# An Exploratory Study of Data Physicalization Using Household Objects

by

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B.Tech., Anna University, 2014
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Supervisory Committee

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# ABSTRACT

We explore people's perceptions and ideas regarding creating data physicalizations using household objects such as chairs, flower pots, and photo frames to enable data-driven self-reflection. By conducting a sketching-based qualitative study with 11 participants we identified styles of physical encoding participants used, strategies for creating physicalizations they employed, and techniques for constructing physicalizations they relied on. From the study results we contribute i) a bottom-up list of physical variables people might use for different data types, ii) a comparison between the theory about visual variables and the empirical use of physical variables, iii) an identification of the need for flexible taxonomies for physical representations, and iv) a discussion of the relationship between social pressure and location of physical representations in the household.

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**My family and friends,** for motivating and believing in me.

# DEDICATION

I dedicate this project to my parents and friends. For their endless love, support, and encouragement.

# Chapter 1

# Introduction

In this project, we investigate how people might represent and interact with personal data at home when represented on household objects. Household objects can be a support for ambient and physical visualizations. *Ambient visualizations* have been shown to leverage peripheral human attention [47], to support representing data in public spaces in a subtle way [60], to reduce the attention required for the usage of the system [17, 21, 53], and to enhance engagement [17, 21, 53]. *Physicalizations* also have established benefits such as increasing motivation [32, 31], awareness and participation [20, 23, 27], and can help people better understand data, which in turn can help change their behavior [48].

To the best of our knowledge, existing ambient physicalizations rely on creating and adding to an existing environment a dedicated device such as a 3d-printed sculpture [61, 32, 10], a custom device [22, 31], or a plant – organic [4] or robotic [19]. However, no research has investigated the use of household objects as ambient physicalizations to represent personal data, although representing personal data directly on already-existing household objects can bring "psychological and physiological wellbeing of inhabitants, and [...] multifaceted aesthetic interiors" [50], echoing the original vision of ubiquitous computing [64]. Research like [30] explored the potential of designing relevant data objects that are similar to the context of the data according to the needs of the user.

To address this gap, we conducted the first study that investigates the use of ambient physicalizations that are augmentations of existing household objects to represent personal data. In our exploration, we follow a large body of work that has investigated the representation of physical activity data in digital forms (e.g., [40, 7]) and in physical forms, often with 3d sculptures (e.g., [61, 10, 32]) but also using a wide range of modalities such as vibration, airflow and color [22, 18], change in shape [25], and taste [31].

## 1.1 Motivation

The motivation behind this project grew out of a desire to explore non-traditional visualizations for personal data like physical activity data of the user that may help in increasing awareness about their data and improve their participation or interaction in the future. We were inspired by the research done by Sara etal., [50] that showed us different ways to use interactive interior design and household objects to represent personal data and the research talked about the importance of using existing household objects to improve the psychological and physiological wellbeing of the users. Similarly, a study by Karyda etal., [30] discussed the potential of enhancing users experience by representing the data on the objects they are familiar with like household objects. Along with that, studies like [44, 58] showed us the potential of household objects to represent the personal data inside the household and its benefits. These benefits of the household objects along with the physical and tangible nature of the data physicalization make them susceptible to their surrounding audience and context, and all the interactions that can exist within and around them as suggested by Sauve etal [56]. Therefore, we based our study on the potential of using household objects to represent the personal data of the user inside their home.

## 1.2 Contribution

The primary goal of the project is to understand people's perception of personal data when represented on household objects and what they think about it. To achieve this, the contributions of the project are as below:

1. The qualitative study with 11 participants to understand the benefits and limitations of visualizing a pre-defined personal activity dataset through household objects. Participants created sketches to demonstrate why, when, and how they would represent the data using household objects. This allows us to unveil i) what household objects they would use to represent their data; ii) what data mapping strategies they would employ to represent their data; and iii) how they would interact with the represented data.

2. Our results reveal the household objects participants would use, the physicalizations they might create, and the strategies they would adopt for creating and placing data representations in their homes.

3. We contribute recommendations for constructing data physicalizations using household objects by considering i) the affordances of household objects, ii) the relationship between physicalization style and its consequences on social interactions in a household setting, and iii) the nature of the data and activity.

We formulated a research question for the experiment

**RQ** How would people represent personal data physically in their household using household objects?

- **RQ 1** What visual and physical data mappings would they employ?
- **RQ 2** Where in the household would they place their physicalizations?
- **RQ 3** What strategies would be used by the people to create the data physicalization with the household object inside the home?
- **RQ 4** What challenges and concerns would they have?

## 1.3 Outline

The project report is organized as follows:

**Chapter 1** provides a brief introduction to the importance of data physicalization for physical activity data inside the household. It includes the motivation of the project, the research gap, and project contributions.

**Chapter 2** discusses the related work and background knowledge related to promises of using household objects for data representation and different representations of physical activity data.

**Chapter 3** describes the design and implementation of the study. It includes the design of the study, data, and participants.

**Chapter 4** presents the result of the qualitative study. It includes styles of encoding, strategies for creating the representation, and techniques for constructing the visualization.

**Chapter 5** includes the design and implementation of a tangible prototype using origami and electronics.

**Chapter 6** includes a discussion of the results of the study. It includes the types of different types of encoding for different data types of physicalization, a comparison between standard visual encoding and encodings used in physicalization, the need for flexible taxonomies for physicalization, and the relation between social pressure and location of the representation in the household. It also talks about the limitations of the project and possible future work.

**Chapter 7** concludes the report of the project

# Chapter 2

# Related Works

## 2.1 Benefits of Ambient and Physical Visualizations

### 2.1.1 Ambient Visualization

Ambient visualization is a "category of data representations that conveys time-varying information in the periphery of human attention" [47]. Ambient visualizations have been the subject of recent research [54, 25, 19] that includes studies [47, 60, 33], theoretical models [36] and systems [54, 25, 19, 59].

The major benefit of ambient visualizations is that, in contrast to standard screens or other traditional computing displays, they can be used to represent data in a subtle way in a space where multiple people can co-exist [60]. As ambient visualizations are integrated with the architectural setting of a (shared) space, they can trigger diverse human senses, for example by changing their shape, by emitting sounds, by changing their temperature or by diffusing odor [66]. Ambient visualizations also give people in the same space as the visualization the ability to encounter data coincidentally, which when it represents personal data, fosters people's reflection on their everyday lives (e.g., [25, 19]).

### 2.1.2 Physicalizations

A data physicalization is a "physical artifact whose geometry or material properties encode data" [27]. Physicalization has seen a growing interest in the research community in the past decade (e.g., [32, 22, 10]), including theoretical frameworks [26], surveys [11, 13], studies [28, 9], toolkits [62] and systems [32, 61, 31]. Physicalizations can leverage people's perceptual skills as perception closely depends on motor control [16]. They can also increase data accessibility by supporting non-visual mappings of data values to the physical properties of physical objects. For example, Card et al. [5] used tactile cues to notify the users of important features of a dataset. Physicalizations can also increase people's cognitive capability and support learning of the underlying data. For example, research showed benefits in using physical representations to teach basic concepts of mathematics [14] and chemistry [67]. In addition, there is evidence that the intrinsic interactive nature of physicalizations can benefit learning [26], and that physicalization can foster deeper engagement with the data it represents [27, 9].

## 2.2 Promises of Using Household Objects

To the best of our knowledge, existing work on ambient physicalizations has relied on creating and adding to an already-existing environment a dedicated device; for example with systems such as breakaway [25], infortropism [19], TastyBeats [31], and PhysiKit [22]. Our goal is to explore the use of already existing objects to represent personal data in already existing environments, specifically in people's homes.

In studies focusing on representing data inside the home settings, Kim et al. [55] stated the importance of using a physical representation of data by an artifact in the everyday life of the user can make the user understand their data in-depth and reflect upon it.

Projects have demonstrated the benefits of data representation using household objects. For example, researchers have explored using objects such as drink coasters to navigate through the recorded videos by an always-on recording system to connect to the past [58]. A case study of potential interactive technology inside the household was discussed by Nabil et al. [50] to demonstrate the potential to support users and respond to or represent effectively various kinds of personal data in the home using the objects household objects like the couch, paintings, etc. This research suggests that users will only have objects that make them comfortable in their household and combining technology with it can only make them more comfortable. Using these technologies that can blend with the environment easily can reduce the gap between the devices and other physical objects. Research on the psychological connection of the user with the residential spaces or physical environment has been fairly explored.

Such as research like [29, 3] talked about the sense of place concept that explains the relationship that people show towards the physical environment that they are used to. [42, 41] also talked about the emotional connection that is developed towards the places they live in. Also, [39] point out that interior elements, furniture and decorative objects inside the household plays a major role in making a ‘space’ into a ‘place’ and this helps the user to feel the quality of life.

All this research shows the importance and influence of the residential space and the objects in it in the life of the user. It also talks about the importance of adding technology to these objects. But, no research has empirically investigated ambient physical visualizations of personal data using household objects. So we decided to get inspired from all this literature to focus on the use of household objects to represent personal activity data like the physical activity data of the user

## 2.3 Visualizing Physical Activity Data

Many researchers have used physical activity data to conduct research at the intersection of data physicalization, ambient visualizations, and representation of data in personal environments like a home. In this section, we discuss this body of work that informs the design of our study.

### 2.3.1 Standard representations

A majority of the technology that has been designed and studied to represent physical activity data relies on representing the data by showing *numbers and standard charts* on a screen [34]. For example, applications such as RunKeeper [1] use a combination of numbers and charts to display personal running data. However, numbers and standard charts have limitations in that some data related to physical activity, such as heart rate data, do not have a well-defined graphical equivalent [46, 48]. Additionally, many people who struggle to understand statistical data due to their low graph literacy skills, motivating researchers to investigate alternative data representations [15].

### 2.3.2 Virtual metaphors

As an alternative to standard graphical and numerical representation, researchers have explored the use of *virtual metaphors* to represent physical activity data. For example, Lin et al. [40] designed a computer game in which one's number of steps taken is mapped to the emotion of a virtual fish. Flowers in a virtual garden have also been used as a metaphorical representation of physical activity data on a smartphone app [8], where the size of the flower changes as the user performs their activity. The authors found that compared to standard charts, these digital metaphors can be more interactive and engaging for the users. For example, people were trying to be more physically active to make the flowers grow bigger [8]. Interestingly, researchers also mentioned some drawbacks to using virtual metaphors, notably that participants who were not active chose not to look at the virtual metaphor to not see the fish representing their data sad because of them [40].

### 2.3.3 Physical metaphors

In other studies, data from physical activities have been represented using physical objects. For example, research from Khot et al [32] and Stusak et al [61] represented the physical activity data of the user using 3D printed artifacts. They used the shape and geometry of the 3D printed artifact to represent the data and gave it to the user as a reward for the day's activity. In Breakaway [25], a tabletop physical artifact, the artifact changes its shape and movement if the user is sitting in the same place for a longer period of time urging them to be active physically. Khot et al, [31] explored the possibility of using taste as a way to represent the physical activity data. They developed a system that can serve drinks with electrolytes if the user is really active on that day or give water if the user is not active. Researchers have also given attention to fashion as a tool to represent data. For example, Lee et al [38] developed an activity tracker band that engraves a pattern on the tracker according to the tracked data set of the user.

These research projects show the possibilities of using a physical representation of data to support the user to achieve their physical activity goals. They also discussed the user perception of using this type of visualization for representing their physical activity data and found that it could be used as leverage to motivate the users to be active

# Chapter 3

# Exploratory Study

We designed a two-day qualitative study to understand how people envision using their household objects and devices to represent their physical activity data. The goal of our study was to unveil the different mediums and strategies that people might use to represent their physical activity data using the objects in their own households and to identify what is unique or different from using existing household objects. In this section, we present the study design, participants, data collection, and data analysis. This study was approved by the human research ethics board at our university.

## 3.1 Study Design

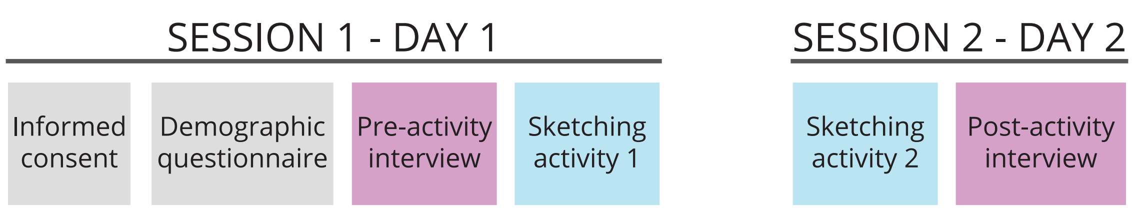


Figure 3.1: The image has a visual representation of the different steps in the two-day study.

The study consisted of two sessions conducted remotely with a researcher and held over consecutive days. Figure 3.1 shows an overview of the study. In the first session, they provided consent to participate and completed a demographic questionnaire, then they took part in a semi-structured pre-activity interview, and then they participated in the first sketching activity. In the second session, they participated in the second sketching activity and engaged in a semi-structured post-activity interview. the choice of sketching as a tool for illustrating the idea of the participant was inspired by a study by Leblanc etal., [37] that suggests that sketching can externalize their thoughts, and methodically explore the creative option while communicating their ideas. Sketching the potential visualization can also let the users be very creative without thinking about logistical issues while creating the visualization by hand. On average, each session lasted 1.5 hours. We describe the study steps below in chronological order.

### 3.1.1 Demographic Questionnaire

Participants started by completing a short demographic questionnaire consisting of 13 questions regarding i) the types of physical activity they engage in, ii) their familiarity with the idea of representing data in visual forms or in other formats, and iii) their current approaches to visualizing personal physical activity data, if any. This questionnaire had seven multiple-choice questions (including two on Likert scales) and five short-answer questions. The demographic questionnaire is provided in Appendix 8.2.

### 3.1.2 Pre-activity interview

The researcher explained to the participants that the goal of the study was to explore how people might represent information of physical activity data (like running and jogging) if they were to use objects found in their homes such as a blender or a chair. The researcher then asked a set of questions informed by the demographic questionnaire responses in a semi-structured interview, to learn more about i) the participant's typical physical activity routines, ii) the data they have collected from such activities (e.g., from a Fitbit device), and iii) how they have made sense of that data. Participants who did not collect data about their physical activity were asked to talk about their reasons for not doing it. Participants were also asked about the objects or devices in their home that they thought could be used to represent their physical activity data. They were also asked about privacy concerns they might have when representing their activity data in a home setting. Each pre-activity interview lasted approximately 20 minutes.

| | Temporality of representation | | Number of users | | Time span of data collection | | | Running data attributes | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | After the activity | During the activity | 1 | 2 | 1 day | 5 day | 1 activity | Distance | Time | Heart rate | # of steps |
| Scenario 1: Single day | X | | X | | X | | | X | X | X | |
| Scenario 2: Multi-day | X | | X | | | X | | X | X | X | |
| Scenario 3: Multi-day multi-user | X | | | X | | X | | X | X | X | |
| Scenario 4: Real-time | | X | X | | | | X | | | X | X |

Table 3.1: The four scenarios that were used in the four sketching tasks, along with their characteristics.

### 3.1.3 Sketching Activities

The sketching activities consisted of four sketching tasks overall, each with a different scenario and dataset related to running. Each sketching task asked participants to sketch at least one physicalization concept for that particular scenario and dataset, using household objects. Participants completed the first two sketching tasks at the end of the first session and the last two sketching tasks at the beginning of the second session. To facilitate the sketching activity, we provided participants with a Google Doc template (provided in Appendix 8.1) that outlined the scenario and prompted participants to think about a few questions that would help them consider which objects they might want to use and why, and how the sketched idea could be potentially useful or limited in their use.

We opted for a sketching activity because research suggests that during sketching, people initially create a model of the design problem they have in their mind, and then the model is changed and improved by understanding the uncertainties in the given design problem [57]. Sketches can also trigger discussions (in our case, with the researcher), which can lead to improving the proposed ideas [51]. In addition, we had found through pilot studies that when provided examples for inspiration using researcher-created sketches, participants tended to create similar sketches. Therefore, in the study we explained each scenario with examples from existing research publications [4, 65, 12] instead, to offer more breadth and help avoid idea stagnation. We also split the sketching activity into two sessions because we observed from pilot studies that sketching four ideas in a single session was too demanding for the participants. When completing sketching tasks, participants were asked to describe their sketches by thinking aloud [24] so that the researcher could understand the participant's design thinking and provide help when they faced unexpected challenges or blockers.

Table 3.1 provides a summary of the four scenarios that were provided to the participants for the four sketching tasks. As shown in the table, the scenarios were designed so that together they cover a range of dimensions that people might consider when visualising activity data:

- **Temporality of representation** refers to when the data is to be represented in the visualization. We enforced the temporality of representation for each scenario after having observed in pilot studies that most participants would by default sketch simple feedback mechanisms (i.e. real-time representations). This resulted in simple, usually single-data point representations, that might not necessary fall within the realm of data visualizations. We set the temporality to 'after the activity' for three scenarios for that reason.

- **Number of users** refers to the number of people whose activity data is collected and represented in the scenario. While by default there is a single user, we set the number of users to two for one scenario so that participants could think of designs in a less private way than when representing only their own data.

- **Time span of data collection** refers to the size of the dataset, i.e. the number of running activities to represent. Scenarios exposed participants to a single activity in the dataset, to five activities, and to one activity but with multiple data points (taken at two-minute intervals during the activity). This allowed participants to consider visualizing one or multiple data points, about one or multiple activities.

- **Running data attributes** refer to the attributes of data points in the dataset. The first three scenarios characterized each activity with their associated distance, time, terrain, and average heart-rate. Scenario 4 characterized the activity in real-time with time-series values for average heart-rate, terrain and number of steps. We selected these attributes because they are of various types (e.g., quantitative and qualitative) and standard descriptors of running activity datasets.

### 3.1.4 Post Activity Interview

At the end of the second session, we conducted a post-study semi-structured interview during which participants were asked prompted to discuss physicalization aspects such as the accuracy of the representation and the location of the representation in the home. They were also asked if they thought the data physicalizations would affect them if their family members, friends, or other housemates saw and commented on the representation.

## 3.2 Participants

Eleven adult participants who are or want to be physically active in their daily lives were recruited for the study. Table 3.2 shows the consolidation of some of the important demographic details collected from the participants. Among the participants, 8 self-identified as men and 3 self-identified as women. They were 21 to 55 years old (median 27), and were undergraduate students (2), graduate students (6) and professors (2), all from the field of engineering. Two participants lived alone, five in shared accommodation, two with their partner and two with family (one lived with children). All the participants did some type of exercise to be physically active such as going to the gym, cycling, running, swimming, and climbing. Seven of them exercised 2-3 times a week, two once a week, one every day, and one a few times a month. From the demographic questionnaire, we learned that five participants had never collected personal physical activity data before, five had previously collected data but were not collecting data at the time of the study, and one was actively collecting their physical activity data at the time of the study. We gave participants a 30 CAD e-gift card for their participation.

Table 3.2: Consolidation of all the demographic details of participants.

| Partici-pant No | Age | Gender | Educational Expertise | Household Composition | How often do you exercise? | Experience in collecting data |
|---|---|---|---|---|---|---|
| P1 | 25 | Man | Graduate degree in Computer Science | Single | Few times a month | Collected data in the past |
| P2 | 24 | Woman | Graduate degree in Compurer Science | House-mates | 2-3 times a week | Collected data in the past |
| P3 | 28 | Man | Bachelors degree in Aerospace engineering | House-mates | 2-3 times a week | Never collected data |
| P4 | 25 | Man | Graduate Degree in Renewable Energy | House-mates | Once a week | Collected data in the past |
| P5 | 25 | Man | Graduate Degree in Biomedical Engineering | Couple | 2-3 times a week | Never collected data |
| P6 | 36 | Man | PhD in Computer Science | Family (with children) | 2-3 times a week | Collected data in the past |
| P7 | 30 | Woman | Graduate Degree in Environmental Engineering | House-mates | 2-3 times a week | Currently collecting data |
| P10 | 55 | Woman | PhD in Educational psychology | Couple | Every day | Collected data in the past |
| P11 | 33 | Man | Graduate Degree | Single | 2-3 times a week | Never collected data |
| P12 | 27 | Man | Graduate Degree in Engineering | House-mates | Once a week | Never collected data |
| P13 | 21 | Man | Bachelors Degree | Living with Family | 2-3 times a week | Never collected data |

## 3.3 Data Sources and Analysis

We collected four sketches per participant, and two video recordings (one for each sketching activity session). This resulted in 44 sketches and 24 hours of video recordings that were then transcribed and analyzed using NVivo through three rounds of open coding [2, 52].

Initially, the sketches and transcript of one participant were coded by one researcher in three rounds as mentioned before. Initially, the researcher did a basic reading of the transcript and did coding on paper. In the second phase, a rereading of the transcript is done along with memoing and coding with NVivo to develop a codebook with initial categories of code. Finally, the codes are categorized based on categories, dimensions, and properties. Then similar patterns were identified to find the themes. The researcher then discussed the codebook with two other research team members and iterated until a full agreement was reached. Once the codebook was deemed reliable [43], the researcher coded the material for all other participants.

# Chapter 4

# Results

We report the study results according to the four themes that emerged from the data analysis: (1) styles of physical encoding, (2) strategies for creating the representation, and (3) techniques for constructing the visualization.

## 4.1 Styles of Physical Encoding

Participants used a variety of visual and physical encodings in their sketches.

### 4.1.1 Encoding with Color Hue

11 participants used *color hue* to represent data in 26 sketches. One participant (P13) used the color of a household object to represent the different attributes of the data when sketching for scenario 2 (see Figure 4.1 (A)), saying *"It's because there's a bunch of different colors. So my kind of thinking [...] you could get different shades of colors of beads to represent some sort of scale on each of the four attributes, like four colors, and then a different gradient for each of the four."* In another sketch in scenario 3 (see 4.7), P1 used color to represent bins of quantitative values. They grouped the heartbeat values into high, normal, and low bins and colored the object based on the corresponding bin. They wrote in the template: *"The color of the magnets will denote the avg. heart rate, red color for higher heart rate, green or blue for normal, and yellow for lower."*

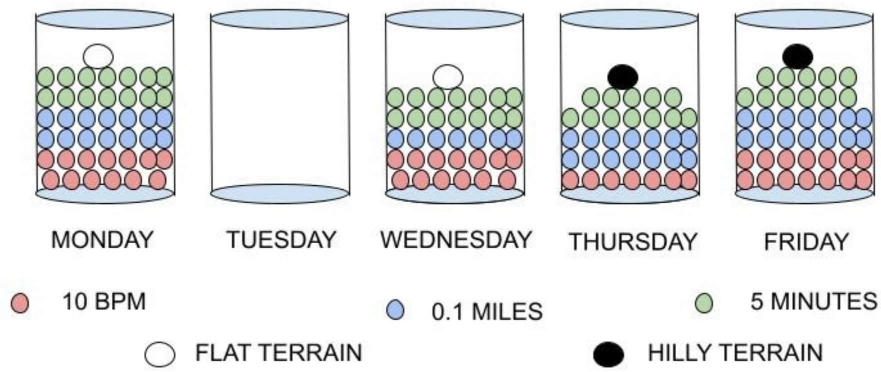


Figure 4.1: Redrawn image of P13's sketch for scenario 2. Beads of red, blue, and green colors are used to represent heart rate, distance, and time, respectively. The number of beads of one color represents the value for the corresponding attribute. The size and color of the bead represents the type of terrain.

### 4.1.2 Encoding with Color Value

Two participants encoded data with color value in six scenarios. P5 wrote in their template about their sketch for scenario 2, shown in Figure 4.2: *"this stock, would be formed by rocks of different colors, where lighter rocks represent a low heart rate and darker rocks represent a high heart rate"*. Here P5 used a darker shade to represent a higher heartbeat rate and a lighter shade for a lower heartbeat rate. Participants used this encoding style five times to represent heartbeat data, and once to represent the intensity of the run.

### 4.1.3 Encoding with Flicker

Two participants used the flickering frequency of lights to represent data on three different sketches. For example, P3 used this encoding to represent heartbeat values in scenario 2 (see Figure 4.3), saying *"The light would kind of flash with the same [...] number of beats per minute that you find on a specific day"*. This encoding was used only to represent heart rate values.

### 4.1.4 Encoding with Size

Nine participants used size to encode data in 19 sketches. For example, P13 used different sizes of the same object to represent different data dimensions for scenario 2 (see Figure 4.1). They used small beads to represent quantitative values like time,

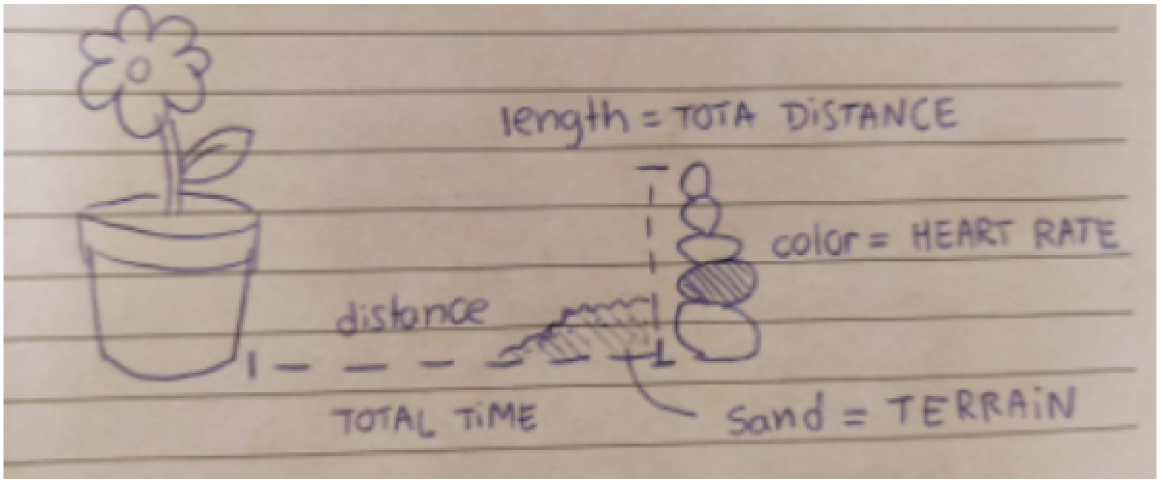


Figure 4.2: For scenario 2, P5 encoded time with the distance from the flower pot to the stone stack, distance with the height of the stone stack, terrain with a heap of sand, and average heart rate with the color value of the stones in the garden.

distance and heart beat, and large beads to represent qualitative data like terrain. P13 repeated this style of representation in scenarios 3 and 4. Similarly, P7 used the length of a string to represent the distance covered each day (see Figure 4.5). P11, for scenario 3, used books of different heights to represent the different types of terrain: small books for hilly terrains and short books for flat roads. They also encoded the distance of the run with the thickness of the book stack (see Figure 4.4). In total, participants used size 18 times for representing distance, 8 times for time, once for heart rate, five times for terrain, and one participant used size to represent speed that they calculated based on distance and time.

### 4.1.5 Encoding with Position

All 11 participants used position to encode data in 34 sketches. For example, P11 set the position of different chess pieces on one chess board based on the values of data dimensions, with the larger the value the more forward the position of the chess pieces (see Figure 4.6). P11 wrote in the template *"Each row of the chess board represents the days of the week while each column represents the distance (0 miles for the far left edge and 8 miles for the far right) and time(10 min for each line)"*. Similarly, P1 positioned magnetic stickers according to speed values calculated based on distance and time for a particular day for scenario 3 (see Figure 4.7). The higher the speed, the higher the magnetic sticker. Overall, participants used position twice

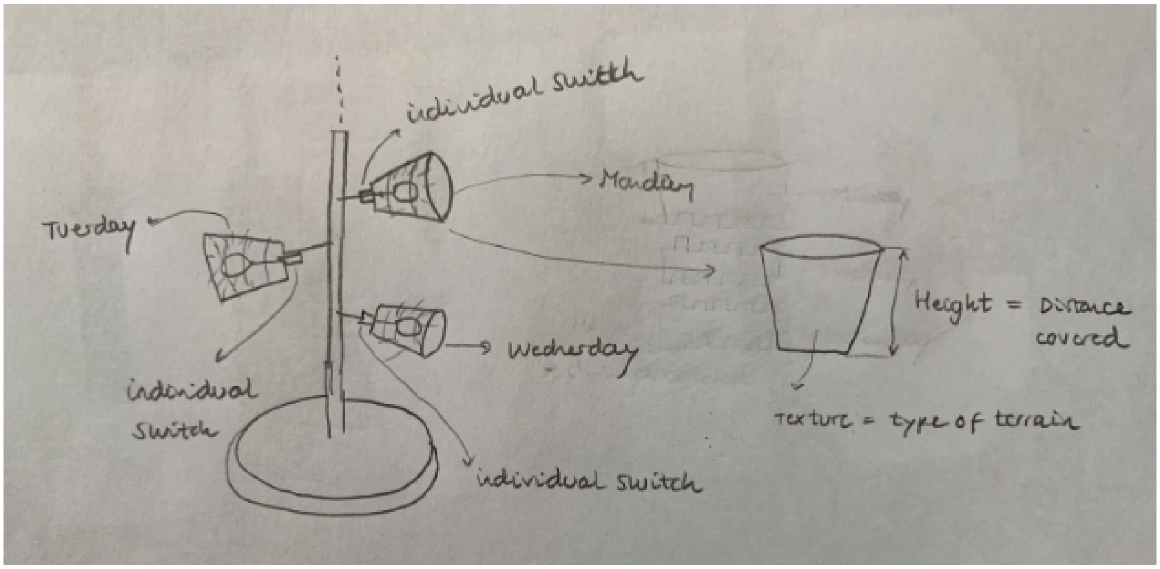


Figure 4.3: For scenario 2, P3 represented the different days of the week with different bulbs, distance with the height (i.e. length) of the lampshade, terrain with the texture on the lampshade, and heart rate with the flickering frequency of the light in a bedroom lamp.

to represent distance, once to represent duration, once to represent heart rate values, three times to represent time of day, seven times to represent day of the week and once to represent speed based on distance and time.

### 4.1.6 Encoding with Orientation

Three participants used orientation to encode data in 3 sketches. For example, P1 rotated square magnetic stickers 45 degrees to represent hilly terrain, while non-rotated squares represent flat roads in scenario 3 (see Figure 4.7). P1 wrote in the template *"I used color-changing magnets that can change the location and have a rotation mechanism. [..] Finally, the angle of rectangular magnets may denote the terrain. For a flat path, it will remain mostly flat for the hill it will rotate clockwise."*. Overall, participants used orientation twice to represent terrain and once to represent time.

### 4.1.7 Encoding with Shape

Four participants used shape to encode data in five sketches. For example, P7 represented the different types of data dimensions with different shapes of beads in scenario

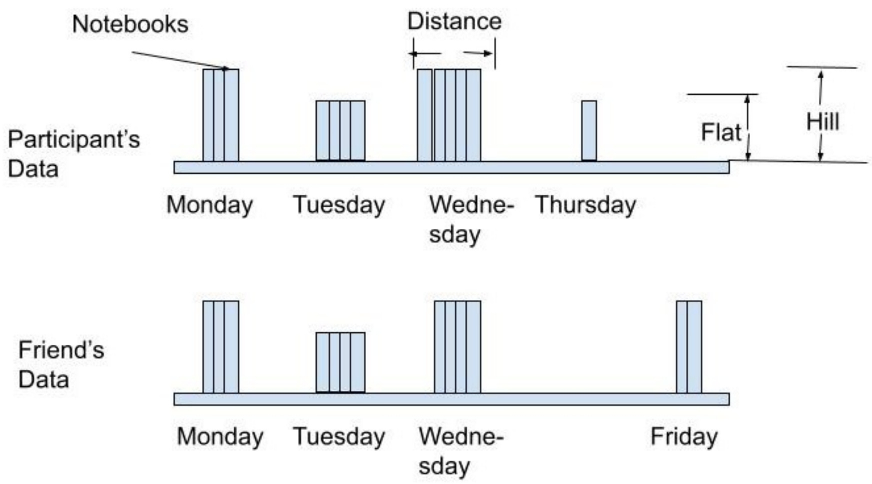


Figure 4.4: Redrawn image for P11's scenario 3 that represented distance with the thickness of book stacks and terrain over the week with the height of each book representing terrain. The book stack on the top shelf represents the participant's data and the one on the bottom shelf represents their friend's data.

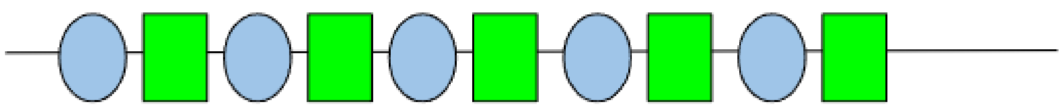

Figure 4.5: For scenario 1, P7 represented heart rate with the number of spherical beads, time with the number of cubical beads, distance with the total length of the string holding the beads, and terrain with the shape of the string.

1 (see Figure 4.5) and scenario 2. P7 wrote in the template *"For the time, a different colored bead and shape will be used and each will represent 10 mins"*. They used spherical beads to represent heart rate and cube-shaped beads to represent time. P7 also used the shape of the string holding the beads to represent the terrain, with a flat string representing a flat terrain and a cylindrical string representing hilly terrain. P1's rotation of square magnetic stickers in scenario 3 (see Figure 4.7) can also be interpreted as using different shapes (squares and diamonds) to represent terrain. P6 also used the shape of tokens to encode the type of data attribute being represented (see Figure 4.8). For example, heart-shaped tokens on their kinetic mobile represent heart rate values. Across the five sketches where shape was used, participants represented all the different categories of data attributes (distance, time, heart rate, and terrain).

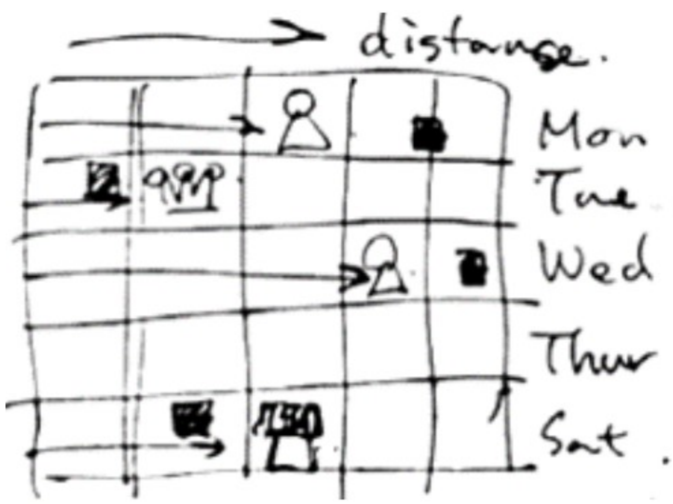


Figure 4.6: For scenario 2, P11 represented different data attributes with the position of chess pieces on a chess board.

### 4.1.8 Encoding with Pattern (Visual Texture)

Two participants used pattern to encode data in three sketches; twice to represent terrain and once to represent time. For scenario 1, P6 mentioned that *"maybe the terrain could be the pattern, [...] flat terrain could be, you know, a flat knitting pattern, and then if there are hills it'll [...] have some wave"*. Here, P6 used flat and wavy patterns on a tapestry to represent the different terrains they ran on that particular day (see Figure 4.9).

In another example, P3 used the density of the pattern shown on a flower pot to represent their running time in scenario 3. As shown in Figure 4.10, P3 added different patterns for different layers, each representing one day in the scenario. The density of each pattern represents the total running time on that day. P3 wrote in the template (using "number of patterns" to refer to pattern density) that *"the number of drawn patterns (e.g. circles, squares, triangles,...) would correspond to the total time"*.

### 4.1.9 Encoding with the Angle Between Components

Four participants used the angle between components of an object to encode data in five sketches. For scenario 1 (see Figure 4.11), P13 said *"the higher heart rate means it will be up and then all the other angles are like in the moderate heart rate and then to the rest"*. Here P13 used the angle between different parts of a wooden

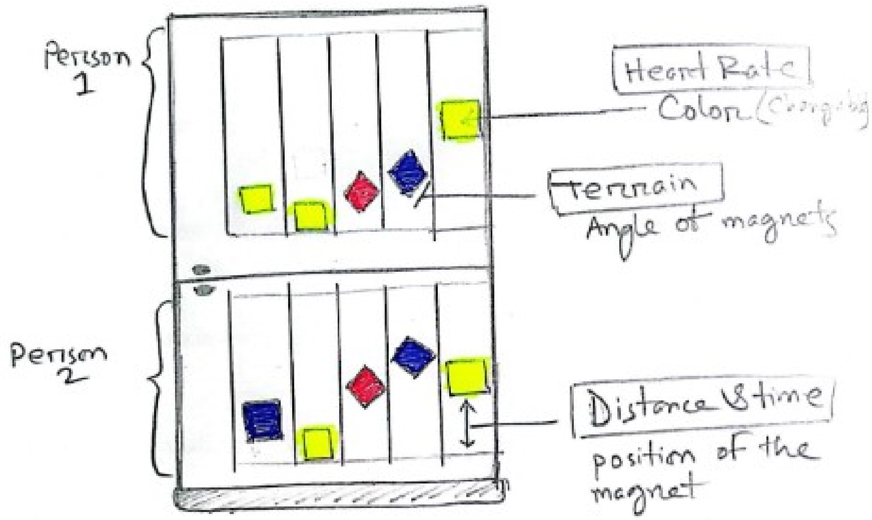


Figure 4.7: For scenario 3, P1 represented terrain with orientation, distance and time with position, and heart rate with color hue of magnetic stickers.

figurine to represent heart rate, with a larger angle corresponding to a higher heart rate. In another example, P1 encoded terrain with the angle of the backrest of a chair in scenario 1 (see Figure 4.13). They mentioned that *"if the terrain is not flat the backrest will be angular backward and if it is flat it will be in a 90-degree angle"*. Overall, participants used angle once to represent distance, twice to represent time, once to represent heart rate and three times to represent terrain.

### 4.1.10 Encoding with the Amount of Objects

Eight participants used the amount of objects to encode data in 15 sketches. For example, P13 used the number of beads in a jar to represent the values of distance, time, and heart rate for scenario 2 (see Figure 4.1). P13 said *"the number of beads then correlates to some sort of place on the scale [...] it could be like point one mile is one bead"*. P7 used the number of beads on a string to represent the total time and heart rate value on that particular day for scenario 1 (see Figure 4.5). P7 wrote in the template *"For the heart rate, each bead would represent 10 BPM (e.g., 12 beads for 124 BPM). For the time, a different colored bead and shape will be used and each will represent 10 mins (e.g., 3 beads for 30 mins)"*. Overall, participants used the amount of objects 11 times to represent distance, 13 times to represent time, and 11 times to represent heart rate.

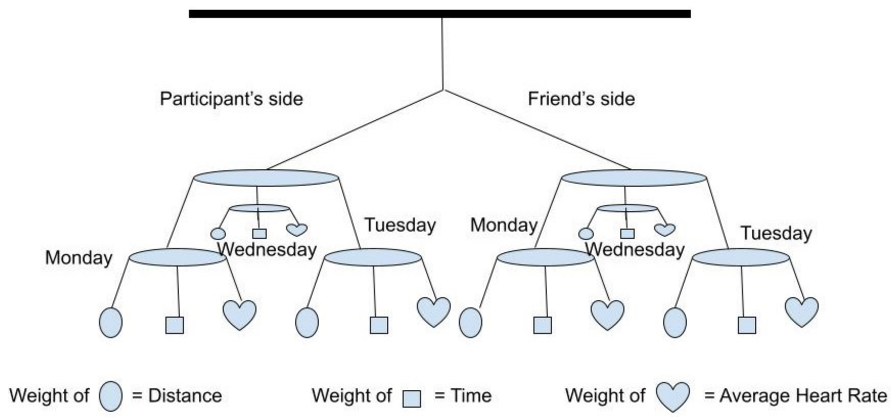


Figure 4.8: Redrawn sketch of P6's sketch for scenario 3. P6 represented the data using tokens of different weights, with heavier tokens corresponding to larger data values. The left side of the kinetic mobile represents the participant's data and the right side represents their friend's data.

### 4.1.11 Encoding with Weight

One participant (P6) used weight to encode data in one sketch (scenario 3), with the heavier an object the heavier the intensity of a run. P6 said, *"the different data points are going to be things attached to the sleeves with different weights"*. In P6's kinetic mobile shown in Figure 4.8, the left side shows the data of the participant and the right side the data of their friend. Each side of the mobile has four subparts, one for each data attribute. Each one of these subparts has seven tokens, each representing one day of the week. The weight of each token encodes the data value for that day and that attribute. As a result, the kinetic mobile would remain stable if the participant's running activity is similar to their friend's running activity over the week.

### 4.1.12 Encoding with Physical Texture

Two participants used physical texture on the surface objects to encode data in five sketches. For example, P3 used the physical texture of a flower pot to represent terrain in scenario 1 (see Figure 4.12). P3 said *"if the terrain is flat then we will have to create the texture which is similar to flat or if the pot has texture then it means a different terrain"*. As another example, P4, for scenarios 2 and 3, noted in the template: *"The texture of the window [curtain] will indicate the terrain (Rough-Hill, Plain-Flat Road)"*. Both participants used a metaphorical smooth texture on the surface of an object to represent a flat road and a rough texture to represent a

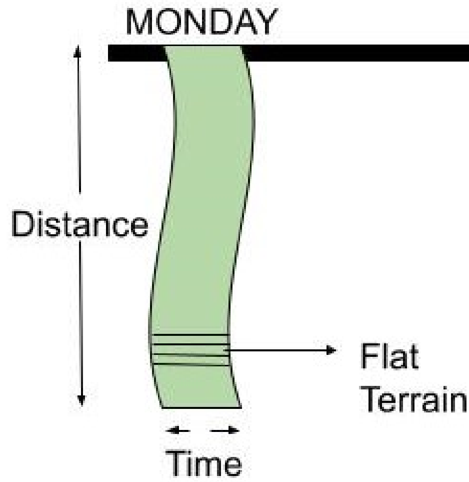


Figure 4.9: Redrawn sketch of P6's sketch for scenario 1. P6 represented distance with the length of the tapestry, time with its width, terrain with its pattern, and heart rate range (or bin) with color hue.

hilly terrain.

### 4.1.13 Encoding with Haptics/Vibration

Three participants used haptics or vibrations to encode data in three sketches. For example, P1 added a massager on a chair and encoded heart rate with the duration of vibration of the massager in scenario 1 (see Figure 4.14). P1 wrote in the template *"I would like to add a portable back massager, it will give a back massage for a certain time based on the average heart rate"*. P10 also used a chair as their household object and encoded data with vibration as well. P10 explained in the template that they would use *"headrest haptic feedback (e.g., pulsation) to indicate average heart rate data for running activity for a day, right armrest haptic feedback (e.g., low vibration) for total distance data, left armrest haptic feedback for total running time"*. Overall, participants used haptics/vibration twice to represent heart rate, twice to represent distance, and once to represent time.

### 4.1.14 Encoding with Taste

One participant (P5) used taste to encode data in one sketch (scenario 1). P5 encoded the extent to which they achieved their activity goal with the taste of a drink (see Figure 4.15). They said *"salt if your activity time was lower than expected or sugar*

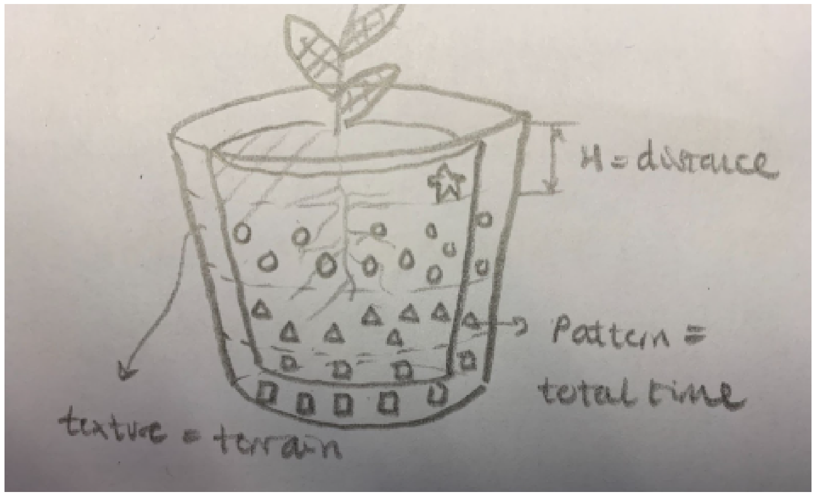


Figure 4.10: For scenario 3, P3 represented distance run each day with the height of different sections of the pot, total exercise time with the density of pattern on the surface of the pot, and terrain with the type of pattern.

*if your activity time was higher than you expected".*

## 4.2 Strategies for Creating the Representation

Through analyzing the data, we found that participants used two types of strategies for creating visualizations: representation strategies and data strategies.

### 4.2.1 Representation Strategy 1: Combining Multiple Objects

In our study, two participants created four visualization sketches by combining two different objects in their household. For example, P13 used a spice rack, spice jars, and beads to represent the physical activity data of multiple users over multiple days for scenarios 2 (see Figure 4.1), 3 and 4. P13 used one spice jar for each day of the week and put a number of beads in each jar corresponding to the data for that day. P13 mentioned in the template *"On a wall-mounted spice rack, small spice jars of the same size can be placed in a horizontal line, uniformly spaced beside one another. Within each jar is a collection of multicolor glass beads".*

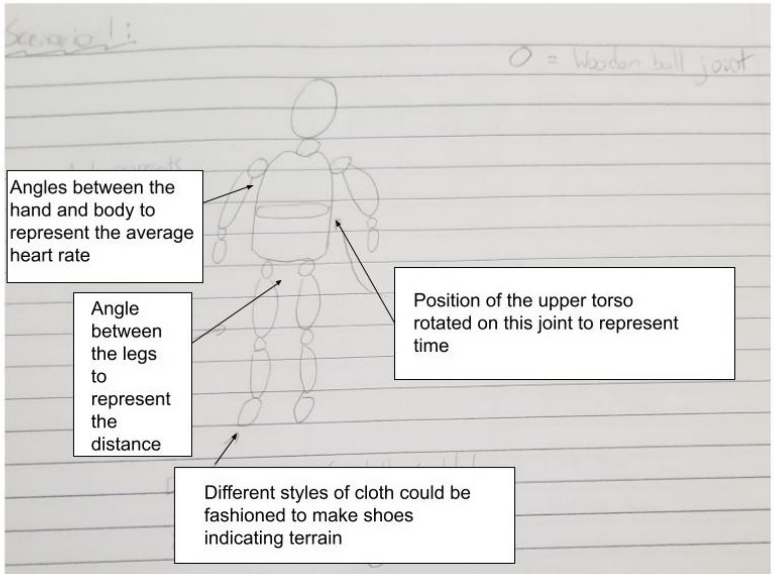


Figure 4.11: For scenario 3, P3 represented distance run each day with the height of different sections of the pot, total exercise time with the density of pattern on the surface of the pot, and terrain with the type of pattern.

### 4.2.2 Representation Strategy 2: Using Metaphors from Real Life

Two participants used real-life metaphors to create five sketches. For example, P13 said, for scenario 1, *"But for a flat road, I might choose black, like indicating tarmac"*. Here P13 used a color that symbolizes their model of what a road is to create the representation. Similarly, P1 placed magnetic stickers straight to represent flat terrain, and they rotated them so that they look like a hill for hilly terrain (see Figure 4.7).

### 4.2.3 Representation Strategy 3: Focusing on Aesthetics

The participants did not want to focus only on accurately representing the data, but also on the aesthetics of the visualization. Six participants created 11 sketches with this strategy. For example, P6 said *"I'm really thinking about this more like a decoration thing so it should look good"*. By focusing on aesthetics, P6 created the tapestry for scenario 1 shown in Figure 4.9 that represents the data but that is also a decorative object that can be kept in a public space of their household. Similarly, P11 in scenario 2 preferred not to modify the chessboard and the chess pieces shown in Figure 4.6, which are used as decorative objects in their home.

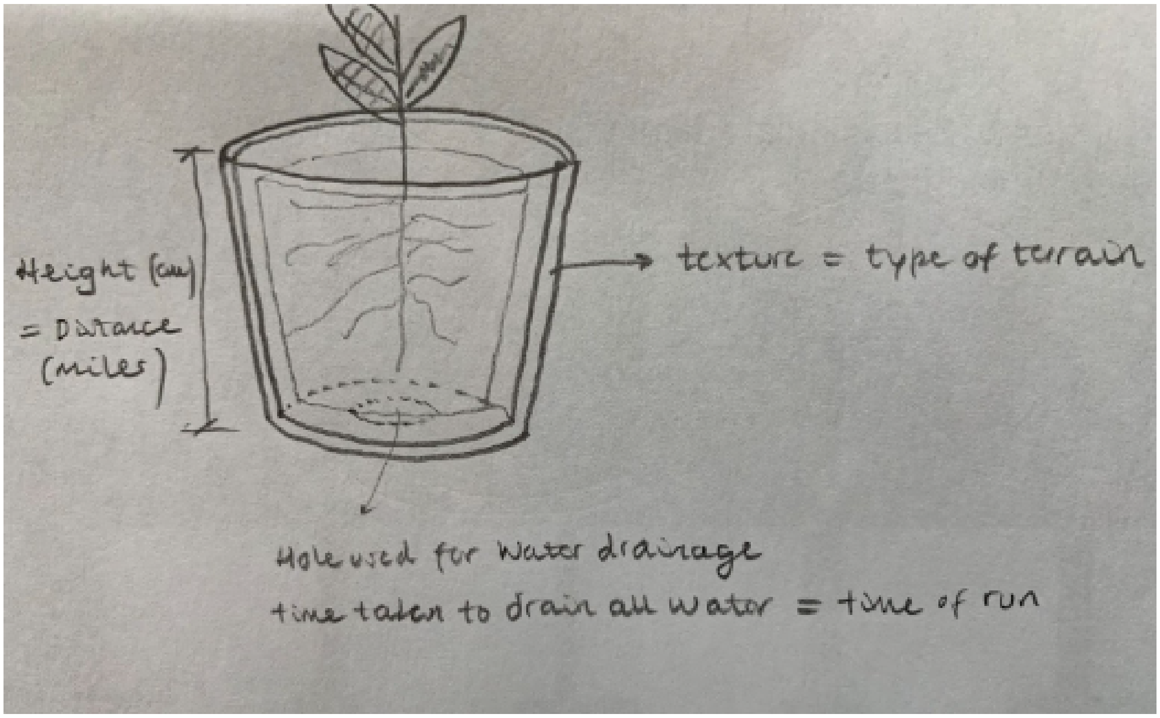


Figure 4.12: For scenario 1, P3 represented distance with the height of a flower pot, time with the dimension of the drain terrain with the physical texture on the surface of the flower pot.

### 4.2.4 Data Strategy 1: Combining the Given Data to Create New Data

Two participants created three sketches by that represented new data they had derived from the original dataset. Both participants calculated speed using distance and time. For example, P1 encoded speed with the position of the magnetic stickers on the refrigerator as shown in Figure 4.7. P1 said *"I think there is a relationship between distance and time ie., speed"*. This strategy was mainly employed with objects that have lesser flexibility like chairs, water dispensers, and magnetic stickers, and when the derived data was more meaningful to the participant than the original data.

### 4.2.5 Data Strategy 2: Rounding the data

Five participants rounded the original data in 19 sketches. All these participants rounded the numbers to 10s so that they could use one object for every 10 units of the data. P6 said *"I'm not concerned with the exact statistics [...] it would be*

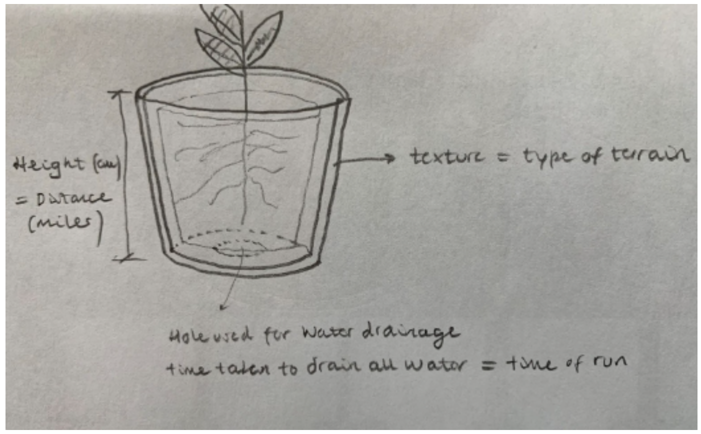


Figure 4.13: Modified image of P13 in scenario 1 for better understanding of the reader, P13 used a wooden figurine, angles between the legs of the figurine represent distance, rotation of the torso represents time, the angle between the hand and body represents average heart rate and the cloth on the feet represents the terrain

*rounded to make it I guess as close as possible"*. This strategy was mainly used when participants were not concerned with the exact data values and for whom an approximate representation was enough to track their progress on a daily basis.

### 4.2.6 Data Strategy 3: Scaling the Data

Eight participants scaled quantitative data values in 27 sketches. For example, P13 for scenario 1 said *"then one red bead would be, say 10 BPM. So yeah, obviously not an exact representation, but it's close"*. Here P13 used a number of red balls to represent scaled heart rate data where each ball represents 10 BPM, as shown in Figure 4.1. Participants used this strategy to make the visualization smaller, more manageable, and aesthetically appealing.

## 4.3 Techniques for Constructing the Visualization

We identified three aspects of visualization construction that were important to participants: aspects that relate to how public or private the space where the visualization would exist is, and aspects that relate to how manual or automated the visualization would be.

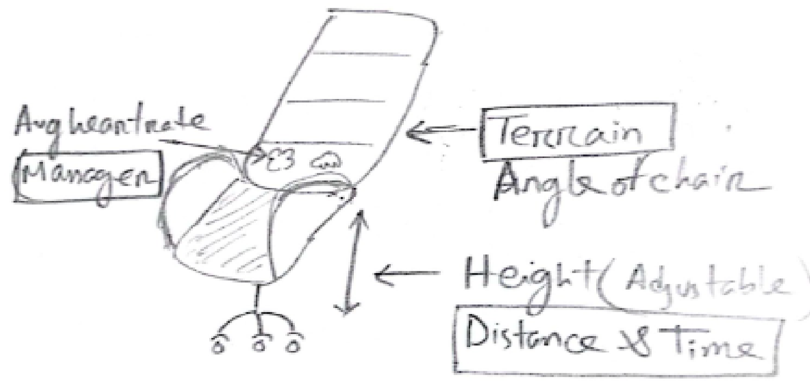


Figure 4.14: For scenario 1, P1 represented distance and time with the height of the chair, average heart rate with the duration of vibration of the massager, and terrain with the angle of the backrest.

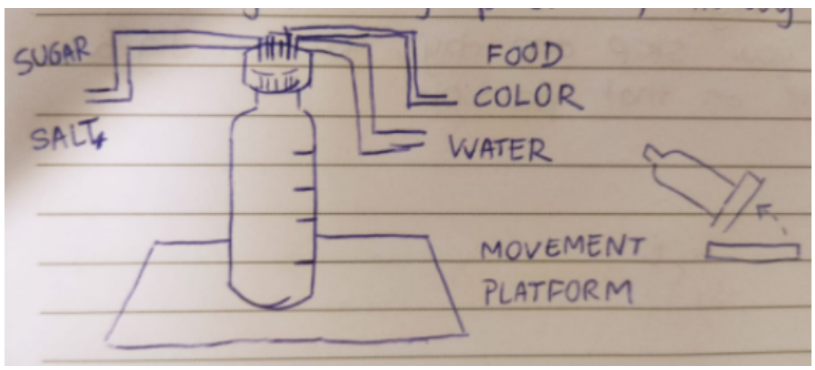


Figure 4.15: For scenario 1, P5 represented distance with the height of the water level in the bottle, time with the taste of the drink, heart rate with the food color, and terrain with the angle of the platform.

### 4.3.1 Public/Shared Space

We found that 10 participants would choose to display their visualization in a public space in 25 sketches, in most cases because they had chosen decorative objects and kitchen utensils to represent the data. Yet, participants thought about the social pressure of showing their data to other people living in their home. For example, P3 said *"the abstract representation just makes it more mysterious especially for people that visit you or your place"*; they opted for imprecise and sometimes undecipherable designs so that the data would be anonymous or meaningless to everyone in their home but them. Out of the 25 sketches, 20 were approximate representations.

### 4.3.2 Private Space

Eight participants preferred to keep the visualization in a private space in their home in 19 sketches. They did not want their physical activity data to be seen by other people living in the same household and other visitors because of the social pressure that would put on them. Out of the 19 sketches, 19 were approximate representations.

### 4.3.3 Manual, Automatic, and Mixed

Participants imagined employing manual, automatic and mixed techniques to create the visualizations in their sketches. 11 sketches relied on manual construction, 30 on automatic construction, and one on a mix of manual and automatic construction. Those who opted for automatic automatic construction did so for efficiency reasons. For example, P13 said *"of course, yeah for any of the representations I would automate if I could."* They further explained *"it just comes down to, I guess, like the motivation to actually build the representation each day! Because that's kind of the highest barrier"*. P13 also acknowledged, however, that manual creation could motivate them to get a more thorough understanding of the data.

# Chapter 5

# Prototype

We present a tangible manifestation of our research findings in the prototype section of this project report, aimed at addressing identified challenges and leveraging insights gained from an in-depth study. Based on empirical data and analysis, we developed a prototype to demonstrate the potential of physical variables of data physicalization to represent different types of household data.

## 5.1 Design

This work is the very beginning of exploring how people might use household objects to create physicalizations of their data. In the study, the participants mostly used color hue, size, amount of objects, and spatial region to represent the given data. Among those, the color hue of the light is mainly used to represent categorical data and ordinal data, and the color value and flicker of the light were also mainly used to represent the ordinal data. For quantitative data, participants mostly used size and position when representing their physical activity data in a household setting. Novel technology such as thermochromic pigments like in wearable dynamic display [63], multi-color LEDs as used in physikit [22], actuators with origami patterns like Adaptive Acoustic Origami [68], and shape memory alloys that can dynamically change the physical properties of objects are promising avenues for designing technology that would facilitate the implementation of such physicalizations. Another important design consideration while designing a data physicalization within a household object inside the household is the representation should support a range of abstractness or subtleness when representing the data. Especially when placing it in a public space inside the household.

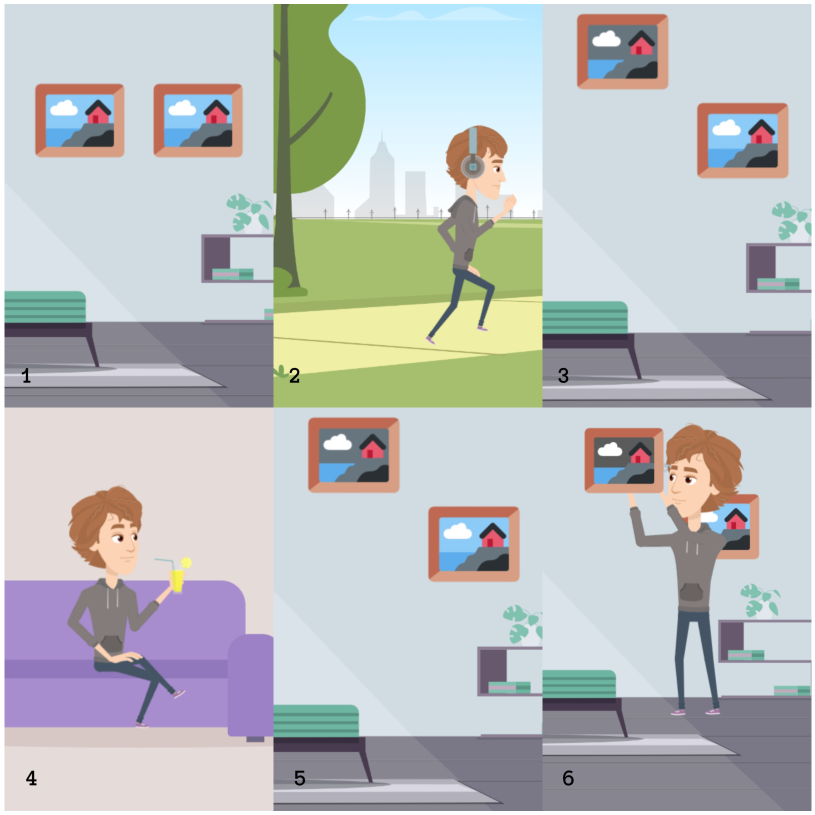


Figure 5.1: Image of an imaginary scenario of data physicalization to represent the running data of the user inside the household by using the photo frames

Interaction is also an important element to add to a data representation inside the household. The physical properties of the data physicalization offer different types of interaction possibilities like physical switches, touch, comparing the data points, etc. From the results, it was identified that participants most preferred interaction was to compare the data points of two different dates to know about their progress and few also preferred to modify the data points to their liking due to social pressure. For example, consider a scenario where the user recently redesigned the household's interior and added framed photos in his bedroom. These photo frames are mechanically designed to change height automatically according to the physical activity data of the user as shown in 5.1. The user connected his physical activity data from his smartwatch with the photo frames so that its position and physical properties change automatically to the data to represent it on the wall. After going for the daily run, the data will be transferred to the hardware, the first photo frame will change its height and color on the frame according to the speed of the run and the heartbeat rate during the run respectively of that particular day. On the second day, the user didn't go for running and was relaxing the whole day. So the data of that day will also be represented on the wall by the second photo frame by not changing its position and color. This allows the user to see both the day data simultaneously on the wall of his bedroom and lets the user compare their data points of two different days. This system allows the user to analyze the data over multiple days and he can modify the data points by using the app or change the height manually if he feels like it's affecting the aesthetic of the room or feels like changing it due to social pressure as shown in the 5.1.

## 5.2 Implementation

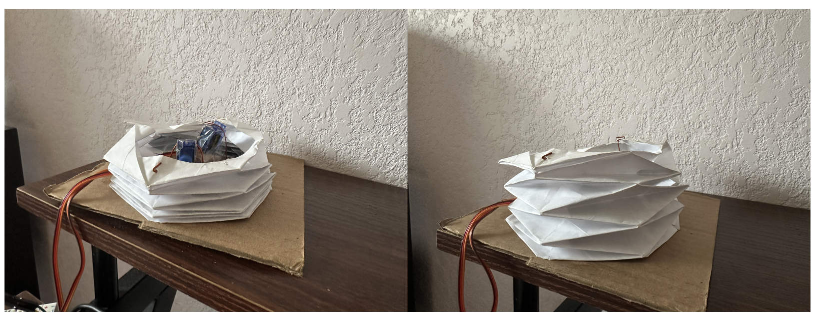

Figure 5.2: Image of the prototype with two Yoshimura patterns with two motors. (Left) The pattern forms a cylindrical shape that is compressed in height (Right) The height of the cylindrical pattern is increased by pushing it upward by the actuators

For the prototype, we used an origami pattern with the support of electronic actuators to augment the physical properties of the object to represent the data by the change in height and color of the object as shown in Figure 5.2 to show the potential of the origami in the field of data physicalization inside the household. In this, we used two Yoshimura origami patterns [45], that can give a small cylindrical thin-walled shell with a buckling pattern, along with LED to make it a cylindrical object that can change its height and color along with the data as shown in Figure 5.2 and Figure 5.5. Yoshimura pattern is an origami pattern that has the shape of a semi-cylinder and two of it was used to make it a complete cylindrical profile that can be buckled to reduce the height of the cylinder.

In the prototype, We used two micro servos, two 220 ohm resistors, one red, and one green LED. We used Arduino Uno as the microcontroller to control the actuators and the LEDs. Servo motors have 3 wires: power, ground, and signal. In most cases, the power wire is red and should be connected to the positive pole (+) of the power source. Ground wires are usually black or brown and should be connected to the negative pole (-) or GND of your power source. The signal pin is typically yellow or orange and should be connected to the PWM pin on the board. For the prototype, both the motors are connected to pin 9 and pin 10 on the Arduino Uno. For the LEDs, one leg of the resistor is connected to the digital pin on the microcontroller, then the anode of the LED to the other leg of the resistor, and the cathode of the LED is connected to GND. Green LED is connected to pin 7 and Red LED is connected to pin 8. The digital representation of the prototype hardware setup is shown in Figure 5.3. The circuit diagram of the whole hardware setup is shown in Figure 5.4. Each of the two halves of the cylindrical origami pattern had a micro servo attached to them. Servos are attached to the base and the shaft of the motor is connected to the top of the cylinder. So that the rotary motion of the motor is converted to linear motion which can push and pull the Yoshimura pattern which in turn increases and decreases the height of the cylinder. The attached servo motors have a rotating range of 180 degrees each. With every 5-degree angle rotated by the motor shaft, 1mm of the semi-cylindrical origami pattern is pushed vertically, giving the whole system an up-and-down movement of 3.6 cm approximately in total. We used Arduino Uno as the microcontroller to control the actuators and the LEDs.

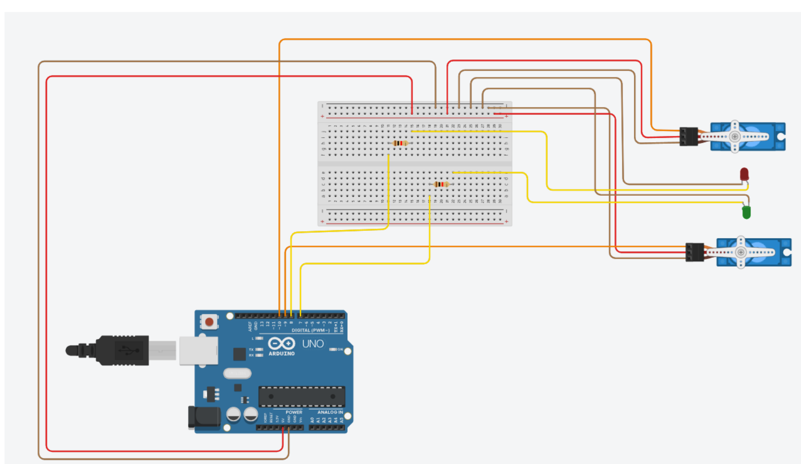


Figure 5.3: Digital representation of the hardware setup

As discussed in the results and discussion of the study, participants used size 32 times to represent the quantitative data type and color hue was used 30 times

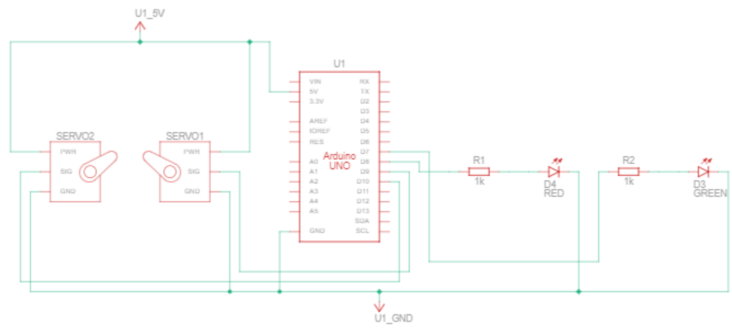


Figure 5.4: Circuit diagram of the hardware setup

to represent the categorical data type as shown in the table 6.2. As the size and color hue are the most frequently used encoding styles to represent quantitative and categorical data, we decided to use a change in size (height of the hardware) to represent the distance ran and the color hue (red and green LED) to represent the range of the heart rate data. As two motors can independently control two semi-cylindrical origami patterns, they can be used to represent the physical activity data of the user for two different days.

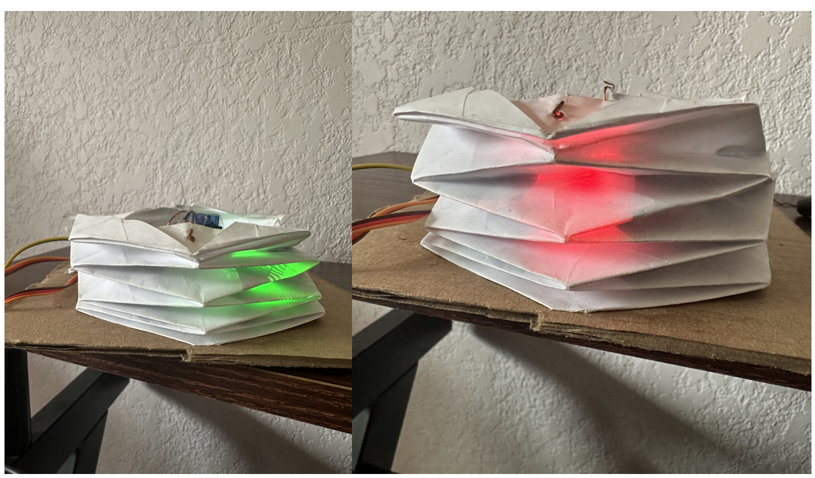

Figure 5.5: (Left)The prototype representing low-intensity data with smaller height and green light, (Right) The prototype representing the higher intensity data with an increase in height and red color

For instance, if the user has been lazy on the 1st day and has been active the next day, the system reduces its height according to the distance covered by the user on a lazy day and changes its color to green indicating the low heart rate on a lazy day as shown in the left of Figure 5.5, and then if the user wants to represent their physical activity data of an active day the system will increase its height according to the distance ran by the user on that particular day with red color representing a high heart rate during the run as shown in the right of Figure 5.5 showing the high-intensity workout of that particular day. So that the user can not only understand the data on the 1st and the 2nd day but also compare between the two days, that can allow the user to understand the data in depth and make changes to the routine to improve. For this example, we mapped every 5-degree rotation of the motor shaft or for every 1mm upward movement of the semi-cylindrical origami pattern to 100 meters run by the user. So, 1km run by the user is represented by a 1cm upward movement by the origami pattern. This cylindrical shell that can change its height and color to represent the data can be used as the cover or skin for the flower pot, pen holders, etc so that users can represent the data inside the household. This prototype is the very beginning of exploring the possibility of representing personal data inside the home using objects in the household.

## 5.3 Self Critique

We believe that this prototype can be the beginning of exploring the use of household objects to represent the data. This prototype can be used as the cover of an existing flower pot or a pen holder and blend with the aesthetic of the room seamlessly making the representation obfuscate to the others in the household. This can help the user to reduce the social pressure when others see their data in the representation. As discussed in the previous sections, we used color hue to represent the ordinal data and size to represent the quantitative data in this prototype to create the physicalization, which was the most used type of visual variable for the corresponding data types. This can help the representation to convey the data to the user in an efficient way. However, there are other major encoding styles like positions and modifying the amount of objects which are also found as the heavily used type of variables for representing quantitative data by the participants, which was not considered in this prototype. But for a system similar to 5.1, position can be used to represent the quantitative data. Similarly, a designer can choose the encoding styles according to the preference for representing the data efficiently. The material used for the prototype is origami paper which might not be suitable for a long-term application. Replacing the paper with a fabric will help to overcome that problem. The fabric along with stronger motors can help to make a bigger and more stable structure than the existing prototype.

# Chapter 6

# Discussions

Our study revealed that people are willing to use household objects to create physicalizations in their homes, and that they can think of various objects and ways to represent personal data. Participants to our study used a wide range of objects such as chair, curtain, tapestry, kinetic mobile, photo frames, refrigerator and water dispenser. They could project themselves creating and using such physicalizations in their homes to live closer to their personal data, while considering the social factors and privacy concerns that arise from displaying one's data in material form in a space accessible to others.

Our findings highlight four main considerations for personal data physicalization using household objects. We discuss i) the types of encodings that our participants used to imagine physicalizations, ii) how the use of these encodings compares with traditional use of encodings in visualization, iii) the need for flexible taxonomies for phyysicalizations, and iv) the social factors of in-home physicalization using household objects.

## 6.1 Types of Encodings for Different Data Types in Physicalization

As shown in Table 6.1, participants used a wide range of encodings to design their physicalizations such as like lights and colors, size, position, orientation and shape. Most used encodings include color hue, size, amount of objects, and spatial region. Among those, color hue of lights were mainly used to represent categorical data like terrain and ordinal data like heart rate ranges (low, medium, high). Similarly, color

Table 6.1: Consolidation of all the types of encoding styles used for different data types and their numbers of occurrences.

| Encoding Styles | Number of Scenarios | Number of data points represented | Quantitative | Categorical | Ordinal |
|---|---|---|---|---|---|
| Lights and Color | 31 | 60 | 13 | 30 | 16 |
| Hue | 26 | 51 | 11 | 30 | 9 |
| Value | 6 | 6 | 1 | 0 | 5 |
| Flicker | 3 | 3 | 1 | 0 | 2 |
| Size | 26 | 38 | 32 | 6 | 0 |
| Position | 34 | 49 | 35 | 14 | 0 |
| Orientation | 3 | 3 | 1 | 2 | 0 |
| Shape | 7 | 11 | 0 | 11 | 0 |
| Patter (Visual Texture) | 4 | 7 | 0 | 7 | 0 |
| Angle b/w Components | 4 | 5 | 2 | 4 | 0 |
| Amount of Objects | 18 | 42 | 42 | 0 | 0 |
| Weight | 1 | 3 | 3 | 0 | 0 |
| Physical texture | 11 | 11 | 0 | 10 | 1 |
| Spatial Region | 2 | 2 | 1 | 1 | 0 |
| Haptics/ Vibration | 3 | 5 | 4 | 0 | 1 |
| Taste | 1 | 1 | 0 | 0 | 0 |

value and flicker of lights were mainly used to represent ordinal data like heart rate range. Size and position were often used to represent quantitative data. Size was mainly used to represent distance, time, and sometimes calculated speed. Position, on the other hand, was often used to represent days of the week and time of day, enabling comparison of data values over time. Participants also used this style of juxtaposed representation to encode categorical data such as the different data attributes and the different people whose data was being represented. Shape and texture (visual and physical) were also mostly used to represent categorical data.

Several participants leveraged the tactile properties of physical objects by encoding data with physical texture. The angle between components, weight of the object, haptics/vibration, and taste are the other physical encodings that participants used. Previous work has leveraged such physical properties for data physicalization: Sweat Atoms [32] exploited physical size, Tasty Beats [31] taste with electrolyte drinks, and go & grow [4] with amount of water provided to a plant. Thus addressing the research question R1. Our findings suggest that other variables need to be supported for creating physicalizations using household objects. For example, technology like physikit [22], Cubble [35], and dynamic display on the wrist using thermochromic pigment [63] could be leveraged to facilitate the use of color hue and color value to represent ordinal and categorical data. Thermochromic pigments of different colors also provide new avenues for representing categorical data. Shape memory alloys or actuators could be used to change the shape and size of existing household objects, following the steps of Adaptive Acoustic Origami [68] that relies on linear actuators and origami patterns to make hardware that can changes its shape and length according to data.

*Implication: we need to leverage recent technological advances in physical computing to research and develop ways for people to encode data physically using a wide range of physical encodings.*

## 6.2 Comparison Between Standard Visual Encodings and Encodings Used in Physicalization

The visualization has built a thorough understanding of visual variables and their use for creating visualizations (e.g., [6, 49]). For example, we know that position is best suited for representing all types of data, and that shape, color hue, and texture should be used to represent categorical data. When it comes to physicalizations, however, except a few exceptions (e.g., [28]), we lack empirical knowledge about what variables should be used for what data types, especially when we consider other factors than time and accuracy of simple detection and estimation tasks. Interestingly, participants to our study often utilized visual encodings in ways that align with visualization guidelines in that regard; but we also observed some differences. Table 6.2 (top part) summarizes the standard visual variables that participants to our study used and compares that usage to visualization guidelines, while physical variables are shown in Table 6.2 (bottom part).

Participants often used standard visual variables in ways that align with visualization guidelines (e.g., using color hue and shape to encode categorical dimensions and using size and position to encode quantitative dimensions). However, they sometimes went against these guidelines. We see for example that participants often used color hue to represent quantitative and ordinal dimensions; and that they sometimes used shape, position and orientation to encode categorical dimensions.

Participants' choices of visual variables might be due to their lack of experience with data visualization, even though we added a session before the sketching activity to introduce data physicalization with many examples to increase their familiarity. But the fact that physicalization has the advantage of being physical and having physical properties like weight, physical texture, etc that all the participants have already experienced in their day-to-day lives, made them confident in their choices while sketching their visualization.

*Implication: it is possible that the physical affordances of physical objects dictate encodings that might not align with visualization best practices.*

## 6.3 The Need for Flexible Taxonomies for Physicalization

While analyzing the data we had collected for the study, we realized that it was often difficult to code, qualify, and classify the sketches that participants had created. One of the reasons for this is that participants often used several encodings to represent one type of data (i.e., redundant encoding). For example, for scenario 3, Pl changed the orientation of the square-shaped magnetic sticker by rotating it clockwise to represent the type of terrain but while rotating it clockwise it also changed the shape

Table 6.2: Consolidation of visual and physical variables used by the participants during the study with the visualization guidelines. Numbers indicate how many times an encoding style was used by participants in our study for each data type. Green numbers indicate that the theory agrees with the use of that variable for that data type, red that the theory disagrees, and yellow that the participant did not use the visual variable recommended by the theory.

| | Encoding styles | Quantitative | Categorical | Ordinal |
|---|---|---|---|---|
| Standard Visual Variables | Color hue | 10 | 30 | 10 |
| | Color value | 1 | 0 | 5 |
| | Flicker | 1 | 0 | 2 |
| | Size | 32 | 6 | 0 |
| | Position | 35 | 14 | 0 |
| | Orientation | 1 | 2 | 0 |
| | Shape | 0 | 11 | 0 |
| | Pattern (Visual Texture) | 0 | 7 | 0 |
| | Spatial Region | 1 | 1 | 0 |
| New Variables | Angles between the components | 2 | 4 | 0 |
| | Modifying the amount of object | 42 | 0 | 0 |
| | Weight | 3 | 0 | 0 |
| | Physical texture | 0 | 10 | 1 |
| | Haptics/Vibration | 4 | 0 | 1 |
| | Taste | 0 | 0 | 1 |

of the object from square to diamond (see Figure 4.7). Existing taxonomies require us to determine what encoding is used to represent data, but in such a case one person could consider that the dimension is encoded using shape, while another person might consider it is encoded using orientation.

*Implication: Things do not always fit in one column and there might not always be a one-to-one mapping between encoding and data dimension. With physicalizations come a larger number of possible encodings, and a larger number of possible encodings means both more opportunities to encode the data redundantly and more ambiguity in encodings.*

We also realized that data types are not as clearly defined as we may think. For example, some participants converted the average heart rate (quantitative data type) into different ranges, or bins, of high, medium, and low (ordinal data type). Then, they used a color hue to represent that data. Some participants also combined distance and duration to calculate speed by using position in their sketches; and others combined quantitative dimensions like distance, time, and heart rate to calculate the intensity of a workout, which they then represented using color value. These are just some of the strategies used by the participants to create the representation, addressing the research question R3.

Even though these strategies can be considered as the types of strategies that can be used in the creation of standard visualization, the context in which the participants used these strategies in the context of this study was mainly for keeping their visualizations abstract or subtle for factors such as social pressure. For instance, changing qualitative data like heart rate data into ordinal data like different ranges can hide the actual value of the data to other people living in the household but can still represent the data in a way only the user can understand.

*Implication 2: Data types are not set in stone and are subject to interpretation. Technology for representing data on household objects should support customization that allows people to edit data points and data types with operations such as aggregation, rounding and binning.*

## 6.4 Social Pressure and Location of the Representation in the Household

When considering the idea of using household objects to represent the data in their home, most participants thought they would display their physicalization publicly in the household. However, they also thought about privacy concerns and the social pressure they might feel if their personal data was visible and made understandable at all times by other household members or visitors. For that reason, they would design abstract visualizations that would either be imprecise so that the data would not be fully readable, or they would design one that obfuscates the data so that only they could read it. Thus addressing the research questions R2, R3, and R4. Their choice of object, its location, and the representation are all influenced by the social pressure it might create for them. Future technology should consider the choice of object and the location at which it is placed. Ambient visualizations for example are well suited to artistic, decorative visualizations that can subtly represent data, especially in a household where multiple people co-exist [60].

*Implication: Technology for representing personal data in a household setting should support a range of abstractness and data obfuscation options to support varying degrees of privacy.*

# Chapter 7

# Conclusions and Future Works

## 7.1 Conclusion

In this project, we explored the use of household objects to represent home physical activity data inside the home by conducting a qualitative study with 11 participants to understand the benefits and limitations of visualizing a pre-defined personal activity dataset through household objects. Based on the findings, we explained 1) different styles of physical encoding, 2) different strategies adopted by the participants for creating representation, and 3) different techniques for constructing the visualization. From the analysis of the result, we discussed about the different types of encoding styles that can be used for different data types in the physicalization that people might use for different data types when creating such physicalizations. We also made a detailed comparison between standard visual encoding and encoding used in creating data physicalization. Our research highlights the need for flexible taxonomies for physical representation because there might not always be a one-to-one mapping between encoding and data dimension as users can manipulate the encoding according to their liking. The research also stresses the importance of supporting ways of designing the data physicalization inside the household with privacy and social pressure as first considerations.

## 7.2 Limitations

In the study conducted, due to the recruitment being on a first-come, first-served basis, all participants were recruited from the engineering field; further studies could explore the participants from other backgrounds. Even though participants were from computer science and were familiar with the standard data visualizations of physical activity data like bar charts, line graphs, etc provided by devices like Fitbit, they were not familiar with the term data physicalization. To counter that, we added a 10-minute session before the sketching activity to introduce data physicalization with many examples to increase their familiarity. However, the inexperience of the participant in the field of data physicalization might be the reason for the choices of visual variables for some data types that are not agreed upon by the standard data visualization theory. Future studies can be conducted with a different set of participants who are experts in the field of data physicalization to know whether it can influence the result differently. However, the current findings are still valuable and provide some useful avenues for further study because of the exploration of several new physical variables, strategies for creation in the data physicalization context, the choices of location to place it, and the reason for it.

## 7.3 Future Work

All participants to our study were from the field of engineering and most were male; further studies should consider participants with different backgrounds and demographics. Conducting a study with participants with a wider range of educational backgrounds and genders is likely to reveal new ways of representing data using objects in the household. In addition, we designed the study using a dataset of running activity and this likely affected the results as well. Future studies with other datasets could likewise reveal additional insights. Studying in depth the role of privacy in data physicalization is also an important avenue for future research. Unlike digital visualizations that are easily disposable of easily made invisible to others, physicalizations have a more permanent presence that comes both with benefits and drawbacks worth investigating.

# Chapter 8

# Additional Information

## 8.1 Sketching Template

| | |
|---|---|
| **Object:** | **Object Location:** |
| **Explain the representation:** | |
| **Who has access to the object in the household?:** | |
| **How does the representation change if the object is already in use?** | |
| **How is the representation affected if another family member/roommates/a visitor wants to use the object?** | |
| **Sketch:** | |

Figure 8.1: Sample Sketching Template

## 8.2 Demographic Questionnaire

# Pre-Interview Questionnaire

This information is collected for knowing the demographics, familiarity with the data representation, physical activity routine and current data representation of the physical activity.

* Indicates required question

1. Age *

   ______________________

2. Gender *

   *Mark only one oval.*

   - ( ) Man
   - ( ) Women
   - ( ) Prefer not to say
   - ( ) Other: ______________________

3. What is your educational expertise?

   ______________________

4. What is your professional expertise?

   ______________________

5. What are your hobbies?

   ______________________

6. Please select the household type *

*Mark only one oval.*

- Apartment
- House
- Other: ____________

7. Please select the household composition *

*Mark only one oval.*

- Family (with children)
- Family (without children)
- Joint family
- Couple
- Housemates
- Single
- Other: ____________

8. Are you a person who does any type of exercise or is physically active? *

*Mark only one oval.*

- Yes *Skip to question 9*
- No
- Sometimes *Skip to question 9*

Active participants

9. What are the types of exercise/activity you engage in? List the exercise/acrtivity

10. How often do you exercise? *

*Mark only one oval.*

- Rarely/Never
- Once a month
- Once a week
- 2-3 times a week
- Every day

11. What is your experience collecting the physical activity data (e.g. using apps/devices such as Fitbit, google fit, Mi Fit/Mi Band, manually writing it down etc.)? *

*Mark only one oval.*

- Currently I collect data *Skip to question 12*
- I previously collected the data *Skip to question 12*
- I have never Collected data

Data Collection

12. If you collect/ed your physical activity data, please specify the type of data (like distance, duration, heartbeat etc.) and how do/did you collect it (specify the name of the app/device)? *

13. If you collect physical activity data using apps/devices, how often do/did you carry the data collection device with you? *

*Mark only one oval.*

- Never
- Rarely
- Every time I do an activity
- During day time
- Nearly all the time

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Google Forms

Figure 8.2: Demographic Questionnaire

# Bibliography


[1] Runkeeper. *http://runkeeper.com/*, 2013.

[2] Anne Adams, Peter Lunt, and Paul Cairns. A qualititative approach to hci research. 2008.

[3] Timothy Auburn and Rebecca Barnes. Producing place: A neo-schutzian perspective on the 'psychology of place'. *Journal of environmental psychology*, 26(1):38–50, 2006.

[4] Fadi Botros, Charles Perin, Bon Adriel Aseniero, and Sheelagh Carpendale. Go and grow: Mapping personal data to a living plant. In *Proceedings of the International Working Conference on Advanced Visual Interfaces*, pages 112–119, 2016.

[5] Stuart K Card, Jock Mackinlay, and Ben Shneiderman. *Readings in information visualization: using vision to think*. Morgan Kaufmann, 1999.

[6] M Sheelagh T Carpendale. Considering visual variables as a basis for information visualisation. *Computer Science TR# 2001-693*, 16, 2003.

[7] Sunny Consolvo, Katherine Everitt, Ian Smith, and James A Landay. Design requirements for technologies that encourage physical activity. In *Proceedings of the SIGCHI conference on Human Factors in computing systems*, pages 457–466, 2006.

[8] Sunny Consolvo, David W McDonald, and James A Landay. Theory-driven design strategies for technologies that support behavior change in everyday life. In *Proceedings of the SIGCHI conference on human factors in computing systems*, pages 405–414, 2009.

[9] Foroozan Daneshzand, Charles Perin, and Sheelagh Carpendale. Kiriphys: Exploring new data physicalization opportunities. *IEEE Transactions on Visualization and Computer Graphics*, 29(1):225–235, 2022.

[10] Audrey Desjardins and Timea Tihanyi. Listeningcups: a case of data tactility and data stories. In *Proceedings of the 2019 on designing interactive systems conference*, pages 147–160, 2019.

[11] Pierre Dragicevic, Yvonne Jansen, and Andrew Vande Moere. Data physicalization. *Handbook of Human Computer Interaction*, pages 1–51, 2020.

[12] Pierre Dragicevic and Moritz Stefaner. Meshu.io: Data jewellery you can order online. *http://dataphys.org/list/data-jewelry/*, 2012.

[13] Žarko Dumičić, Katja Thoring, Hermann W Klöckner, and Gesche Joost. Design elements in data physicalization: A systematic literature review. 2022.

[14] F Froebel. The education of man (translated by jarvis, j.). *New York: A. Lovell and Co*, 1885.

[15] Mirta Galesic and Rocio Garcia-Retamero. Graph literacy: A cross-cultural comparison. *Medical decision making*, 31(3):444–457, 2011.

[16] James J Gibson. The ecological approach to the visual perception of pictures. *Leonardo*, 11(3):227–235, 1978.

[17] Rebecca Gulotta, Jodi Forlizzi, Rayoung Yang, and Mark Wah Newman. Fostering engagement with personal informatics systems. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*, pages 286–300, 2016.

[18] Anton Gustafsson and Magnus Gyllenswärd. The power-aware cord: energy awareness through ambient information display. In *CHI'05 extended abstracts on Human factors in computing systems*, pages 1423–1426, 2005.

[19] David Holstius, John Kembel, Amy Hurst, Peng-Hui Wan, and Jodi Forlizzi. Infotropism: living and robotic plants as interactive displays. In *Proceedings of the 5th conference on Designing interactive systems: processes, practices, methods, and techniques*, pages 215–221, 2004.

[20] Eva Hornecker and Jacob Buur. Getting a grip on tangible interaction: a framework on physical space and social interaction. In *Proceedings of the SIGCHI conference on Human Factors in computing systems*, pages 437–446, 2006.

[21] Steven Houben, Ben Bengler, Daniel Gavrilov, Sarah Gallacher, Valentina Nisi, Nuno Jardim Nunes, Licia Capra, and Yvonne Rogers. Roam-io: Engaging with people tracking data through an interactive physical data installation. In *Proceedings of the 2019 on Designing Interactive Systems Conference*, pages 1157–1169, 2019.

[22] Steven Houben, Connie Golsteijn, Sarah Gallacher, Rose Johnson, Saskia Bakker, Nicolai Marquardt, Licia Capra, and Yvonne Rogers. Physikit: Data engagement through physical ambient visualizations in the home. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 1608–1619, 2016.

[23] Hiroshi Ishii and Brygg Ullmer. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*, pages 234–241, 1997.

[24] Riitta Jääskeläinen. Think-aloud protocol. *Handbook of translation studies*, 1:371–374, 2010.

[25] Nassim Jafarinaimi, Jodi Forlizzi, Amy Hurst, and John Zimmerman. Breakaway: an ambient display designed to change human behavior. In *CHI'05 extended abstracts on Human factors in computing systems*, pages 1945–1948, 2005.

[26] Yvonne Jansen and Pierre Dragicevic. An interaction model for visualizations beyond the desktop. *IEEE Transactions on Visualization and Computer Graphics*, 19(12):2396–2405, 2013.

[27] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. Opportunities and challenges for data physicalization. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 3227–3236, 2015.

[28] Yvonne Jansen and Kasper Hornbæk. A psychophysical investigation of size as a physical variable. *IEEE transactions on visualization and computer graphics*, 22(1):479–488, 2015.

[29] Bradley S Jorgensen and Richard C Stedman. Sense of place as an attitude: Lakeshore owners attitudes toward their properties. *Journal of environmental psychology*, 21(3):233–248, 2001.

[30] Maria Karyda, Merja Ryöppy, Jacob Buur, and Andrés Lucero. Imagining data-objects for reflective self-tracking. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pages 1–12, 2020.

[31] Rohit Ashok Khot, Jeewon Lee, Deepti Aggarwal, Larissa Hjorth, and Florian'Floyd' Mueller. Tastybeats: Designing palatable representations of physical activity. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 2933–2942, 2015.

[32] Rohit Ashok Khot, Florian'Floyd' Mueller, and Larissa Hjorth. Sweatatoms: materializing physical activity. In *Proceedings of The 9th Australasian Conference on Interactive Entertainment: Matters of Life and Death*, pages 1–7, 2013.

[33] Tanyoung Kim, Hwajung Hong, and Brian Magerko. Design requirements for ambient display that supports sustainable lifestyle. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems*, pages 103–112, 2010.

[34] Predrag Klasnja and Wanda Pratt. Healthcare in the pocket: mapping the space of mobile-phone health interventions. *Journal of biomedical informatics*, 45(1):184–198, 2012.

[35] Robert Kowalski, Sebastian Loehmann, and Doris Hausen. Cubble: A multi-device hybrid approach supporting communication in long-distance relationships. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*, pages 201–204, 2013.

[36] Andrea Lau and Andrew Vande Moere. Towards a model of information aesthetics in information visualization. In *2007 11th International Conference Information Visualization (IV'07)*, pages 87–92. IEEE, 2007.

[37] Tatjana Leblanc et al. Sketching as a thinking process. In *DS 82: Proceedings of the 17th International Conference on Engineering and Product Design Education (E&PDE15), Great Expectations: Design Teaching, Research & Enterprise, Loughborough, UK, 03-04.09. 2015*, pages 606–611, 2015.

[38] Moon-Hwan Lee, Seijin Cha, and Tek-Jin Nam. Patina engraver: Visualizing activity logs as patina in fashionable trackers. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 1173–1182, 2015.

[39] Laura Lentini and Françoise Decortis. Space and places: when interacting with and in physical space becomes a meaningful experience. *Personal and Ubiquitous Computing*, 14:407–415, 2010.

[40] James J Lin, Lena Mamykina, Silvia Lindtner, Gregory Delajoux, and Henry B Strub. Fish'n'steps: Encouraging physical activity with an interactive computer game. In *International conference on ubiquitous computing*, pages 261–278. Springer, 2006.

[41] Lynne Manzo and Patrick Devine-Wright. *Place attachment: Advances in theory, methods and applications*. Routledge, 2013.

[42] Lynne C Manzo. Beyond house and haven: Toward a revisioning of emotional relationships with places. *Journal of environmental psychology*, 23(1):47–61, 2003.

[43] Nora McDonald, Sarita Schoenebeck, and Andrea Forte. Reliability and interrater reliability in qualitative research: Norms and guidelines for cscw and hci practice. *Proceedings of the ACM on human-computer interaction*, 3(CSCW):1–23, 2019.

[44] Daphne Menheere, Evianne Van Hartingsveldt, Mads Birkebæk, Steven Vos, and Carine Lallemand. Laina: dynamic data physicalization for slow exercising feedback. In *Designing Interactive Systems Conference 2021*, pages 1015–1030, 2021.

[45] Andrea Micheletti, Ilaria Giannetti, Gabriele Mattei, and Alessandro Tiero. Kinematic and static design of rigid origami structures: Application to modular yoshimura patterns. *Journal of Architectural Engineering*, 28(2):04022009, 2022.

[46] A Vande Moere and Stephanie Patel. Analyzing the design approaches of physical data sculptures in a design education context. *Visual Information Communications International (VINCI'09)*, 2009.

[47] Andrew Vande Moere. Towards designing persuasive ambient visualization. In *Issues in the Design & Evaluation of Ambient Information Systems Workshop*, pages 48–52. Citeseer, 2007.

[48] Andrew Vande Moere. Beyond the tyranny of the pixel: Exploring the physicality of information visualization. In *2008 12th International Conference Information Visualisation*, pages 469–474. IEEE, 2008.

[49] Tamara Munzner. *Visualization analysis and design*. CRC press, 2014.

[50] Sara Nabil and David Kirk. Interactive interior design and personal data. In *People, Personal Data and the Built Environment*, pages 103–122. Springer, 2019.

[51] Marija Nikolić, Stanko Škec, Tomislav Martinec, and Nikola Horvat. The role of sketching activities and outcomes in conceptual design phase. In *Proceedings of the Design Society: International Conference on Engineering Design*, volume 1, pages 399–408. Cambridge University Press, 2019.

[52] Judith S Olson and Wendy A Kellogg. *Ways of Knowing in HCI*, volume 2. Springer, 2014.

[53] Kim Sauvé, Saskia Bakker, and Steven Houben. Econundrum: Visualizing the climate impact of dietary choice through a shared data sculpture. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*, pages 1287–1300, 2020.

[54] Kim Sauvé, Saskia Bakker, Nicolai Marquardt, and Steven Houben. Loop: Exploring physicalization of activity tracking data. In *Proceedings of the 11th nordic conference on human-computer interaction: shaping experiences, shaping society*, pages 1–12, 2020.

[55] Kim Sauvé and Steven Houben. From data to physical artifact: challenges and opportunities in designing physical data artifacts for everyday life. *Interactions*, 29(2):40–45, 2022.

[56] Kim Sauvé, Miriam Sturdee, and Steven Houben. Physecology: A conceptual framework to describe data physicalizations in their real-world context. *ACM Transactions on Computer-Human Interaction*, 29(3):1–33, 2022.

[57] Stephen AR Scrivener, Linden J Ball, and Winger Tseng. Uncertainty and sketching behaviour. *Design Studies*, 21(5):465–481, 2000.

[58] Samarth Singhal, Carman Neustaedter, William Odom, Lyn Bartram, and Yasamin Heshmat. Time-turner: designing for reflection and remembrance of moments in the home. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–14, 2018.

[59] Tobias Skog. Activity wallpaper: ambient visualization of activity information. In *Proceedings of the 5th conference on Designing interactive systems: processes, practices, methods, and techniques*, pages 325–328, 2004.

[60] Tobias Skog, Sara Ljungblad, and Lars Erik Holmquist. Between aesthetics and utility: designing ambient information visualizations. In *IEEE Symposium on Information Visualization 2003 (IEEE Cat. No. 03TH8714)*, pages 233–240. IEEE, 2003.

[61] Simon Stusak, Aurélien Tabard, Franziska Sauka, Rohit Ashok Khot, and Andreas Butz. Activity sculptures: Exploring the impact of physical visualizations on running activity. *IEEE transactions on visualization and computer graphics*, 20(12):2201–2210, 2014.

[62] Saiganesh Swaminathan, Conglei Shi, Yvonne Jansen, Pierre Dragicevic, Lora A Oehlberg, and Jean-Daniel Fekete. Supporting the design and fabrication of physical visualizations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 3845–3854, 2014.

[63] Muhammad Umair, Muhammad Hamza Latif, and Corina Sas. Dynamic displays at wrist for real time visualization of affective data. In *Proceedings of the 2018 ACM Conference Companion Publication on Designing Interactive Systems*, pages 201–205, 2018.

[64] Mark Weiser. The computer for the 21st century. *ACM SIGMOBILE mobile computing and communications review*, 3(3):3–11, 1999.

[65] Mitchell Whitelaw. Mitchell whitelaw's weather sculptures. *http://dataphys.org/list/weather-bracelet-and-measuring-cup*, 2009.

[66] Craig Wisneski, Hiroshi Ishii, Andrew Dahley, Matt Gorbet, Scott Brave, Brygg Ullmer, and Paul Yarin. Ambient displays: Turning architectural space into an interface between people and digital information. In *Cooperative Buildings: Integrating Information, Organization, and Architecture: First International Workshop, CoBuild'98 Darmstadt, Germany, February 25–26, 1998 Proceedings 1*, pages 22–32. Springer, 1998.

[67] Hsin-Kai Wu and Priti Shah. Exploring visuospatial thinking in chemistry learning. *Science education*, 88(3):465–492, 2004.

[68] Xuyou Yang. Adaptive acoustic origami. *Melbourne School of Design. University of Melbourne. Date: Interview No.: Name of Auditorium*, 2017.