cognitive mapping technique and a methodological extension of George Kelly's Personal Construct Theory (PCT), used to systematically elicit the way in which people construe their experience of objects, people, and events [32], and has been proven to be a valuable technique in phenomenological studies to understand, for instance, user experience [17], perceived qualities of computational objects [12] and to reveal rich design-relevant insight [21]. In contrast to similar methods that are typically based on predefined, given constructs (e.g., Semantic Differential [60]), the RepGrid elicits personal constructs from participants first-hand. While a typical RepGrid study is conducted with individual participants, we conducted it as a focus group sessions [21], to enable participants to explore, compare, and discuss the representational modalities in form of our design probes, leading to richer characterizations of their experiences.

Participants & Procedure

Twelve participants (21–36 years; mean 23.2, SD 4.3; 6 female; all final year design students) took part in the study. Participants knew each other prior to the study. The study was conducted in a large room and followed the minimum-context



Figure 2. Participants exploring the design probes during the RepGrid familiarization phase.

triad procedure [14], which involves investigating three objects in the same study; in our case the three design probes.

Familiarization Phase. The study commenced with a 1-hour familiarization session. Participants were first introduced to the three design probes, the data these represent, and how to interact with them. After this, we randomly divided participants into three groups of four, with each group spending 20 minutes with one probe before moving on to the next, until all groups had explored each probe. Participants’ approaches to exploring the probes during this phase can be characterized as a shared activity, facilitated by the probes’ form factor: The probes were passed around so that one participant could individually interact with it, while verbally sharing their experiences with the other participants. Other group members typically participated in such explorations passively through comments (see Fig. 2). Group discussions revolved around the interpretation of the data represented by the probe through their haptic, visual or auditory modality.

Construct Elicitation Phase. The familiarization phase was followed by a focus group session where all participants together established a list of personal constructs that described their experience of and with the probes. A personal construct is a bipolar dimension, which describes the meaning people apply to an object or event [32]. To establish a range of personal constructs participants were asked to describe how two probes are similar (Convergent pole) but differ from the third (Divergent pole). Once consensus was reached, the personal construct and the position of each probe on the bipolar dimension was recorded (see Table 1). This process was repeated until the participants agreed they could not come up with any further personal constructs.

A researcher was present during both the familiarization and construct elicitation phase to answer any questions, and both phases were video- and audio-recorded.

Data Analysis

In total 15 personal constructs emerged from the construct elicitation phase and form the basis of the RepGrid. 13 of these were established directly by the participants, while the last two were derived from our transcript analysis as described below. Table 1 presents the personal constructs (PC) in the order they were recorded during the focus group session, so PC 1 (*Ambiguous – Precise*) was the first to be established by participants. The RepGrid not only contains the list of agreed upon personal constructs, but also includes indicators that show at which end of the dimension the participants choose to place each probe. For example, PC 1 shows that there was

PC		Haptic	Auditory	Visual	
1	Ambiguous	←	←	→	Precise
2	Difficult to interpret	←	←	→	Easy to interpret
3	Engaging	←	→	←	Non-engaging
4	Narrow	→	→	←	Wide
5	Sonic	←	←	→	Silent
6	Unfamiliar	←	←	→	Familiar
7	Passive	←	→	←	Harsh
8	Playful	←	←	→	Logical
9	Analogue	←	→	→	Digital
10	Tangible	←	→	→	Non-tangible
11	Interpretive	←	←	→	Informative
12	Invisible	←	←	→	Visible
13	Instinctual	←	←	→	Knowledgeable
14*	Evocative	←	←	→	Straightforward
15*	Mixes Senses	←	→	→	Single Modality

Table 1. The RepGrid produced by participants. PC1–13 were agreed by the participants. PC14 & 15 were derived from our analysis.

an agreement that the haptic and auditory probe should be described as *ambiguous*, unlike the visual probe, which was described as *precise* (see Table 1).

All participant statements during the familiarization and construct elicitation phases were fully transcribed. The established personal constructs were then linked back to the transcripts of the familiarization and construct elicitation session. The aim for establishing such links is fourfold: (1) to trace the emergence of the personal constructs, (2) to examine the meaning participants’ attribute to constructs, (3) to search for further constructs that may not have been recorded in the focus group, and (4) to establish themes around personal constructs.

We describe our findings below. Participants’ statements can be distinguished by their identifier in square brackets.

Findings

The constructs formed by participants encompass three themes: Describing Characteristics of Modalities, Issues with Interpretation, and Experiential Responses.

Describing Characteristics of the Modalities

While the primary aim of our RepGrid study was to shed light on how participants experienced the probes, five constructs reference aspects of the modalities that are more easily discernible; they directly characterize the probes based on the modalities they incorporate. These include PC5: *Sonic – Silent*, PC12: *Invisible – visible*, and PC10: *Tangible – Non-tangible*, which are arguably obvious constructs to apply to the probes.

Slightly less obvious is PC9: *Analogue – Digital*. Participants considered the haptic probe to be analogue as there was a sense that the feedback was more natural than in the other probes, or as one participants remarked “*When I feel the vibrations I can almost see something rubbing of the inside of my hand.*” [P6]. In contrast, the auditory display was considered digital or “computer generated”, possibly to the nature of sounds it was emitting. The numerical display was also described as digital due to the discrete nature of the representation, which is illustrated by a participants remark: “*This one [the visual probe]*

only shows one number at a time, the others seem to get bigger or smaller without you even knowing about it.” [P2].

Finally, PC15*: *Mixed Senses – Single Modality* is the result of our transcript analysis. It refers to the notion of multi-modality. Eight participants experienced the haptic probe to incorporate more than one modality—a haptic and auditory representation—and six participants explicitly stated that they would focus on the sounds emitted from the vibrations when trying to interpret the data. This was not the case with the auditory or visual probes. Participants seemed to experience the redundant representation of data through multiple modalities as positive. Four participants mentioned a desire to augment the other two probes with additional modalities to make their representation more engaging and easier to understand.

Issues with Interpretation

Tracing the personal constructs back to the study transcripts, we identified five constructs that reflect on participants’ interpretations of the data through the probes’ modalities. These include PC1: *Ambiguous – Precise*, PC2: *Difficult to interpret – Easy to interpret*, PC4: *Wide – Narrow*, PC11: *Interpretive – Informative*, and PC13: *Instinctual – Knowledgeable*.

PC1 reflects participants’ characterization of the probes based on the accuracy in which data could be perceived: *Ambiguous – Precise*. In contrast to the visual probe, the haptic and auditory probes were described as *ambiguous* (see Table 1; PC1). Participants’ discussion provides explanations, as illustrated in the following extract of a group comparing the accuracy in which data can be experienced:

[P3] “It [the audio] is better than the haptic one. Like, when you are trying to understand where the shaky [haptic] one is.” [P2] “Yeah, but do you know that we are not getting an exact measurement? Like, we cannot tell if it is exactly 70 or whatever in here. What if there were three or four distinct sounds, like a high sound and a low sound and then something that would be more precise in the middle.”

This dialogue reveals participants’ awareness that the data represented through sound is more precise than through haptic feedback such as vibration, but neither is as clear as the number display. Typical words to describe the visual representation included: *clear, precise, accurate* and *exact*. Similarly, PC2: *Difficult to Interpret – Easy to Interpret* reflects on how much the modalities facilitate understanding of the represented data (see Table 1; PC2). Although all participants managed to generate meaning from all three probes, participants agreed that, compared to the visual probe, the haptic and auditory probes were difficult to interpret. This is not surprising as the visual probe shows the data as definitive digits.

While Constructs PC1 and PC2 reflect on the ease in which meaning is ascribed to the representations, PC4: *Narrow – Wide* relates to how nuanced changes in the data were perceived (see Table 1; P4). The visual probe allowed for the perception of fine-grained “narrow” changes in the data, while changes had to be more pronounced or “wide” in order to be perceived in the other probes. While large differences in data are easily recognized (“You know a low tone, and you know a high tone.” [P2 about the auditory probe]), all participants mentioned struggling with more subtle changes.

Related to the level of interpretation allowed by each probe, our participants agreed to describe the haptic and auditory probe as *interpretive*, but considered the visual to be *informative* (see Table 1; PC11). The last construct within this theme relates to participants’ process of interpretation (PC13: *Instinctual – Knowledgeable*). Again, the auditory and haptic probes were grouped together as with them participants had to rely on their instinct when interpreting the data, in contrast to the visual probe, as reflected in the following extract:

[P4:] “I suppose it is the exact reading you are getting [with the visual probe], and there is nothing else influencing it: you just look at the numbers and it should be clear.” [P2:] “Yeah, not like the sound or vibration. They are influenced by what you know already or what your feeling is about the sounds or vibration.” [P1:] “This one [the visual probe] 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?”

Experiential Responses

Five personal constructs reflected on how the different probes shaped participants’ experiences of the data, ranging from PC3: *Engaging – Non-engaging*, PC6: *Unfamiliar – Familiar*, PC7: *Passive – Harsh*, PC8: *Playful – Logical*, and PC14: *Evocative – Straightforward* (see Table 1).

In contrast to the auditory probe, participants described their experience of the haptic and visual probes as *engaging* (see Table 1, PC3). Their discussions reveal that reasons for this characterization of the haptic probe lie in its multimodal nature. Four participants mentioned that they found the sounds emitted from the motor to reinforce the sensation felt in their hands when handling the haptic probe: they experienced the data through two sensory channels instead of only one, as with the auditory and visual probes. One participant remarked: “I think the sound is reinforcing the vibration, and it is more engaging than when you just read off a screen [referring to the visual probe]” [P6]. However, all participants found the visual probe to be most engaging because the representation of data through simple digits easily showed even subtle changes in the data. It is likely that this is the reason why we observed participants shaking the visual probe more frequently, requesting data updates more often than with the other two probes.

Participants also found differences in the intensity of the representational feedback experienced through each probe. They considered this experience to be *passive* with the haptic and visual probes, whereas the auditory was experienced as *harsh* as illustrated in the following extract:

[P2]: “The sounds seem to alert you more than the vibration, these sounds are almost painful, something like it is trying to warn us. Where the vibration was just like a sensation, it didn’t really hurt me.” [P1:] “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.”

Furthermore, the RepGrid shows the haptic and auditory probes are considered *playful*, while the visual probe was experienced as *logical* (see Table 1, PC8). While the transcripts revealed this construct to be related to propagating a playful or logical experience, it is also related to aspects of interpretation (e.g., PC13: *Instinctual – knowledgeable* as dis-

cussed in the previous paragraph. The probes considered to be playful seemed to allow for increased exploration, whereas the visual probe returned a logical stream of numbers. This is closely related to PC6: *Unfamiliar – Familiar*, which relates to participants' acknowledgment that the haptic and auditory probes are unusual data representations, whereas the numerical display used in the visual probe is more familiar.

PC14: *Evocative – Straightforward*, the final construct under this theme, was not established during the construct elicitation phase, but emerged when we examined the study transcripts. We found that participants' experience of the auditory and haptic probes evoked memories of past events and objects. For example, when exploring the auditory probe, participants continuously compared its sounds to other sounds they heard in the past, including an ambulance siren, an alarm, buzzing bees, or dogs howling. The following dialog illustrates this and shows how such connections are used when interpreting the meaning of the represented data:

[P6:] “It sounds like Morse code.” [P8:] “No, more like a dial-up tone.” [P4:] “Yeah.” [P6:] “But Morse code is more like it, because that’s a kind of communication as well, it could be words or numbers in sound.” [P8:] “The dial-up is numbers as well.” [P6:] “Is it?” [P8:] “Well, yeah, zeros and ones—it’s the sound of data being transferred from one place to another, like this device.”

Similarly, on six occasions, participants mentioned recalling past experiences that were similar to the sensation provided by the haptic modality. Sometimes this helped them make sense of the data, such as comparing weak vibrations to a mobile phone’s buzz and strong vibrations to traveling on a train. One participant used this continuous spectrum of vibration strength to judge the real-time data readings. In other instances, participants discussed the communication of information through vibration, for example, how difficult it is to communicate precise information using the analogy of vibrations of an alarm clock: the vibration alerts you to wake up but cannot indicate the time directly. In contrast, for the visual probe, while more straightforward to understand, there is no evidence that it evoked familiar real-world analogies, nor did participants use past experiences to interpret the numbers.

To summarize our findings, our analysis of the RepGrid produced by participants (see Table 1), alongside the transcripts from the focus group session, shows that the auditory and haptic probes produce similar experiences (in 10/15 constructs). Our participants described their experience of the auditory and haptic modality to be: *ambiguous* [PC1], *difficult to interpret* [PC2], *narrow* [PC4], *sonic* [PC5], *unfamiliar* [PC6], *playful* [PC8], *interpretive* [PC11], *invisible* [PC12], *instinctual* [PC13], and *evocative* [PC14*]. In contrast, the visual probe was only considered to be similar to the auditory probe in four constructs: both were characterized as *wide* [PC4], *digital* [PC9], *non-tangible* [PC10], and *single modality* [PC15*]. Similarities between the visual and the haptic probe were only found once with participants characterizing their experiences with both these probes as *engaging* [P3]. Our findings can be partly explained by the implicit nature of the audio and haptic modality which provides a sense of the represented data, in contrast to the visual probe which shows the actual numbers.

While the RepGrid allowed us to uncover how participants characterized their experience with the different representational modalities, these are based on brief ad-hoc interactions in a study environment. In order to capture more nuanced details on how the different modalities influence experiences with data representations, we conducted a second study that allowed people to interact with the probes over a longer time and in a more familiar environment.

MICRO-PHENOMENOLOGICAL INTERVIEW STUDY

For our second study, participants were given one of the three probes to take home for one week to use and explore in their own time. We then conducted a Micro-phenomenological interview with them to capture their experiences with the probe. The Micro-phenomenological interview is a retrospective interview technique, and a method of the phenomenological tradition known as psycho-phenomenology [62]. First developed by Pierre Vermersch [61] to be used in an educational context, 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 participant is guided back toward the re-enactment of the experience under investigation in order for them to provide an account, not only about conscious acts but also those actions or cognitive processes that occur sub-consciously [49].

Participants & Procedure

Twelve participants (19-45 years; mean 28.1, SD 9.2; 5 male) took part in the study; none of them had participated in the RepGrid study. Unlike the RepGrid study the participants' professional backgrounds vastly varied and ranged from computer programmers, teachers, athletes, to secretaries as we sought to study a wider user group and use scenarios. Each participant was assigned one type of probe to take home so that each modality was explored by four participants over the course of one week. During this time, participants used the probes as they saw fit, but they were encouraged to use it as much as possible. A researcher contacted the participants each day to monitor the use of the probe and to answer questions.

At the end of the week we interviewed each participant individually about their experience of their probe using the Micro-phenomenological interview technique [19]. In contrast to other interview methods, this technique focuses on a particular experience that is clearly defined through space and time. Each interview therefore started with the researcher and participant agreeing on a memorable episode the participant had with the probe, which would become the focus of the interview. The episodes chosen by the participants all differed and varied from the first time using the prototype, a moment of insight, a moment of confusion, or the last time they used the probe. The interview itself included a series of questions that aimed at guiding participants back to the place and time of their original memorable episode. This included questions such as: “When did this episode happen? Where were you at the time?” as well as questions about sensory experiences to help guide the participant toward a “state of evocation” [19]. Each interview took approx. 30 minutes and was video- and audio-recorded, resulting in a total of just under six hours of recorded data.

Data Analysis

We transcribed the video- and audio recordings including all verbal data and some non- and para-verbal cues, including speech tempo, pauses, facial expressions, body gestures and eye directions. These transcripts were then analyzed using a Thematic Analysis approach [5] which involved five discrete phases: (1) familiarization, (2) thematic coding, (3) extracting themes, (4) reviewing themes, and (5) defining and naming themes [19]. In an open coding approach, 72 unique thematic codes emerged from the transcripts. These were reviewed and grouped into broader themes in relation to the research question that applied across transcripts [6]. A total of 22 initial themes emerged from the analysis, 16 of which included more than 10 codes, that is, they were apparent in more than ten statements across participants. Since a full description of all sixteen themes would exceed the space limits of this paper, we will present the five most prominent themes in detail (see Table 2). A list and description of all 22 themes is included as additional material to this paper².

Findings

The five most prominent themes that emerged from our interview analysis are: awareness of the body during interaction (Theme A), making sense of data (Theme B), finding meaning in the presented data (Theme C), and using spatial cues to assist sense- and meaning-making (Theme D & E)(see Table 2).

Awareness of Body

9/12 participants referenced their body when recalling their experience with the probes (Theme A, see Table 2). Compared to others, this theme is composed of more codes (59), which suggest an importance of people's embodied experience when they interacted with the probes. The distribution of the codes across the probes—haptic: 29, auditory: 27 and visual: 3—suggests that the auditory and haptic probes heighten people's awareness of their body. For example, participants who used the haptic and auditory probes more often mentioned their hands, illustrated in this comment by a participant talking about using the auditory probe for the first time: *"I do the high value first, so I hold it on the low side, with my left hand and knock with my right hand where it says high."* [CN]. As this statement already suggests, participants also frequently talked about their interactions with the probes (knocking and shaking, holding, touching, grasping, and feeling the probes). This is further illustrated in the following statement of a participant talking about their first time using the haptic probe: *"[...] it felt solid, it felt strong, it felt secure, and the next step, I tried the low and the high to see the difference in sound [mimicking a shaking gesture] and then I shock it to hear [brings hands up to his ear] to see what the sound was."* [FS].

Eight participants stated to recall haptic sensations through particular body parts, as illustrated in the following interview excerpt (statements from the interviewer in bold italic).

[KP; haptic probe:] *"I feel the vibration and I think back to what it was like before."* **How do you think back?** **[KP:]** *"I have a feeling stored in my mind, and I recall that when I want to compare it."* **So you recall the sensation from the morning. How do you recall this, how does this appear?**

[KP:] *"It doesn't appear, I don't see it."* **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. [pauses for a few seconds, stares into space] Yeah, it is like, it is in me. [points to his chest]."* **In your chest? [mirrors the gesture]** **[KP:]** *"Yeah in... somewhere in there [points to chest again]."* **Ok, so if we go back to when you are standing, holding 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."*

Two other participants who used the haptic probe described feeling sensations from within their body (e.g., in their head, chest, or hands) in similar ways. Six participants, who used the auditory and haptic probes also talked about their body position when interacting with the probes, for example, standing, sitting, walking or bending down, as the following statements illustrate: *"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, auditory probe]. We also found examples where participants mentioned moving the probe towards themselves to facilitate the interpretation of the data: *"I put it up to my ear, so I could hear it better because of the ambient noise in the room."* [MC, auditory probe].

While the tangible interface of the probes may have triggered such mentions of the body, we only found three such comments in relation to the visual probe, compared to 27 with the auditory and 29 with the haptic probes. This suggests that it is the representational modality and the way in which it is manifested in the probes that influenced participants' awareness of their body when interacting with the data probes.

Making Sense vs. Meaning Making

Our interview analysis revealed episodes where participants experienced moments of insights, and we grouped these into two themes: Making Sense and Meaning Making (Themes B and C, see Table 2). Both themes represent key phases when generating insight from data. Their differences are subtle but became apparent in participants' statements. The theme "Making Sense" includes codes regarding the *process* of understanding the representation and its underlying data, whereas the theme "Meaning Making" refers to instances where the participants were trying to interpret their observations to arrive at higher-level insights—an *outcome*. For example, in some episodes, participants recalled moments where they were attempting to interrogate or find patterns in the data (Making Sense); in others they were trying to contextualize the data to gather a general meaning (Meaning Making). The following excerpt illustrates this distinction:

[JC; haptic probe:] *"I was trying to find a pattern. [pauses 1 sec.] I was trying to find a pattern between the vibration levels."* **The high and the low?** **[JC:]** *"Yeah, between the high and the low. And I was wondering then 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."*

In the first statement the process of making sense of the data is apparent: JC is seeking to find a pattern between the different data streams (high and low values). In the second part,

² <http://www.tactiledata.net/elicitationthemes/>

Theme {Prominent Codes}	Participants (Probes)	Descriptions	Illustrative Quotes
(A) Awareness of Body (59) Use of hands {14}, Body position {10}, Movement {11}, Use of Body {7}, Bodily Impact {5}	9 <i>{4 Audio}</i> <i>4 Haptic}</i> <i>1 Visual}</i>	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)
(B) Making Sense (52) Making sense {22}, Finding patterns {6}, Makin sense by listening {3}, Processing data {5}, Recording data {3}, Using colour {3}	11 <i>{4 Audio}</i> <i>4 Haptic}</i> <i>3 Visual}</i>	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 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) Finding meaning {20}, Generating insight {4}, Judging {3}, Understanding the data {5}	10 <i>{4 Audio}</i> <i>4 Haptic}</i> <i>2 Visual}</i>	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.	- "ygg 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).
(D) Using Spatial Cues (35) Spatial Cues {19}, Reasoning about space {6}, Translating modalities {6}, Spatial cues disappears {3}, Using proximity {3}	7 <i>{2 Audio}</i> <i>4 Haptic}</i> <i>1 Visual}</i>	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.	- "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" (Audio)
(E) Visual Cues (21) Use of visual cue {10}, Using text {2}, Swapping modalities {3} Visual Interface {2}	8 <i>{4 Audio}</i> <i>3 Haptic}</i> <i>1 Visual}</i>	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" (Audio)

Table 2. Themes and their corresponding codes that emerged from the transcript analysis. The numbers in the theme column refer to the number of occurrences of the codes. The numbers in the participants column refers to amount of participant transcripts that the codes were applied to

then, however, she tries to put her observations into context; explanations that would justify the data readings she is experiencing through the representation. This excerpt illustrates a fluid transition from making sense to meaning making—the process of discovery from first making sense of the data and then finding a justification/interpreting for this observation.

Using Spatial Cues

7/12 participants recalled episodes where the appearance of “mental images” helped them to make sense of and interpret readings from the data probes. For example, five participants working with the auditory and haptic probes described that handling the probes triggered a mental image where data values were transformed into objects arranged in space. The proximity between objects within this mental image helped them to interpret the difference between data values.. The following interview extract illustrates this:

[TH; auditory probe:] “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.”
Ok, so do you see this bar? [TH:] “Aehm... [pauses for 2 sec. and stares into space] No, I don't. It is there but I don't see it. It's like I know there is something there, but I don't see a picture of it. But there are two sounds on it.”

Interestingly 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. Five participants using the haptic and auditory probes described similar episodes. One participant, for instance, mentioned how he recalled and compared the haptic data representations: “It is just like... [pauses for 2 sec.] It's just how I placed it with my head maybe... I just place it closer to the high sound than to the low.” [KP, Haptic]. Another participant described a similar strategy comparing two data readings (past and real-time) of the auditory probe: “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.” [MC, Auditory].

Only one participant using the visual probe described such mental images. Recalling her experience of comparing three data points this participant stated: “I am just thinking about... [pauses for 3 sec.] Where it [the current value] would fall between the two [previous values] on a number line. Would it be closer to this end of the scale [draws a line with her hands and then moves both hands to the left], then it would be up here [moves right hand over to the right].” [AS, Visual].

These examples show that mostly participants interacting with the haptic and auditory probes (subconsciously) translated the represented data points into mental images where the sounds and vibrations became visual markers whose spatial proximity indicated the differences in their corresponding values. Partic-

ipants described these markers as three-dimensional shapes, such as boxes, blocks, or spheres, except the one participant who used the visual probe: who described them as being actual numbers, but different from those used on the probe: “*They are numbers. Yeah, they are characters... [pauses 3 sec., then draws the number in the air with her fingers] That kind of font, it was from my old maths book or something...*” [AS, Visual].

The mental images that some participants described were similar to typical visualizations such as scatter plots or spectrographs that are used to visualize audio frequencies. While this similarity could be due to the ubiquitous nature of such visualizations in everyday life, we know from previous studies on how children communicate complex math problems, that such visual mental models are quite common to make sense of data [39]. What is interesting is that, in particular, the haptic and auditory modality seem to trigger these mental images.

Sharing Discoveries and Data Experiences

Although the Micro-phenomenological interviews focused on an episode where participants felt they formed meaning from their interaction with the data probes, the transcripts also revealed how they share their experiences with others. On occasions participants talked about being eager to tell others about their latest reading and to alert them about low air quality. This is illustrated in the following extract:

[AS; visual probe:] “*Well it is not just bad for me, it’s bad for everyone*” **For everyone?** **[AS:]** “*Yes for the rest in the room, it is their air as well, so I should tell them about it.*” **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:]** “*[Pauses for 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 [daughter] about it.’*” **And what do you do next?** **[AS:]** “*I go over, with the cube to talk to her about it.*”

There were also occasions when participants wanted to confirm the real-time readings with others who shared the space.

These findings confirm and expand the RepGrid study in that they show similarities in experience of the haptic and auditory probes that differ from the visual probe, but reveal more details on how people formed an understanding and meaning through their interaction with the probes and the role of embodiment as part of this. In the following we discuss the findings from both studies, also in the light of previous work.

DISCUSSION

Synthesizing our findings from both studies, we discuss the characteristics of peoples’ experience with different probes and their inherent modalities, further elaborate on issues related to their shareable and tangible nature, and highlight research questions that our findings inform.

Characterizing Experiences with Different Modalities

When examining the results of both studies it becomes apparent that the haptic and auditory representational modalities as represented through our probes are experienced similarly, in contrast to the visual modality, in particular when it comes to the interpretation of data and embodied experiences.

Data Interpretation & Process

Both studies show that data interpretation using haptic and auditory probes was more difficult and lacked accuracy compared to the visual probe, in particular when it came to recognizing subtle changes. This is not surprising, given we typically rely much more on our visual senses than on haptic and auditory perception. However, our analysis of the micro-phenomenological interviews shows that participants’ interpretation process of the probes not only consists of *sense-making*, that is trying to decipher the represented data values and seeking patterns or correlations in this data, but also of *meaning-making*, a phase which typically follows sense-making and that involves trying to understand what the data readings actually mean and what their implications are in a particular context (e.g., is the air quality concerning or not).

Regarding the strategies that participants employed to interpret the data, our findings confirm previous research [20]: participants tried to find analogies between the readings from the data probes and familiar sounds or sensations that they had previously experienced to make sense of the data. However, the micro-phenomenological interviews indicate that participants subconsciously made use of mental images to make sense of the data (e.g., translating sounds into points on a horizontal line, revealing higher and lower values), which parallels previous research on children solving math problems [39] and how people experience simple graphs and charts on a personal level [19]. What is interesting about these findings is that these mental images seemed to be triggered predominately by the haptic and auditory probes but not by the visual one. These results expand previous research on how insight is generated through visualization (cf. [47, 50]), but also raise new questions. For example, how significant are these mental images for sense- and meaning making and for recall? Do such mental images play a role in non-numeric visual or multimodal representations? Our findings suggest that auditory and haptic data representations may be more successful in combination; participants found the haptic probe to be richer in representing data as it also emits sounds as a side-effect of the vibrations. Future research has to investigate if and how haptic and auditory modalities in combination with with visual representations enrich or change experiences.

Our findings on data interpretations are influenced by the particular design of our probes which represent one data point at a time upon request. However, previous studies indicate that auditory and haptic modalities can also facilitate the recognition of patterns in continuous data streams (cf. [44]). Future studies will investigate how people experience different representational modalities designed in different ways with continuous data streams as well as other types of data.

The Role of the Body

The micro-phenomenological interviews also highlight the importance of considering the body when it comes to designing data representations beyond the screen. We found that participants often referred to their body when describing their experiences and interpretation processes of the data, in particular when interacting with the auditory and haptic probes. The haptic probe seemed to trigger a particular awareness of hands and fingers, but vibrations were also perceived in

other body parts such as the chest. Similarly, participants mentioned experimenting with the auditory probe, holding it far away from their body, or closer to their ears, or holding it in different ways to hear how the sounds changed. These observations can be better understood by aligning them to Merleau-Ponty's concept of *Maximum Grip*, which pertains to how people continually strive toward an equilibrium with the world. In other words, people are solicited by objects that emit stimuli by placing themselves in the best position to experience and perceive these stimuli [41, p.302]. The transcripts show that the haptic and auditory modalities seem to heighten this sense of solicitation, as our participants recalled numerous episodes where they positioned themselves, or the probe to enhance their perception of the data representation; participants interacting with the visual probe did not employ these actions. While the HCI community has embraced the role of the human body in interaction design and cognition [31, 33, 36, 37, 38, 43, 55, 63], the role of the body in data representation has received little attention, with notable exceptions [26, 29]. Our findings suggest that representing data beyond the visual modality affords designers opportunities to promote full-body experiences of data; encouraging people to use their body in way that is not commonplace today with information visualizations. This could prove useful in beyond-the-desktop scenarios such as public spaces, museums, or classrooms [28].

From a methodological perspective, we highlight that these reflections by participants on the role of their body as part of the data exploration were not so apparent in the RepGrid study. This may be due to the study design, as the RepGrid was conducted in a lab where participants interacted with the probes sitting on a table, whereas the probes were deployed in more natural surroundings during the micro-phenomenological study. It may also be a factor of how reflections were elicited during the RepGrid vs. the micro-phenomenological interviews, emphasizing the importance of employing different methodological approaches when studying concepts such as experience beyond the perspective of usability.

The Value of Tangible, Shareable Data Interfaces

In both studies, our participants not only described their experience of the probes in relation to their own body but also in a larger tangible and social aspect. Their experiences relate to the concept of *embodiment* which, from a phenomenological perspective, refers to the phenomenal body—beyond the physiological entity—and to the role it plays in our direct experiences of the world. Embodied interaction as “the creation, manipulation and sharing of meaning through engaged interaction with artefacts” [11, p. 126] is a well-known concept in HCI. Our design probes employ the fundamental characteristics of embodied interaction; they afford natural interaction and are embedded in the world to which they refer. The use of a portable device allows people to sample data around them, and we found that this creates a sense of personal meaning.

Previous research has suggested that tangible, shareable devices to monitor data can stimulate engagement and debate [35]; our findings suggest that this may expand to data representations. Our design probes stimulated conversations and debate during the RepGrid study, and we found similar ten-

dencies during the micro-phenomenological interviews where participants mentioned sharing of the probes as well as insights gained from their readings. Supporting the social aspects of data representation is especially important today, as they play a role in almost every aspect of our lives. Our findings show that tangible and shareable data representations that employ modalities beyond the visual can play an important role in the future design of tools for data exploration.

Limitations

We acknowledge that our design choices manifested in our probes of how to represent data through visual, auditory and haptic means may have influenced participants' experiences. Future research therefore will show how much the findings presented in this paper generalize to other variations of representational modalities. As mentioned earlier, the design space is large here, and other designs and representational mappings may trigger new discussions around similar or different aspects. In particular the sounds emitted by the haptic probe technically make it a multimodal representation which may have contributed to participants' similar characterizations of the haptic and audio modality. Future studies have to investigate how our findings apply to different designs. An obvious next step would be to design visual probes that represent data using typical visualization techniques as opposed to numbers. What our study contributes are first insights into this interesting research area alongside a methodological approach of eliciting experiences from participants directly—within a both an lab or everyday life setting.

CONCLUSION

We have presented the results of two phenomenologically-oriented studies to characterize and compare people's “lived” experiences with variations of three different representational modalities—auditory, haptic and visual. The first study was conducted as a focus group based on the Repertory Grid technique where participants used and discussed three design probes representing each of these three representational modalities. The second study consisted of a series of Micro-phenomenological interviews with a different set of participants after they had interacted with the same design probes for one week in their own pace and personal contexts. We found the visual probe to engage through its familiarity, accuracy and easy interpretation, while the auditory and haptic probes were experienced as more ambiguous, yet stimulate an engaging interpretation of data that involves the whole body. Our findings uncover and discuss aspects of data representation that is hitherto under-explored in previous work, including the role of the body in data exploration and interpretation processes, and social and tangible aspects of data representation. As data representations slowly emerge from the sanctuary of visualization toward less understood modalities such as sound and haptics, more research is needed to better understand how these modalities alter the interpretation and experience of data representations. We hope that this work will future explorations of how to represent data beyond the visual modality and inform future designs.

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