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Data Beyond the Screen:

An Exploration of Data Physicalization's Impact on User Engagement, Management, and Reflection with a comparative study between Pixels and the Third Dimension

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Research thesis
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Abstract in English

Data Physicalization is a captivating field of research that delves into the realm of representing data in a physical, tangible form, that is beyond the traditional fashion of screen-based and visual displays. It encompasses a wide range of physical artifacts, namely from small 3D-printed objects to large sculptural installations, made altogether from various materials, even though the majority takes on a static form that does not align with the premise of data physicalizations that are supported by computer technology. This area of research continues to generate interest among researchers and designers, primarily due to the benefits associated with the aforementioned physical artifacts, that encode data through their geometry or material properties. There has been considerable interest in determining which data representation technique is the best one for exploring, understanding, sharing, and communicating data. Subsequently to this, an exciting area to explore is comparing physicalizations to visualizations through an experimental user study, as to gain insights into whether the ability to have a physical representation of data leads to better understanding and awareness, which in the realm of a directive style of tracking can potentially lead to behavior change. Does it make a difference whether the data representation object is real, in the same room, and incorporated into everyday life, as opposed to it being viewed on a screen? The current state points to a promising direction in focusing on data representations connected to personal data physicalizations, as they have the potential to embody various goals, such as expression and reflection, as opposed to the visual counterpart – visualizations, that are mainly present in the information retrieval context. In particular, this experimental user study focuses on activity tracking, as it serves as a relevant case study to understand if physicalizations can serve as the method of data representation that can rise above and come off as more efficient model of representation. The study led through the design activities succours to learning the potential impact of data physicalizations and understanding their efficiency.

key words: data physicalization, personal informatics, personal data, activity tracking, efficiency of making data physical

Abstract in Italian

La Data Physicalization è un affascinante campo di ricerca che si addentra nel mondo della rappresentazione dei dati in forma fisica e tangibile, al di là della tradizionale visualizzazione basate su schermo. Comprende una vasta gamma di artefatti fisici, da piccoli oggetti stampati in 3D alle grandi installazioni scultoree, realizzati con vari materiali, anche se la maggior parte assume una forma statica che non si allinea con la premessa di data physicalization basata sulla tecnologia informatica. Quest'area di ricerca continua a generare interesse tra ricercatori e designer, soprattutto a causa deglvi artefatti fisici che codificano i dati attraverso la loro geometria o la proprietà dei materiali. La tesi inizia dando una notevole attenzione nella determinazione della tecnica di rappresentazione dei dati più adatta per esplorare, comprendere, condividere e comunicare i dati. Successivamente, è stata eseguita una comparazione tra physicalization e visualizzazione attraverso uno studio sperimentale con utenti, al fine di acquisire informazioni sul fatto che la capacità di avere una rappresentazione fisica dei dati porti a una migliore comprensione e consapevolezza, che può potenzialmente portare a un cambiamento di comportamento. Fa differenza se la rappresentazione dei dati è reale, nella stessa stanza o incorporata nella vita quotidiana, rispetto a quella visualizzata sullo schermo? Lo stato attuale indica una promettente direzione nell'enfasi sulla rappresentazione dei dati connessi alle physicalization dei dati personali, poiché hanno il potenziale di incarnare vari obiettivi, come espressione e riflessione, rispetto alla controparte visiva - le visualizzazioni, che sono principalmente presenti nel contesto di recupero di informazioni. In particolare, questo studio sperimentale con utenti si concentra sul tracciamento dell'attività, poiché serve come un caso studio pertinente per comprendere se le physicalization possano essere il metodo di rappresentazione dei dati che possa risultare più efficiente. Lo studio condotto attraverso le attività di design contribuisce all'apprendimento del potenziale impatto delle physicalization dei dati e alla comprensione della loro efficienza.

parole chiave: fisicalizzazione dei dati, informatica personale, dati personali, tracciamento delle attività, efficienza della fisicalizzazione dei dati

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Introduction

There is an increasing interest in the field of Data Physicalization, as there are many examples where the physical artifacts that are the data physicalizations are explored to gather a better understanding of potential benefits that they can vouch for (Jansen et al., 2015). While the research field of Data Physicalization shows its tendencies to strengthen the resemblance to the ones of Tangible User Interfaces and Shape-Changing Interfaces, relying on their respective technological advancements, for now, data physicalizations tend to be an interesting starting point for understanding the benefits of making data physical in their more static and not that technologically advanced form.

Namely, these static data representations based on their presence in the literature, tend to be enough in understanding the base premise of Data Physicalization, with their numerous benefits, and can always serve as an inspiration for what is there to come for this field in the future (Jansen et al., 2015). This research aims to investigate the potential impact of physical representations of personal data on self-reflection, personal growth, and behavior change. By conducting a literature review and analyzing current data physicalization practices, as well as understanding the quantified self and personal informatics, the study seeks to gain a deeper understanding of the contexts and data types that can be embodied by physical artifacts and how they can be utilized to enhance users' understanding of their personal data.

The ultimate goal is to contribute to the advancement of the field of data physicalization and its potential to promote personal growth and change. The study will focus on the use of physicalizations in self-tracking, specifically in the directive tracking style (Rooksby et al., 2014), with the aim of exploring how data physicalizations, designed in order to show data changes in real-time, through automating the process of achieving the physicalizations themselves, can facilitate self-reflection and help individuals achieve their goals. The study will also investigate the potential benefits of using data physicalizations as a tool that would contribute to better management and display of personal data, with the possibility to compare different representational models of the same data, as to understand the potential impacts that the physicalization can vouch for, as it is important to gather insights that would overweight the costs that underlie in producing the said physicalizations (Jansen et al., 2015).

Chapter 1: Research parameters

1.1. Research problem and significance

The numerous benefits pointed out in the literature review emphasize the ability of the data physicalizations to have an impact and elaborates on their newly discovered potential to help people in gaining a better understanding of themselves, which would subsequently lead to making changes in their life (Jansen et al., 2015).

However, it is acknowledged among the experts that there are currently a great number of opportunities and challenges, namely in the process of crafting the said data physicalizations, as there is no standardized approach that showcases how the physicalizations should be made, which materials should be used, on which technology to relay in order to communicate the data in the most effective way, as well as how exactly people perceive the physicalizations and how they differ from the other data representation techniques, such as the visualizations (Jansen et al., 2015).

The current research in the field of Data Physicalization shows many endeavours that deal with increasing the understanding of data physicalization in various aspects. As an illustration, there is the example of producing insights and gathering an understanding of the efficiency of the data artifacts, with the means of comparing the data physicalizations to their visual counterpart, through performing an experimentative study (Jansen et al., 2013). This approach has contributed to the construction of some base insights, that are, in this case, contextual and built around performing tasks from the likes of low-information retrieval and bound to a specific static specimen. This serves as an inspiration and a starting point that can be followed with crafting additional user studies that can tackle some other aspects in gathering insights about the efficiency of the data physicalizations, for example in use cases that deal with dynamic data representation as the specimen, as well as other contexts that go beyond the low-information retrieval.

With this research, the goal is to tackle and explore some of the open points through an experimentative user study, explained in a more elaborative manner in the research goals and motivations. In order to understand what exactly can be the subject of the research, the research process is explained in the further chapters.

1.2. Research methodology

Understanding the research scope and the intended insights that are to be produced, a user study is the fitting possible course of action, done through the likes of experimental study.

Moreover, given that the nature of the research corresponds with designing a certain design artifact to fit design activities that can contribute to fresh insights and understanding, it also tackles areas of research through design, also referred to as research by design, which is a method of inquiry that combines design methodologies and techniques with the rigor and criticality of conventional research approaches. A design challenge or problem serves as the typical starting point, and new ideas, solutions, and insights are produced using design thinking, prototyping, and testing. In addition to producing design solutions, research through design aims to produce artifacts that serve as exemplars (Zimmerman et al., 2007). Researchers can investigate, comprehend, and communicate problems and phenomena by using design as a method of inquiry.

The research methodology will be reflected upon in a more deeper manner while discussing the details of the user study.

1.2. Research process

In order to gather insights from the field of Data Physicalization and generate an overall understanding of the current findings as encounter the possibility to generate a promising research question, the first section of the research process consists of a literature review, where the second and third section, being the development of data physicalization and user study of the developed data physicalization respectively, are added.

The process of crafting the research question is illustrated in the following chapter, which shows an overview and insights from the literature review itself. The literature review approach consists of three sections that are implicated from each other, starting from an overall holistic overview of Data Physicalization. The outcome of this first section in the literature review determines the direction of the second section, which is the section on Personal Data Physicalization. From here, the second section implicates the third and final section, the Activity Data Physicalization.

By having the research question established, the second section of the research process arises; namely, includes the development of data physicalization, and the physical artifact to be used for the purpose of implementing a user study, which is the third section of the thesis.

SECTION	LITERATURE REVIEW	DEVELOPMENT OF DATA PHYSICALIZATION	USER STUDY
METHOD	scoping relevant papers	double diamond design process	user study
	gaining an understanding of data physicalizations through online list		questionnaire and semi-structured interviews
	questionnaire		reflexive thematic analysis
PARTICIPANTS	researcher (author)	researcher (author)	researcher (author)
	co-supervisor	co-supervisor	co-supervisor
			participants
GOALS	identify key concepts and research gaps	identify a concept that suits the intended user study in terms of design, through activities that include the determination of which hardware and software to be used in order to develop dynamic data physicalization	evaluating the data physicalization and gathering information in regard to the research question
OUTCOMES	research question and objective	data physicalization(s) to be used for the user study	insights consisting of knowledge that is understandable and usable for the future design community

Table 1: Research process

Chapter 2: Literature review

2.1. Overview

The objective of the literature review is to understand in which way this research can contribute to new knowledge in the field of Data Physicalization. Therefore, the literature review is an essential part that leads to the generation of a promising and significant research question. As previously mentioned, the literature review is explored through three distinct sections, implicated from each other.

Each section includes a finishing part that elaborates the explanations of the insights that help to narrow down the scope, discussed in the following chapters.

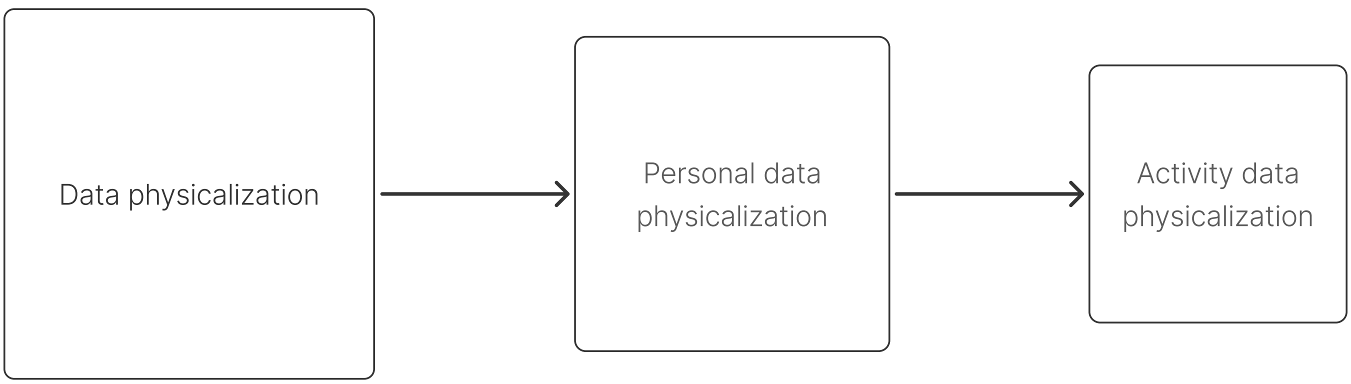

Figure 1: Literature review sections

Starting the literature review by clustering relevant information about the field in a broader manner allowed us to identify key concepts and pivotal moments on how to narrow the scope. Therefore, a promising lead is to tackle and understand more about personal data and representative cases of personal data physicalization. Before continuing with the third and most narrowed section, we encountered the necessity to prepare a questionnaire, in order to understand which personal data to focus on. Therefore, the third section of the literature review deals with representative cases of activity data physicalization.

Chapter 3: Data physicalization

3.1. What are Data Physicalization and data physicalizations?

First things first, to address the terminology itself, the following question arises: What is data physicalization? We can differentiate data physicalization as a research area and a physical artifact (Jansen et al., 2015). In terms of the former one, Data Physicalization (using capital letters in order to distinguish from the physical artifact) is an emerging research area that deals with the use of data representations that are physical and essential in the quest of helping us to explore and communicate data and their support for learning, problem-solving and making a decision.

What concerns the physical artifact portion of the answer, “a data physicalization (or simply physicalization) is a physical artifact whose geometry or material properties encode data (Jansen et al., 2015).” The word physicalization itself is used to address the process of making something physical.

Moreover, when talking about data physicalization, the focus is on the physical representation of data, whereas the interaction with the physicalization can be in the real world without being assisted by a computer (Jansen et al., 2015). Here it is important to note that even though it can happen some handmade physicalizations do not involve computers at all, they are useful as a starting point in the process of envisioning modern physicalizations that are supported by a computer.

3.2. Representative cases of data physicalization

What do, for example, the Mesopotamian clay tokens, the scientists’ physical representations of organic chemistry, and the nowadays designers’ data sculptures have in common? They are useful in helping us to think about data, and explore and share data. Data physicalization artifacts have a lengthy and varied history, and as a result, they have a variety of features, interactions, and structural variations that allow them to be used in a variety of settings (Bae et al., 2022).

Data physicalization intends to use machines to create interactive, engaging, and visually appealing physical representations of data. By taking advantage of technologies such as laser cutters and 3D printers, data physicalization allows people to explore data in a more tangible way, making it easier for them to understand and interpret it. As seen in the online list of data physicalization examples, this technique can be used to create a variety of shapes and sizes, from small objects to large museum installations (List of Physical Visualizations and Related Artifacts, n.d.-b).

Although the majority of the examples do not demonstrate the more dynamic nature that the field of Data Physicalization aims for, they can be used as a model and a jumping-off point for creating more up-to-date data representations that take advantage of recent technological developments like Tangible User Interfaces and Shape-Changing Interfaces, such as physicalizations that update themselves with new data (Jansen et al., 2015).

Here we can also mention the existence of data sculptures. A physical artifact based on data known as a "data sculpture" aims to increase audience members' comprehension of data insights and any underlying socially significant issues (Zhao et al., 2008). A data sculpture provides data-related insights while enticing viewers to consider the social and cultural implications of the dataset. Data sculptures are tangible depictions of data or information, usually made from materials like plastic, wood, or metal. They can come in a variety of shapes, including hand-made models, metal or wood that has been laser-cut, or 3D-printed objects. Data sculptures are frequently used to communicate information in an interactive and engaging way or to visualize and understand complex data sets. In addition to corporate buildings and other settings, they can be found in public places like museums, galleries, and other places.

For example, in 2013 a group of architects created a room-sized physicalization. In this example, the population distribution of the entire world is shaped in the form of an inverted map that visitors could walk into (Population Density Emerging From Walls, n.d.).

Figure 2: Data sculpture of the population distribution of the entire world

Another illustration is the installation of a data sculpture in the White House in 2004 to enhance and 3D-materialize the president's speech (Data Sculpture in the White House, n.d.).

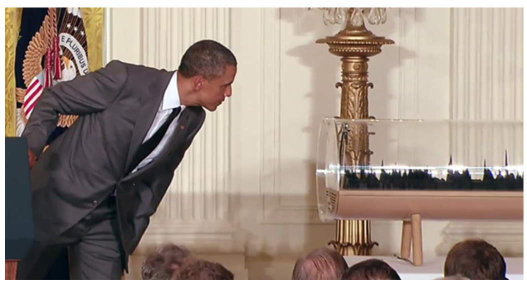

Figure 3: Data sculpture materializing the president's speech

Data physicalization can be used to give data tangible form, which is what truly sets it apart from other data representation modes. However, it should be noted that there is currently no standard method for creating data physicalizations; as a result, the physicalizations must also take into account structural factors, such as the choice of material, and the context in which they are to be used (such as the audience and location), which results in a variety of artifacts (Bae et al., 2022).

There are currently efforts underway to categorize and separate the current data physicalizations, for example, according to the context, data source, and interaction they embody, such as involving interaction mediator from the likes of Graphical User Interface, amongst other differentiating factors (Bae et al., 2022, Dumičić et al., 2022).

In terms of context, a representative sample of data physicalizations demonstrates the embodiment of various goals, including analysis, education, expression, reflection, and enjoyment. Speaking about the data sources, the following differentiation emerges: biological and medical, general statistics, personal, fitness, and wellness, geographical, and environmental. For example, in order to communicate data that is within the topic of general statistics and with the intention of analyzing it, mechanically driven, physical charts were created in 2014. For instance, they were used to display election results to residents and workers on Tenison Road in Cambridge, UK (Dynamic Physical Charts Display Community Data, n.d.).

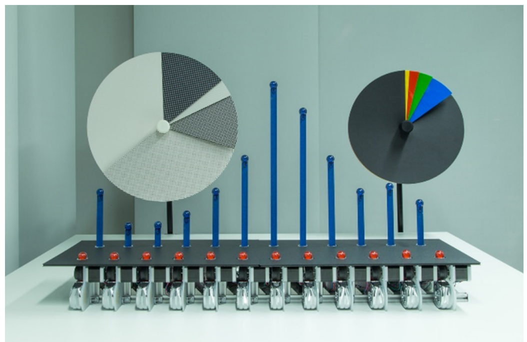

Figure 4: Mechanically driven physical charts

The “State of the World” collection can be used as another illustration of how the physicalization context addresses the educational goal. It is made up of population pyramids, and each of the 100 sculptures encodes information about a particular nation’s population (State of the World as Population Pyramids, n.d.).

Figure 5: Population pyramids as data sculptures

An illustration that embodies the environmental data source is the physicalization from 2017 that shows how the Australian coral reef is being destroyed in relation to the increase in ocean temperature (Coral Reefs, n.d.).

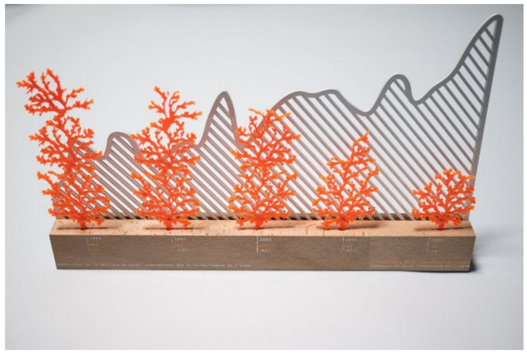

Figure 6: Data sculpture showcasing the relationship between coral beef and the increase in ocean temperature

Moreover, in another production to distinguish between various types of physicalizations, the concept of taking into account physicalization along with the context in which it is used, also known as the “physicalization ecology” or “physecology,” is proposed (Sauvé et al., 2022). Here, the understanding of physicalization in the real world is studied in order to describe the relationships between the various design elements, such as the physical and digital aspects of physicalization, and their coupling to the audience and physical surroundings. This introduces important design elements, including data type and topic.

For instance, in regards to data type, the term “static data” describes a dataset that is offline and/or stored in a static file; as a result, the data is over a fixed time frame and does not permit further forward propagation after the initial file is created, while, on the other hand, dynamic data refers to a dataset that is online, comes from a dynamic stream, and can either be updated through local sensing or outside of the purview of physecology (Sauvé et al., 2022). In correlation to this, the example of data furniture can be mentioned as a representative sample of showing data that is static and over a fixed time frame. This data sculpture graphs national statistics of water usage in the United States over 50 years, from 1950 – 2000 (Adrien Segal’s Data Furniture, n.d.).

Figure 7: Data sculpture showcasing statistics of water usage

The physical weather display, which relies on a dynamic online stream and changes in real-time depending on the weather outside, can be used as an example of physicalization that incorporates dynamic data (Physical Weather Display, n.d.).

Figure 8: Physical weather display

Concerning the interaction mechanisms—another design element—when there is no interaction, physicalization changes are only used as output, and user input is either disregarded, or creators opt not to disclose information on user input (Sauvé et al., 2022). Although there is no direct connection between their actions and the visualization, their audience can still see and hear these physicalizations. The aforementioned physical charts can be used as an illustration of physicalization that does not involve interaction. Another illustration is the piece Living Map. It depicts the variation in summertime precipitation in Europe. The European Environmental Agency is the source of precipitation data. Using a climate simulation model, the information was obtained. It compares the summer precipitation for the decades 1971–2000 and 2070–2100. According to a simulation of climate change, the southern part of the continent will experience nearly 40% less rainfall, while the northern part will experience approximately precipitation increased by 30%. It implies that a significant amount of summertime precipitation will drastically alter our habitable environment (Living Map: Precipitation Visualized With Moss, n.d.).

Figure 9: Data installation illustrating climate change

When physicalization changes are used as both input and output, direct interaction occurs (Sauvé et al., 2022). Systems that, for example, enable the manual rearranging or touching of the physicalization elements are examples of direct interaction physicalizations. For instance, Cairn seeks to comprehend the variety of practices found in FabLabs. In order to make an engaging experience, Cairn looks into practical alternatives to surveys and other conventional evaluation methods, emphasizing aesthetic and affective dimensions. By materializing their actions using tiny, brightly colored wooden tiles, it encourages Fablab visitors to reflect on their practices. People interact with Cairn on an individual level to help create a communal and meaningful sculpture that they can all reflect upon (Cairn: Situated Data Collection and Analysis for Fab Labs, n.d., Gourlet et al., 2017).

Figure 10: Data sculpture showcasing a variety of practices found in FabLabs

When user actions act as input for physicalization, the phrase “implicit indirect interaction” is used (Sauvé et al., 2022). Examples of physicalizations involving indirect implicit interaction include sensor-based systems like x.pose, a dynamic wearable data sculpture that makes the collection of the wearer’s location data visible in real-time in the physical world (x.pose: A Wearable Dynamic Data Sculpture, n.d.).

Figure 11: x.pose makes the wearer’s location visible in real-time

The term “explicit indirect interaction” refers to a situation in which the user consciously acts as input for the physicalization (Sauvé et al., 2022). As an illustration, Pulse transforms online information into a real graph that is displayed directly in the homes of its users. Users of Pulse can easily set up any three information feeds by pairing the device with its online platform, and they can switch between them by tilting the device (Pulse: Tangible Line Graph, n.d.).

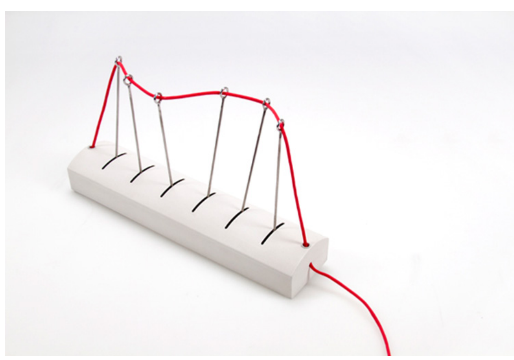

Figure 12: Pulse graphs online information from feeds in real time

3.3. How does Data Physicalization relate to other fields of study?

Data Physicalization, based on the application, has an association with Data Visualization (capitalized to distinguish it from the data visualizations as a visual artifact), even though it excludes the production of artifacts that purely rely on the visual medium (Jansen et al., 2015). Furthermore, it is closely related to Information and Scientific Visualization (Munzner, 2009). To elaborate more on this matter, Information Visualization explores the design, development, and application of interactive graphical representations of information that are computer-generated, which goes in a similar direction to Scientific Visualization, which relies on computer technology and uses it in order to comprehend data gathered through simulation or physical measurement (Chen, 2010, Brodlie et al., 2012).

In the overall comparison to the broad research field that is one of Data Visualization, Data Physicalization emerges as a relatively new field of research, that would make an appearance within the data visualization community as an opportunity to find a mode for viewing and exploring data sets that goes beyond the traditional screen-based fashion (Jansen et al., 2013). For this reason, we will explore the relationship between Data Physicalization and Data Visualization more thoroughly in the following chapters, as there have been some investigations on how they compare to each other.

The nature of the data physicalizations with its research agenda depending on the medium of presentation positions them close to the field of Tangible User Interfaces and Shape-Changing Interfaces (Alexander et al., 2018). For example, the connection to the Tangible User Interfaces can be acknowledged as Data Physicalization as well tends to rely on the physical elements analogously to how the Tangible User Interfaces do (Kenneth, 2004). For example, in the area of Tangible User Interfaces, it has been proved that physicality has instant appeal to people and it encourages the human urge, which contributes respectively for people showing bigger involvement when there is the possibility to interact with mediums in ways that go beyond the scope of interaction with the digital world. This is something that unfolds in the everyday non-digital world, where people are active and creative with their own hands (Shaer et al., 2010, Wilson, 1999).

What concerns the connection with shape-changing interfaces, is mainly due to the knowledge that these types of interfaces aim to communicate information in a shape-changing manner, using these qualities to enhance the interaction with digital information. (Rasmussen et al., 2012). Although many current examples within the Data Physicalizations are mostly static and don't leverage the insights from the affiliated disciplines, they can serve as a starting point in envisioning physicalizations that would benefit from the corresponding technological advancements (Jansen et al., 2013).

3.4. Why data physicalization? What are the benefits?

The aim is to use data physicalizations because of their ability to help us explore, understand, and communicate data (Jansen et al., 2015). The data physicalizations can be traced way back thousands of years ago, but it is the recent technological advances, from the likes of digital fabrication, actuated tangible interfaces, and shape-changing displays that sparkle the interest in exploring new ways to work on developing physicalizations.

Reflecting back on the technological advancements and their implications, the advance in the look and feel of the data physicalizations is expected (Jansen et al., 2015). Even though the today's physicalizations are usually mostly static, they are beneficial for potential perceptual, cognitive, and communicative value, that is not offered by the paper or displays' representation.

The main benefits can be addressed as active perception, depth perception, cognitive benefits (with emphasis on learning), and engagement, amongst others (Jansen et al., 2015). To start off with the active perception, the physicalizations contribute to an active perception that is increased, as the physicality is something that can be touched and the medium, in dependence on the size, can be turned around or explored by walking around. On par with the active perception are the non-visual senses, which can make the physicalizations a haptic display of information. Next, thanks to the shape and the volume, the physicalizations can be perceived with less effort in contradiction to the data seen on computer displays, where depth perception plays an important role (Jansen et al., 2015). The cognitive benefits are due to the understanding that being able to manipulate physical representations, implicates learning and understanding (O'Malley et al., 2004).

In regard to engagement, it can be anticipated that the data physicalizations could make people spend more effort and time exploring data (Jansen et al., 2015).

When thinking about bringing data into the real world, the beforementioned potential benefits need to be traded off against the cost of creating the data physicalizations, although the technological advancements as of now and in the future would decrease the cost of achieving the physicality (Jansen et al., 2015).

As was already mentioned, among the various contexts for which data physicalizations are made, such as the embodiment of various goals, such as analysis, education, expression, reflection, and enjoyment, expression, and reflection sparks the most interest in personal data physicalization (Bae et al., 2022).

Data physicalization has been used to represent a variety of personal data types, including the capacity to comprehend and reveal one's own actions, ideas, and personality (Dragicevic et al., 2020). Techniques for data-driven self-reflection can lead to digital epiphanies, such as accepting or altering one's own behavior. With this being said, adding to the previously mentioned chain of benefits, these data-driven forms of self-reflection can lead to thoughts or actions toward self-improvement.

3.5. How does data physicalization compare to data visualization?

After getting a better understanding of what is data physicalization and its benefits, it is beneficial to understand how it compares to data visualization.

The name itself is analogous to the data visualizations, and the physicalizations can also be referred to with the term physical visualizations (Dragicevic et al., 2020). Data visualizations, in contrast, rely purely on the visual element and, in a broader sense, make use of visual representations of data that amplify cognition through the help of computers (Card, 1999). In comparison, flat visual displays, as the only medium of data representation, are excluded in the research field of Data Physicalization.

Though, what do physicalizations and visualizations have in common? Namely, both aim to enhance people's cognitive abilities in dealing with data through external representations, computing, and interaction (Dragicevic et al., 2020). Although data visualization primarily focuses on a task-centric perspective in designing systems that help people gain specific information from data, in the field of data physicalization other perspectives are explored, such as to express, reflect and enjoy (Sedlmair et al., 2012).

In order to stress furtherly the difference between data visualizations and data physicalizations, a paper written by Dietmar Offenhuber can be reviewed (Offenhuber, 2020). Some points for comparison can be illustrated between the authors' arguments on the data physicalization project Perpetual Plastic by Liina Klauss, Skye Mort, and Moritz Stefaner, and the data physicalization project itself (Perpetual Plastic, n.d., Klauss et al., 2019).

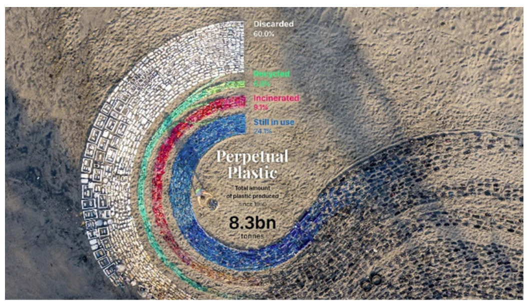

Figure 13: Perpetual Plastic, a data installation that showcases how many percent of plastic is discarded, incinerated, recycled, and reused

The project follows an installation of a sankey diagram installed on a beach in Bali, which purpose is to show how many percent of the plastic is discarded, incinerated, recycled, and reused. The data representation is made up of plastic debris that is collected from the beach where the data physicalization takes place. With mapping data that represents information about plastic onto this physical form that consists of plastic debris, from a location where the plastic is collected, we can investigate how the installation establishes a wide range of meaningful relationships with its surroundings, as opposed to if the sankey diagram was a standard data visualization on a flat display or a piece of paper.

Namely, the following statements can be drawn. The most pertinent point is that while data visualization is usually unproblematic and trivial, data physicalization can force us to expand our narrow understanding of the data and the relationship of the data with the world. The next argument is that while data visualization is usually a file with columns, values, keys, and attributes, it can happen for the data physicalization to not be as abstracted. Another interesting point to consider is that in the case of data visualization, the total amount of information can be quantified, while data physicalization can contain an unquantifiable amount of information. In addition, while the data visualization is less dependent on its surrounding, the data physicalization can be contextual and full of meaning.

There is a study that explores the efficiency of data physicalizations compared to their visual counterpart – the data visualizations. It is an experimental study that tackles people performing low-level information retrieval tasks in order to understand how people behave when they need to perform the same task by relying on different data representations – comparing across modalities (Jansen et al., 2013).

The assessment is done using static physicalization, namely allowing to be referred to as data sculpture, and its corresponding 2D/3D on-screen data visualizations (Jansen et al., 2013). The specimen was selected to communicate small dataset information so as to keep the complexity under reasonable limits and have to do with information that is easy to understand and comprehend – being a small dataset comprising of electricity consumptions over ten years for ten countries.

The tasks comprising of indicating the range of values for a given country and locating pairs of given countries or years to determine with has the lowest value, among the others, were examples of the low-level information retrieval nature for which the performance of each modality was measured and compared (Jansen et al., 2013). The main insight gathered from the studies was that the physical representation of data allowed the user to retrieve the needed information faster, allowing to form the conclusion that physical 3D visualization is more efficient than 3D on-screen data visualization.

The more qualitative remarks are from the likes of people finding the data sculpture to be more fun and comfortable, easier to control, and focus on (Jansen et al., 2013). The study also confirms the beforementioned benefit that is derived from the data physicalizations – active perception, as the role of touch seemed to contribute to significant relevance. Moreover, this experimental study has its limitations in implicating efficiency insights based on the specific data representations in question and as noted by the authors, more research is needed to understand how the different modalities differ.

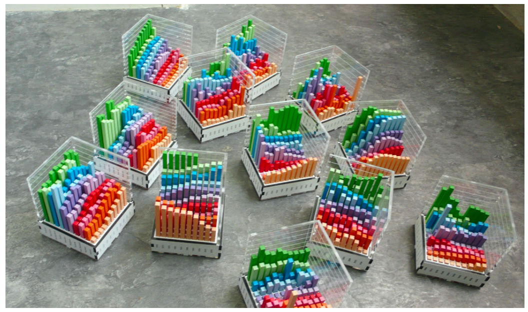

Figure 14: Examples of data representation models used for comparative study

3.6. Conclusions

Deep diving into the broader context behind Data Physicalization was able to help us define the scope of the research and point us in a narrowed-down direction. Namely, getting acquainted with the possibilities and difficulties of Data Physicalization, as well as the knowledge that the current findings about the efficiency of data physicalization were developed under the scope of static data representation and low-level information retrieval tasks, were the crucial turning points.

Moreover, it is promising to conduct a user study that will enable us to comprehend how users evaluate various modalities of data representations in other contextual cases. This is the result of learning more about the various contexts and data types that the physical artifact can embody, which covers the contexts of data representations that deal with expression and self-reflection. These artifacts incorporate the goal to communicate information that helps users reflect and make some changes in their behavior. These self-reflection activities are frequently driven by data practices from the likes of quantified self-practitioners (Swan, 2013) and personal informatics (Lupton, 2014).

Therefore, a promising lead is to compare the effectiveness of various modalities of personal data representations. In particular, we can inquire as to whether the data physicalizations can be used as a medium that will facilitate the users to improve themselves and learn what responses the physicalization elicits. Hence, we carry on with the literature review process by learning more about personal informatics, personal data, and personal data physicalization.

Chapter 4: Personal informatics, personal data, and personal data physicalization

4.1. Personal informatics

It goes without saying that personal informatics must be mentioned when discussing the physicalization of personal data or any personal data at all, as was previously predicted. The work Personal informatics for everyday life: How users without prior self-tracking experience engage with personal data is specifically examined (Rapp et al., 2016). Here we gain an understanding that collecting personal information is a practice that got popular also due to the members of the Quantified Self-movement. The tendency to develop self-awareness and self-knowledge as well as to bring about behavioral change serve as illustrations of the intention (Li et al., 2010).

When it comes to tracking, managing, visualizing, and using data, among other issues, this practice can occasionally be burdensome (Rapp et al., 2016). Additionally, it appears that technological advancements are opening up new opportunities for gathering personally relevant data for self-reflection, where self-monitoring as a stand-alone intervention technique emerges. Then, the loop that is typically included includes preparation, which marks the beginning of collecting personal information, collection, which follows the gathering of the said data, integration, which follows the transformation of the collected data so that the user can reflect on it, reflection, which is self-explanatory, followed by action, where trackers decide how to behave in light of the newly discovered understanding (Li et al., 2010).

A crucial point is that users' needs are not understood by current tools, which is why some participants chose to manage their data using paper graphs (Rapp et al., 2016). In accordance with this assertion, it has been discovered in another work through interviewing the Quantified Selfers that they would experience various problems as a result of a variety of deficiencies in the features of the tools, for example, in the act of tracking, managing, and visualizing their own data (Choe et al., 2014).

In order to better understand how people go about exploring PI tools, a diary study was conducted (Rapp et al., 2016). From this study, it is possible to draw the conclusion that people welcomed the possibility of displaying information through graphs and stats, even though this option can occasionally seem abstract and people lacked the motivation to navigate the data (Marcengo et al., 2014). As a suggestion for the insights, the researchers envisioned new ways of representing the data, such as by incorporating more interesting ideas like gamified graphical user interface and tangible user interface.

4.2. Representative cases of personal data physicalization

Narrowing down the research scope, and having learned about previously teased personal informatics and personal data, we are introduced to some representative cases of personal data physicalization.

According to the paper Feeling your data: Touch and making sense of personal digital data, using personal information can help you reflect and get better (Lupton, 2017). Giving this personal data a physicalization component is crucial for capturing people's sensory attention. Here, the challenge of how to make personal data more understandable and noticeable arises.

The physicalizations present themselves as fresh ways for people to comprehend and use their personal data, such as when they coexist physically with people (Lupton, 2017). The main reason for this is that, despite the fact that the instruments that produce this digital data are physical objects in and of themselves, it is understood that digital data depicts an entirely immaterial event that only engages the sense of sight.

By encouraging interaction with information, which is typically presented through images, visualizations help people make sense of their personal data (Lupton, 2017). This visual nature is viewed as being less effective. To design three-dimensional artifacts for multisensory experiences that are richer and better understood, it is important to understand how to include the other senses while materialization in the field of physicalization remains the primary concern.

There are some examples that are comparable to this quest. In particular, there is the SweatAtoms project's experimentation with 3D printing (Khot et al., 2013). The participants can hold or display their data and compare it thanks to the 3D prints of their physical activity that are incorporated into the study. After engaging in physical activity, a heart rate monitor records the data, and a 3D model is then built using the data. The user used the 3D-printed pattern at the time to cherish it. In this way, physicalization helped users make better sense of their data and engendered emotional responses in a new form of representational medium. It serves as an illustration of how sensitive personal information can be transformed into touchable objects.

Figure 15: SweatAtoms, experimentation with 3D-printing

The investigation into activity sculptures is yet another instance (Stusak et al., 2014). In order to create artifacts in the form of a human figure, necklace, lamp, and jar, user activity data was extracted from various apps in this case. The modularity of the design was taken into account so that the separately manufactured pieces could be combined to create the sculpture. One intriguing finding was that users would attempt to control the shape of the pieces, which would have an impact on how participants planned their runs.

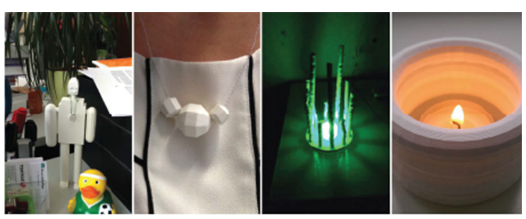

Figure 16: Examples of Activity Sculptures

In the case of EdiPulse, chocolates that depict the self-tracked heart rates of individuals following physical activity were created using 3D food printers (Knot et al., 2015). The sizes of the chocolates varied depending on how much physical activity the users carried out, and the chocolates themselves served as prizes that participants could eat. This is an example of how participants could not only touch but also taste and smell the data being collected.

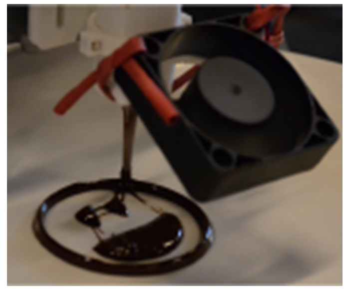

Figure 17: Examples of EdiPulse, data that can be tasted

After going over the aforementioned instances, it can be derived that personal data physicalizations could involve contemplation, and dialogues, and give people more control over their personal data (Lupton, 2017). Particularly, physicalizations frequently serve as constrained representations in which the creators make decisions about what constitutes knowledge and how the public should benefit from physicalizations. Examining how to interpret personal data is a step in the physicalization process.

In another piece of research, we learn what it means to use a phenomenological approach when designing self-tracking technologies (Homewood et al., 2020). In particular, the authors discovered that using a phenomenological approach to self-tracking can help society gain a better understanding of the human body and make creative use of the collected data. This is accurate as well, given that phenomenological commitments emphasize how self-knowledge is created through interactions with others and internal experiences (Rapp et al., 2017).

The ability of self-tracking technologies to boost productivity and enhance health through the implementation of behavioral change strategies is what has generated the majority of interest in this field of study (Ayobi et al., 2016). Since the information gathered from the body itself is not felt or directly experienced through bodily sensations, the authors explain how self-tracking challenges the idea of what is true about the body.

In light of the aforementioned, the Ambient Cycle was developed as a tool that collaborates with the user’s lived experience and felt sensations to co-construct the experience of their menstrual cycle (Homewood et al., 2020). Its goal is to represent data in ways other than the conventional textual and graphical ones and to support ambiguity in data display where a key is required to interpret the said displayed data. This device, although it may not conform to traditional standards for what constitutes a "data physicalization" device, is an ambient display that employs unconventional methods of representing data, such as through light gradients, rather than traditional graphical user interfaces.

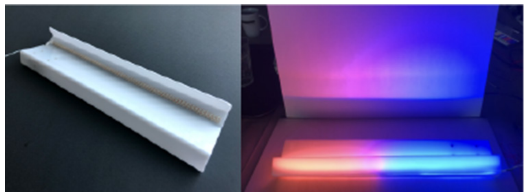

Figure 18: Ambient Cycle, ambient display as a novel representation of data

Ambient Cycle is specifically designed to encourage users to reflect on their emotions and to challenge their perceptions of their own data (Homewood et al., 2020). It aims to provide a unique and alternative way of visualizing personal information, with the ultimate goal of fostering self-awareness and understanding. The device uses ambient lighting to display data, making it less intrusive and more integrated into the user's daily life. By providing an intuitive and non-conventional representation of data, it aims to empower users to engage with their personal information in a more meaningful way.

Ambient Cycle was incorporated in a user study, where participants were asked to reflect on their experience of using the menstrual tracking device both emotionally and physically, in order to understand how it impacted their sense of self (Homewood et al., 2020). The device, which was positioned in the participants' homes, was designed to use customized gradient transitions of LED lights to visually represent different stages of the menstrual cycle, including emotions such as pain. The device not only helped participants to track their menstrual cycle but also acted as a conversation starter, as it provided a tangible representation of the participants' own lives through digital means.

This physicalization of their experiences allowed others to gain a deeper understanding of their internal states without direct or verbal communication (Homewood et al., 2020). The device's unconventional method of representation and ambiguity served as a powerful tool for self-tracking that did not exclude participants' actual experiences. It also raises awareness about oneself that is co-constructed, instead of revealed, which is beneficial in promoting self-awareness, empathy, and understanding.

Another study elaborates on the idea that actual physical interaction with the data is essential for influencing the reflective process (Karyda et al., 2020). The main goal of this research is to examine how to include narration in the design and analysis of personal data physicalization. To that end, the authors introduce the idea of “Narrative Physicalization,” which is achieved by modifying common objects to encourage self-reflection through embodied interaction with the personal data themselves. As it has been demonstrated that a narrative context enhances reflection, the narration component of the physicalizations has been used through the medium of TED Talks.

Additionally, data physicalization is experienced through the body and can be used as a talking point in regular speech interactions (Karyda et al., 2020). Through their physical characteristics, the physicalizations imply reflection and can also be applied to simplify daily tasks. The Narrative Physicalizations study looks at how to combine activity data to create personalized physicalizations as prompts, leading to the creation of three physicalizations for each of the three participants using familiar everyday objects like a foosball table, a one-string instrument, and a treadmill.

Modified everyday objects were established after participants had the opportunity to physicalize their own data through hands-on manipulation and interaction (Karyda et al., 2020). This process allowed them to gain a deeper understanding of the data and led to the creation of tangible representations of the data, in the form of modified everyday objects. The interaction with self-tracking technologies was looked at in this exploration in order to get to the point of producing modified physicalizations of commonplace objects. It was noted that the graph formats of the data can be used as a platform for discussing the real-world encounters of the individuals who created the said data.
A realization is that encouraging others to share data with you can help you reach your goals more quickly. The production of physical graphs that closely resemble the visualizations of the self-tracking technologies is demonstrated by having participants physicalize their personal data.
Although the participants interacted with their data, this interaction was insufficient to link the data to their experiences because their physicalizations primarily served as impressions of the participants’ data and acted as a reminder (Karyda et al., 2020). In order for the participants to express their emotions, the physicalizations would act as a mediator. The understanding of personal data is expanded through the process of

creating one's own unique set of physicalizations, leading to rich narratives based on individual experiences.

Figure 19: Examples of data physicalizations made by the participants and examples of the narrative physicalization made by modifying an everyday object

Another practice that explores the creation of personal data physicalizations, in order to experience the data in a novel modality, can be seen in the following examples. In 2008, Lego bricks were used to reconstruct the layout of the city of Savannah in order to log the activity of visiting distinct places within it, with different colored bricks that represent the different days of the week (Psychogeographical Mapping: Travel Logging With LEGO Bricks, n.d.). In the same year, another example utilizes Lego bricks as well to log personal work activity where each tower of bricks is a day of the week made of brick layers that represent the working hours with different colours or different projects (Activity Logging With LEGO Bricks, n.d.).

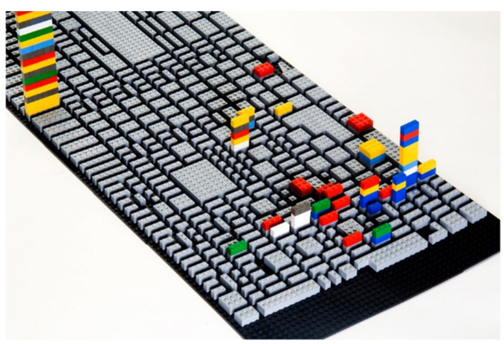

Figure 20: Travel logging with Lego bricks

Figure 21: Activity logging with Lego bricks

In the work of Personal data physicalizations in class, there are multiple reproductions of the standard charts using physical materials, where it was concluded that the process of constructing these physicalizations was detrimental in raising awareness and reflection among the creators (Perin, 2021).

Figure 22: Examples of data physicalizations made by students

4.3. Conclusions

Deep diving into the representative cases of personal data physicalizations as well as gathering an understanding of personal informatics and personal data themselves, was important in order to understand how to define the research goal.

Pivotal points were the realization of how the current self-tracking technologies do not necessarily comply with people's expectations to be able to manage and visualize their personal data more elaboratively. This way, the idea to go in the direction of having a comparison between different representational cases of the same data can be reinforced, and we also want to define which data to take into consideration for the study.

Therefore, we aimed to understand the types of data that people typically track about themselves in order to inform our choice of focus for the data physicalization we were creating. We created a questionnaire asking whether the participants are currently tracking some personal data, or if they have tracked personal data previously. Depending on the answer to this question, in continuation they were able to do a multiple selections of the type of personal data proposed, such as sleep, activity (steps), mood and health, as well as additionally to include data that was not present in the list.

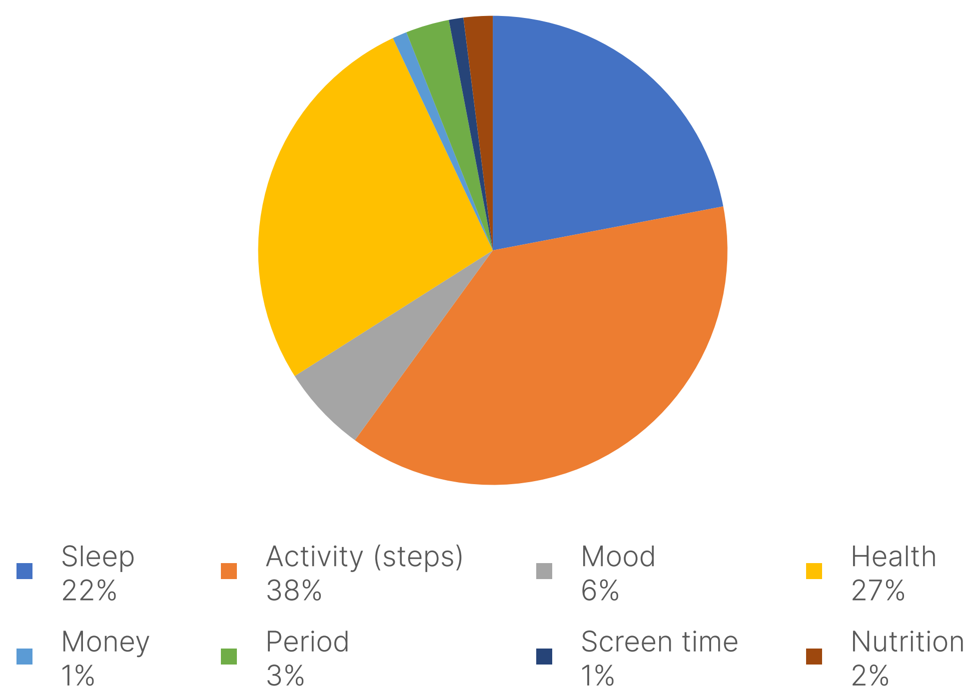

Figure 23: What type of personal data do people track

The participants added the following data to the list: menstrual cycle tracking, weight, nutrition, screen time, and tracking finances. From the fifty-five participants, forty-six (84%) answered that they have tracked or are tracking personal data.

Through conducting a survey, we discovered that the most common type of data tracked is activity data, such as the number of steps taken, with 38% of the votes. This is likely due to the fact that tracking steps are a simple and easily accessible metric, as it can be easily revealed through the use of a smartphone without the need for additional equipment. Next, 27% of the votes were dedicated to tracking health, 22% to tracking sleep, 6% to tracking mood, 3% to tracking menstrual cycle, and 1% each for tracking weight, nutrition, screen time, and finances, respectively.

Understanding the different styles of self-tracking, and taking into consideration the results of the survey, it is promising to deal with data that corresponds to the directive style of tracking, which is linked to achieving a certain goal (Rooksby, 2014). When it comes to activity data and the respective activity data physicalization, we decided to explore the current representative cases, which follow in the next chapter.

Moreover, with learning more about the conclusions and discussions within the selected review papers that tackle the topics of personal informatics and self-tracking, we can create a persona that is a typical representative case of the ‘quantified-selfers‘. Namely, this was found to be helpful in order to highlight the potential lack of the current tracking technologies, mainly in the way in which the personal data is communicated to the users, such as uncovering the series of problems that the quantified-selfers experienced while tracking, managing, visualizing, and using their own personal data (Rapp et al., 2016), which due to a variety of lacks in the standard visualization tools’ features ultimately lead the quantified-selfers to search for a solution that could meet their needs, by building their own tools for tracking or by creating their own visualizations (Choe et al., 2014), while indulging in this self-tracking for self-awareness, optimising and improving their lives (Lupton, 2015):

ABOUT

Introduce yourself to George, a proponent of the "quantified-self". Self-tracking is a technique George uses to better understand his own habits and behavior. He uses technology, such as wearables or apps, to gather information on things like his physical activity, sleep, nutrition, and even his mood or mental state. George wants to use this information to examine his own tendencies and behaviors and make necessary adjustments to better his general health and well-being. He uses the data to track particular objectives like weight loss or fitness improvement and also uses it to get a more comprehensive understanding of his own habits and behavior. The quantified-self is ultimately George's attempt to use data to improve himself and make better choices in his own life.

NEEDS

- gaining awareness of his own actions and routines
- enhancing his general health and wellbeing
- make more informed decisions about his own life
- eager to use data and technology to further these objectives

PAIN POINTS

- the lack of efficient tools for managing and visualizing personal data, which makes it difficult to think about the said data
- the challenge of finding a self-tracking technology that meets all of his requirements and preferences
- it is difficult to integrate and bring the data closer to him because it is scattered across several platforms
- disappointment and annoyance from devoting more time and effort to data management than to decision-making and self-improvement

Figure 24: Persona

Additionally, we can explore what the customer journey for the majority of “Quantified Selfers” can look like.

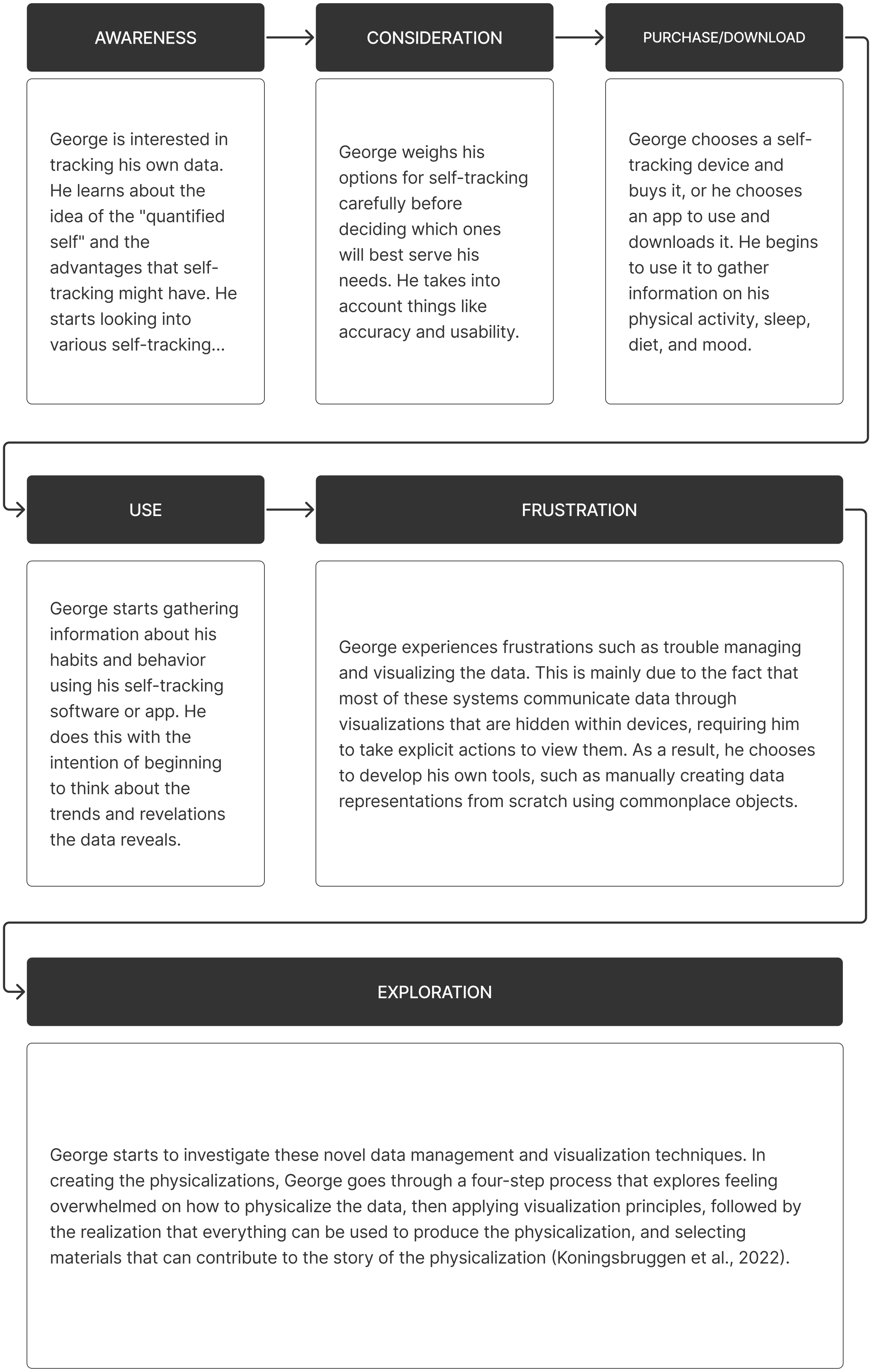

Figure 25: Journey map

Based on the needs, pain points and some key points in the journey of the quantified-selfers, it would be interesting to investigate whether data physicalizations could serve as a platform for improving how individuals interact with their own personal data. Instead of relying on conventional data visualization techniques, George might be able to understand the data more intuitively and directly by interacting with physical representations of it, which is also automatically updated and do not require a lot of effort from his side.

In this manner, we can put the data physicalization to the test to see if it can help with the problems that traditional data visualization techniques can cause. Hence, the need to evaluate the effectiveness of data physicalization is therefore reinforced.

Chapter 5: Activity data physicalization

5.1. Representative cases of activity data physicalization

As our research progressed and the focus shifted towards activity data physicalization, we were presented with the opportunity to examine the physical artifact, LOOP (Sauvé et al., 2020). This physicalization represents a novelty in the field of activity data physicalization. The authors discuss the use of wearable technology and internet-of-things (IoT) sensors to track personal health and activity data. However, it highlights that most of these systems communicate data through visualizations that are hidden within devices, requiring users to take explicit actions to view them, and the majority of activity tracking platforms currently in use rely on Graphical User Interfaces (GUIs) as a means of communicating data to the user. These interfaces often utilize numerical and graphical representations to convey the data.

Figure 26: Loop activity data physicalization

Making data more readily accessible to individuals by exposing it to them more frequently can have a beneficial effect as it allows for more frequent reflection on the meaning and significance of the data (Sauvé et al., 2020). The authors propose the use of an ambient approach to data physicalization, using a physical artifact called LOOP, which provides an abstract visualization of the user's activity data by changing its shape.

While digital visualizations in systems such as Ubifit have demonstrated their ability to motivate and engage users with their data, this approach may not lead to frequent engagement with the data in everyday life as it necessitates deliberate interaction with a smartphone (Sauvé et al., 2020). As an alternative, ambient information systems that present abstract information for both peripheral and focused attention may offer a solution to this challenge. These systems allow for more accidental encounters with the data, providing new opportunities for reflection and integration into everyday life.

LOOP was envisioned as a way to display real-time data in a dynamic way, moving away from static representations and utilizing shape-changing interfaces (Sauvé et al., 2020). Similar to the idea of physicalizations, the purpose of shape-changing interfaces is to improve human interaction with digital information by utilizing physical characteristics (Rasmussen et al., 2012).

With the use of eight wooden moving rings, the physical artifact known as LOOP displays step data obtained from an activity tracker (Sauvé et al., 2020). The rings are meant to make it simple to compare data at different levels and between different days. In order to be meaningful to the user and blend in with the home environment, the design aims to strike a balance between informative and aesthetically pleasing qualities. A combination of absolute and relative cues will enable the user to observe detailed visualization with focused attention and obtain an overview of their performance in the periphery.

During a user study, some participants used LOOP to track their progress, while others were more extrinsically motivated by the system’s ability to change shape (Sauvé et al., 2020). The various layers of information provided by LOOP enabled a variety of interaction possibilities, which are advantageous for the various information needs and goals that activity tracker users may have.

Additionally, the system’s interplay of relative and absolute cues may enable users to derive different levels of detail from the physicalization, depending on their preferences (Sauvé et al., 2020). Future research, according to the study, could investigate how the dynamic nature of physicalizations may affect both intrinsic and extrinsic user motivations over time, as well as create new types of relationships with data that go beyond customary motivations.

Moreover, there are other cases that deal with the physicalization of activity data, but there are mostly static and do not enable the users to reflect in real time. As an example, the SweatAtoms that we previously mentioned in the representative case of personal data physicalizations (Khot et al., 2014), alongside the Activity Sculptures (Stusak et al., 2014).

Another example that deals with the physicalization of activity data are Wearable Self. It is a collection of data jewellery that transforms self-tracking data (daily steps) into fashion items, aiming to make self-tracking more meaningful. It is based on the corresponding data visualizations (Wearable Self, n.d.).

Figure 27: Data jewellery as novel representation of personal data

5.2. Conclusions

By getting familiar with the different representative cases of activity data physicalizations, we learn more about the different natures between dynamic and static data representations. Moreover, the latter tackles the idea to envision new ways to touch and feel the data, without producing a medium that can serve as a specimen in a study that investigates comparison.

Therefore, we are able to determine our objective to design a dynamic personal data representation of activity data, which would be a better fit for conducting the experimentative user study. It tackles the beforementioned idea to understand and envision how physicalization can be leveraged to be used as this additional medium that would be incorporated into everyday life and is able to portray the change in the data through the physical properties, without the burden of maintaining the manual production of static artifacts which is time-consuming.

Chapter 6: Research goal and research question

6.1. Research goal and research question

This research conducts a user study that will help us understand how users evaluate various modalities of data representations and test the efficiency of data physicalizations in particular, as to inquire whether the data physicalizations can be used as a medium that will facilitate the users to produce informed decisions about themselves, through learning what responses the physicalization can elicit.

Learning about the abundant contexts and data types that the physical artifact can embody was helpful in order to determine the setting of the study. Besides, comprehending the contexts of data representations that deal with expression and self-reflection, which are frequently driven in data practices represented by the quantified self-practitioners, was focal. These artifacts aim to communicate information that helps users reflect and make changes in their behavior.

In the process of gathering a better understanding of personal informatics and personal data themselves, pivotal points were the realization of how the current self-tracking technologies do not necessarily comply with people's expectations to be capable to manage and visualize their personal data more elaboratively, given that the current communication through graphical user interfaces can come short.

The decision to compare various representations of the same data can be reinforced in relation to the aforementioned. In this way, we can comprehend whether the physicalizations can rise as mediums or useful tools on which to concentrate design efforts, as we are aware that the current primary challenge when it comes to producing physicalizations is to identify benefits that will outweigh the cost of doing so.

In terms of the research objective, which is the creation of the data physicalization to be used in the user study, the following can be mentioned. Understanding the different styles of self-tracking, and taking into consideration the results of the survey we prepared in order to understand which data is usually tracked by people, it is promising to deal with data that corresponds to the directive style of tracking, which is linked to achieving a certain goal, such as activity data itself (Rooksby et al., 2014). Moreover, activity-based data sculptures are considered a suitable specimen when it comes to introducing novice learners to the field of working with data (Bhargava et al., 2017).

Therefore, the objective is to design a dynamic data representation that translates the likes of the data visualization within the graphical user interface communication, so as to have a fair basis of comparison between modalities. It tackles the beforementioned idea to understand and envision how physicalization can be leveraged to be used as this additional medium that would be incorporated into everyday life and is able to portray the change in the data through the physical properties, without the burden of maintaining the manual production of static artifacts which is time-consuming, as seen is the numerous examples.

Once the physicalization is created, we can proceed with the user study. As previously explained, we will tackle the directive style of tracking personal data, where the users are concerned with achieving a certain goal, which in this case is the step goal. The process of creating the data physicalization and the user study are explained in the following chapters.

Chapter 7: The making of the data physicalization

7.1. Overview

The major takeaway of becoming familiar with the representative cases of activity data physicalizations shows how the artifacts are produced after a certain period of self-tracking. These artifacts as novel representations of data take on a form that prioritizes artistic expression and creativity rather than just conveying factual information. For the premises of this research study, we want to establish a fair basis for comparison, which forces us to think about how to materialize the common visualizations in regard to activity tracking (steps count). Apropos the research objective of designing a dynamic data physicalization which essentially brings the data visualization communicated via the graphical user interfaces materialized in 3D space, we embark on the following double-diamond design process. The design process is an iterative process that is based on achieving a prototype – the data physicalization, that will be used in the user study.

DIAMOND	RESEARCH		DESIGN	
	DISCOVER	DEFINE	DEVELOP	DELIVER
GOALS	research and understand how the data visualization representaation of activity tracking (steps count) look now within the graphical user interfaces	create conceptual proposals that take into consideration how to translate the visualizations into materialized, tangible form	identify hardware and software components necessary for creating the prototype understand how the prototype can communicate the steps count to the user, and how to make it possible through the use of material	create the final prototypes that will be used for the study
OUTCOMES	get inspiration for how the physical representation of the activity data can look like, taking into consideration the analyzed data visualization as a starting point	identify one promising concept about how the data physicalization can look like	a better understanding of which parts would build up the prototype and the connection between the parts and the hardware, as well as the software side	the data physicalizations themselves, that will be tested with participants in the user study

Table 2: Double diamond design process

7.2. Discover

In order to understand how the data visualization representation of activity tracking (steps count) looks within the graphical user interfaces, we identified the following key apps: Fitness app (Apple), Health app (Apple), Fitbit app (Fitbit), Xiaomi app (Xiaomi), StepsApp app (StepsApp), last.fm app (last.fm) and Google Fit (Google). The apps accommodate data visualizations in order to communicate the activity to the users, while last.fm uses visualization techniques in order to show the activity of “scrobbles” (one scrobble is equivalent to one track listened to).

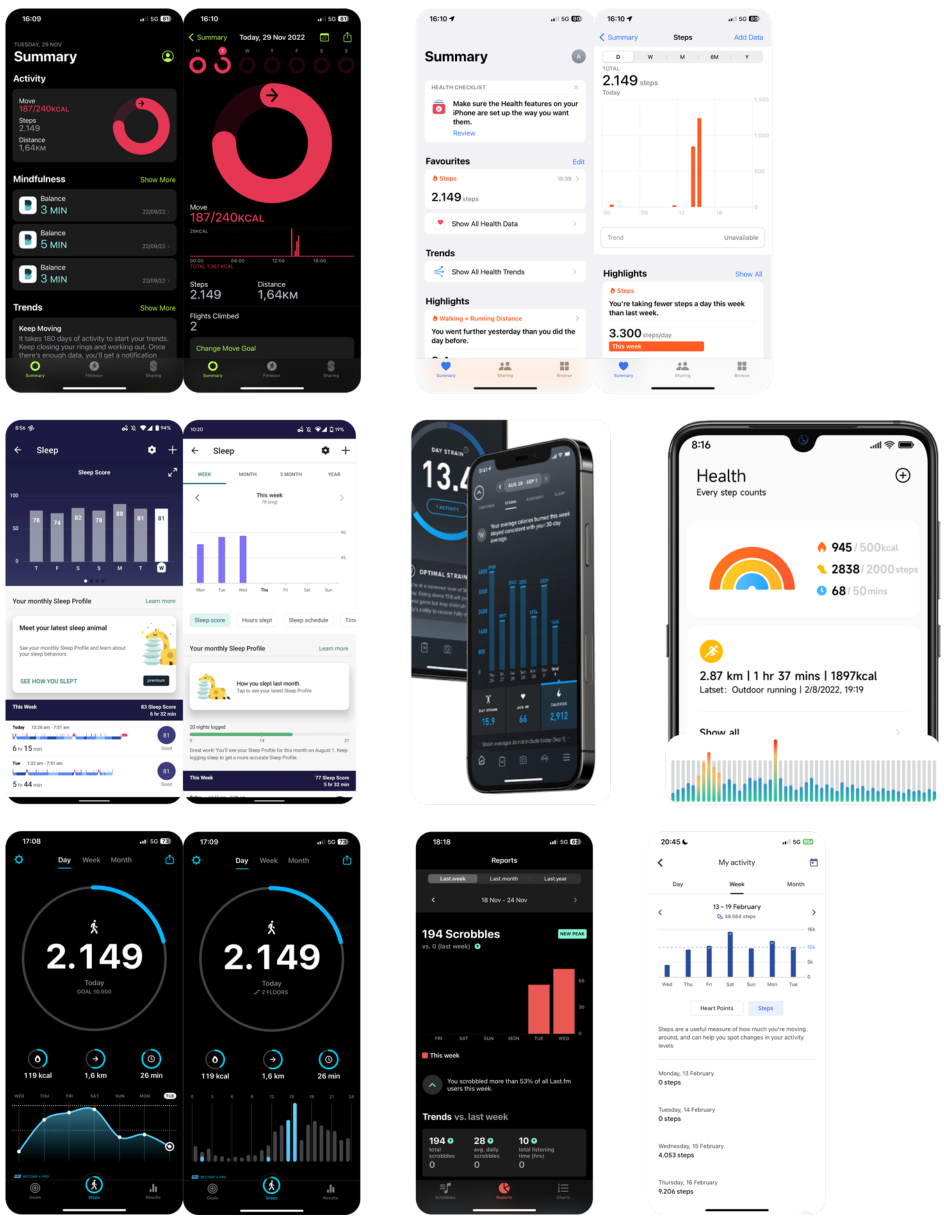

Figure 28: Graphical user interfaces with their respective data visualizations taken in cosideration

This allowed us to isolate the data visualizations and try to understand how to establish concepts for data physicalizations that will in their essence serve to materialize the visualizations themselves. The following data visualization elements are present:

Figure 29: Data visualization elements

Using the isolated elements as a starting point, the concepts created that can serve as a starting point for the data physicalization, are illustrated in continuation.

7.3. Define

As beforementioned, the idea is to bring the data physicalization close to the corresponding data visualization that is available on the platforms that are concerned with personal data activity, as the premise is to achieve a physicalization that mimics the visualizations by materializing them, in order to achieve a fair basis for comparison. At this point in the double diamond design process, we are concerned with proposing promising concepts.

Continuing on the basis of the isolated data visualization elements, a pattern is noticeable, meaning the method of data representation can help us group the corresponding elements of interest. For example, ones that rely on a circular distribution or pie charts (group A), and ones that rely on the rectangular stacks of the said data (group B).

Figure 30: Group A, use of circular representation of data

The goal of the user is distributed on a pie chart and the goal is to 'close the circle'. In the example of Xiaomi, the graphic is used to summarize parameters for the user, but in a way, can be used to get inspired for creating a concept proposal.

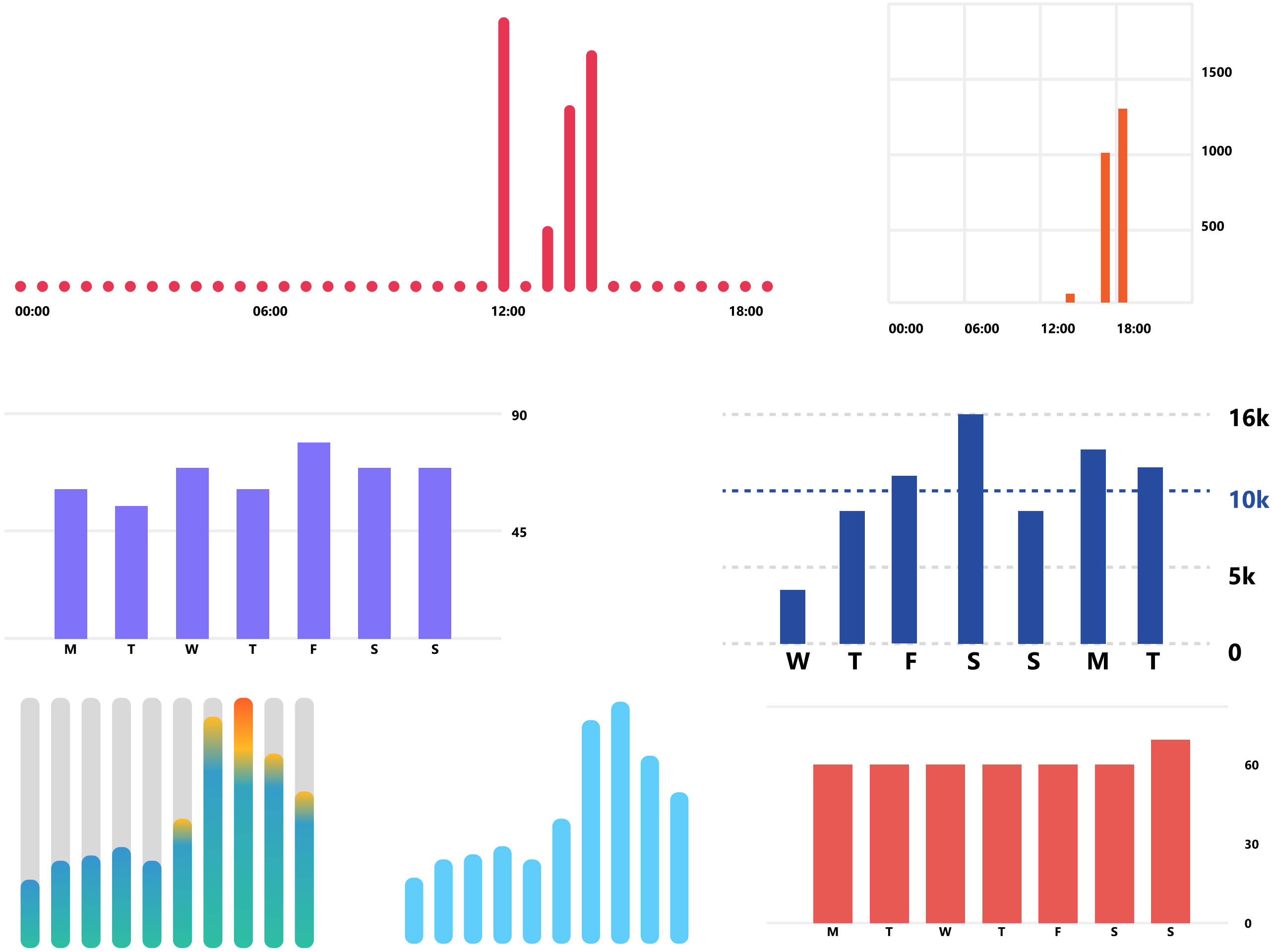

Figure 31: Group B, use of data representation through rectangular stacks

For the ones that rely on the rectangular stacks of the said data, we also noticed available physicalizations in the literature that mimic representations of this kind in the physical world, like the ones that make use of Lego bricks.

Getting inspired by groups A and B respectively, the following concepts were created. We should note that by thinking about the user study in which we can understand whether the physicalization outperforms the visualizations, the idea of physicalization that requires indirect implicit interaction from the users, such as the steps count being indirectly communicated via physical artifact, is current while generating the concepts.

The present element while generating the concepts is to understand how physicalization can be achieved, which means it takes into account the approach of prototyping with technology or electronics in particular. This is a standard approach in the field of interaction design (and moreover the field of it that is involved with electronics known as physical computing), and also relies on the premise of keeping things simple, as the overall impression of the prototype is important (Petrelli et al., 2014). Moreover, in determining which materials will be used, we were concerned with envisioning the use of materials that best fit the concepts, as we know that when it comes to choosing the materials used in building the physicalizations there is still not a standardized approach. The concepts, illustrated through the means of 3D modeling and rendering, are as follows.

Group A concept 1:

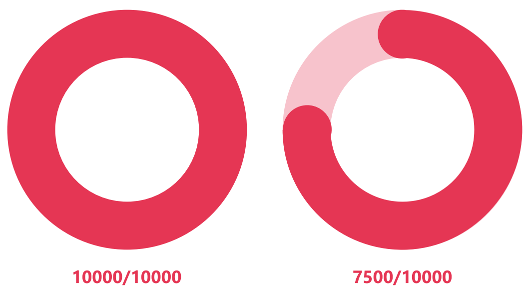

Figure 32: Reference for the first concept

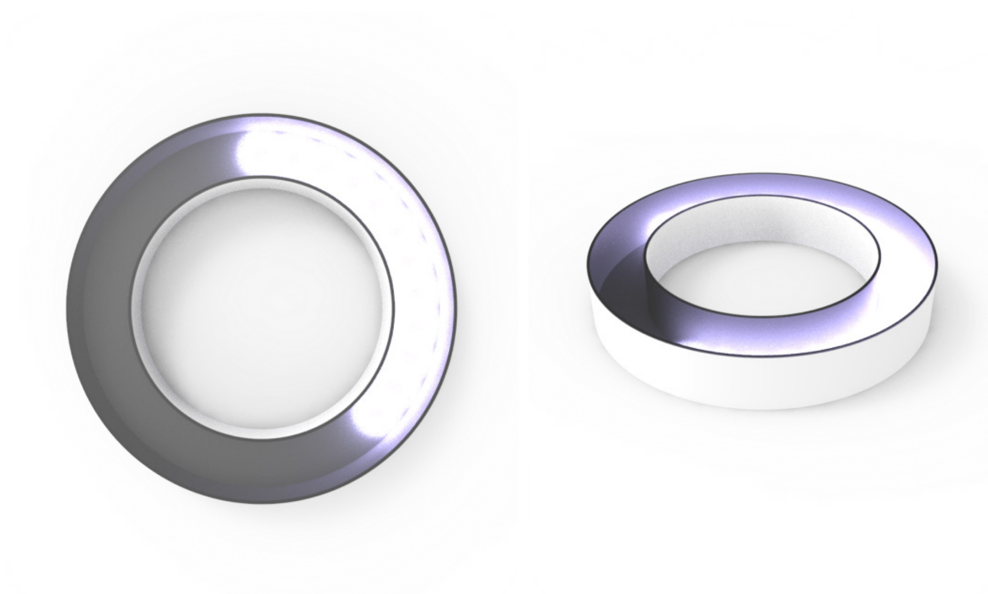

Figure 33: The first concept

Here the idea is to use a phygital representation of the data that is envisioned based on the reference itself. The reference visualization symbolically represents a pie chart, which is updated based on the step count of the user. Knowing the step goal of the user, the general idea of the visualization is to showcase the increase in the step count that leads to the completion of the chart. In regards to this concept, the prototype mimics the data visualization to communicate to the user how much is left to “close the circle” – which is how much is left to achieve the set step goal.

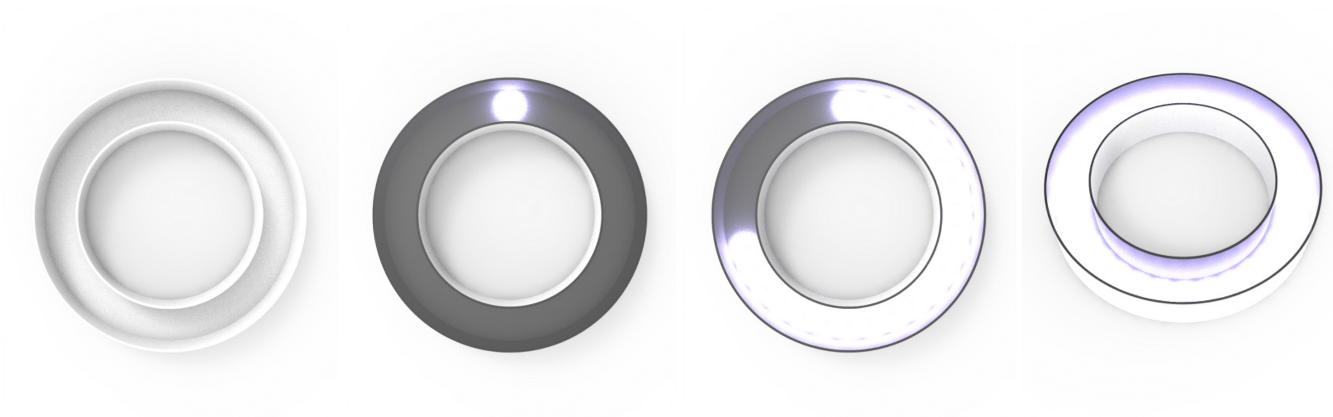

Figure 34: Data communication

The light segments are corresponding to the step value of a given time instance. The step goal, represented with the value m, corresponds to the whole prototype being lit. The corresponding light segments are turned on when a certain value (step count) is reached. To calculate, depending on the number of lights, represented with the value n, the step goal m is divided. The step count is updated on a daily basis.

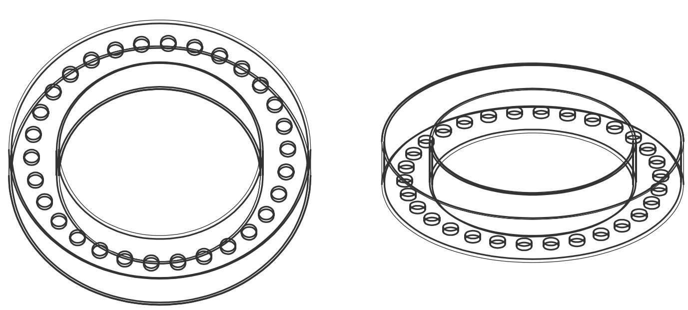

Figure 35: Materialization

To accommodate the concept, led lights positioned in a circular distribution are needed. The led lights are connected to a physical programmable circuit board (microcontroller) and with the use of the software the beforementioned relation between the number of lights and step count is established. The led lights are positioned in a 3D-printed shell compartment. The lid of the shell is characterized by a certain level of transparency, in order to showcase the emitted light. Moreover, Arduino, which is an open-source electronics platform can be mentioned to be used in the role of the microcontroller, while the led lights can be in the form of neopixel led lights stripes or neopixel ring.

Group A concept 2:

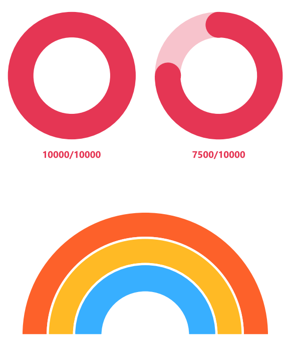

Figure 36: Reference for the second concept

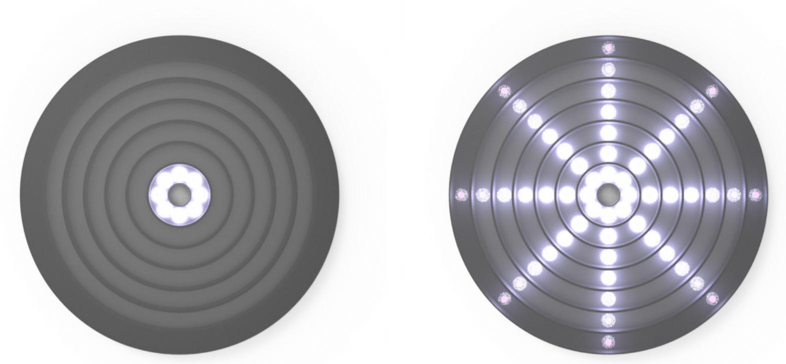

Figure 37: The second concept

This idea is a “continuation” of the previous concept. Moreover, it expands the previously communicated idea with the inspiration of the element that showcases the summary of tracked parameters, as shown in the reference section. It symbolically represents several pie charts nested together, with the premise to communicate the data to the user through this phygital nature. The goal of the user is to reach the step goal, which is communicated by lighting the corresponding concentrical circle. The total number of circles is seven, to communicate the step count for seven consecutive days.

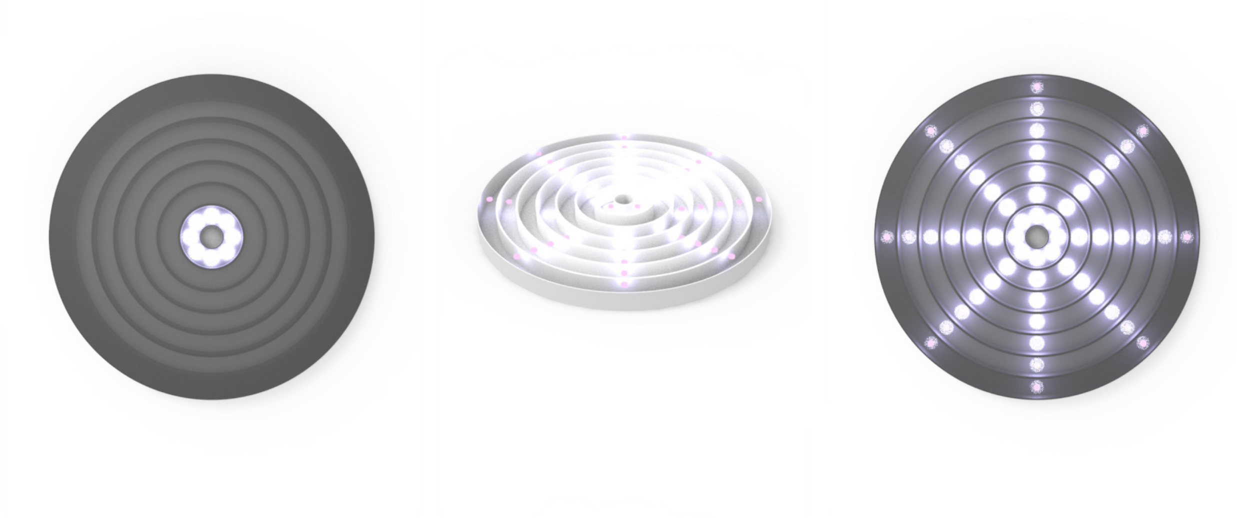

Figure 38: Data communication

The light segments match the step count of the specified time instance. The step goal, denoted by the value m, is the entire concentric circle being lit. When a predetermined value (step count) is reached, the corresponding light segments are illuminated. The step goal m is divided into equal parts depending on how many lights there are, as represented by the value n. Starting from the smaller circle, every day, the step total is updated, to communicate the state of whether the user has reached the step goal.

Another idea is to play with the intensity of the lights, meaning the brightness of all of the lights in the respective concentric circle will light with intensity, which is dependent on the steps.

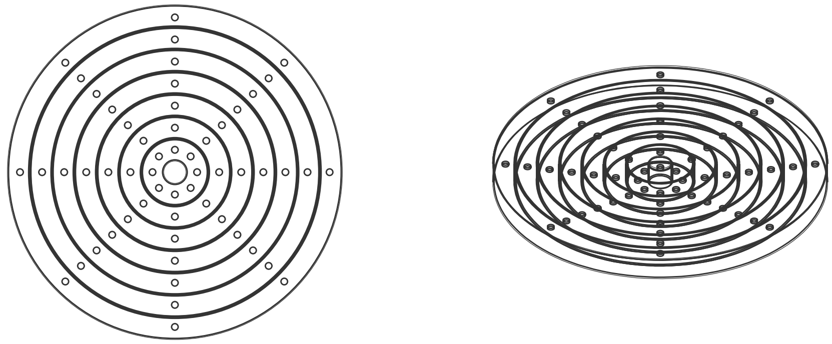

Figure 39: Materialization

In correlation to the previous concept, the recurring element is the led lights that are distributed centrally within 3D-printed shell compartments. With the help of the software, the aforementioned relationship between the quantity of lights and step count is established. The led lights are connected to a physical programmable circuit board (microcontroller). To show off the emitted lights, the shell's lid exhibits a certain amount of transparency. In correlation to the previous concept, here as well, Arduino, which is the open-source electronics platform can be mentioned to be used in the role of the microcontroller. The led lights can be in the form of the neopixel led lights stripes.

Group B concept 1:

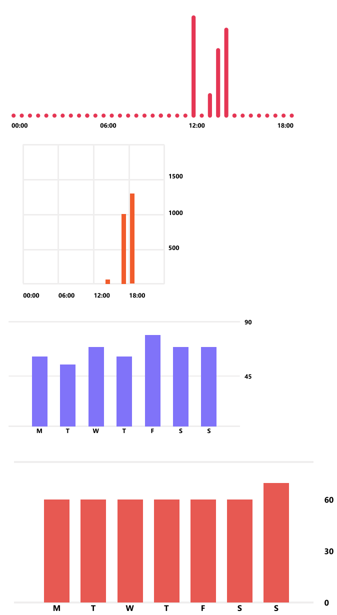

Figure 40: Reference for the third concept

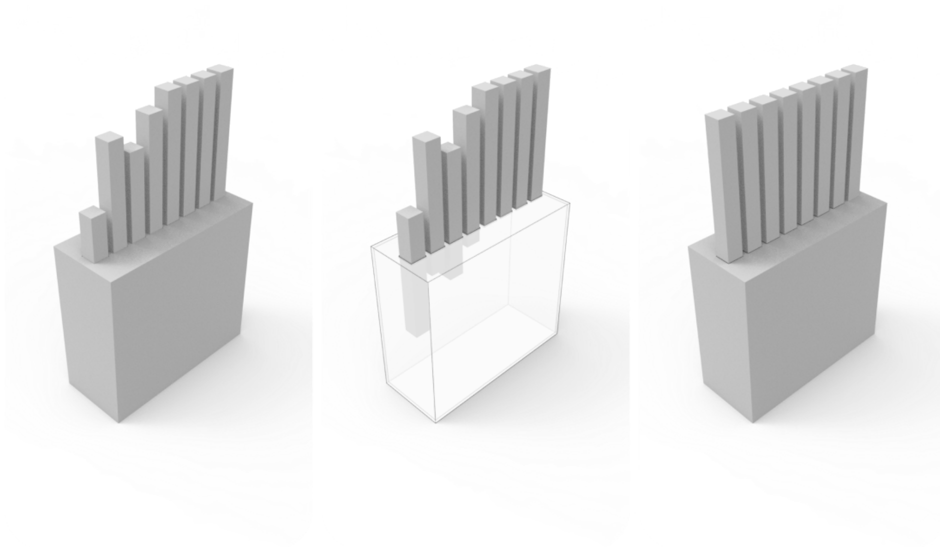

Figure 41: The third concept

Here the idea is to bring the most used visualization, which communicates the step count to the user within the respective graphical user interfaces, in the physical space. In achieving so, seven bars are incorporated, each one representing the step count throughout the days of the week respectively, with the eighth bar representing the step goal, which allows the user to gain an overall understanding of how the given step count refers to the value of the step goal itself.

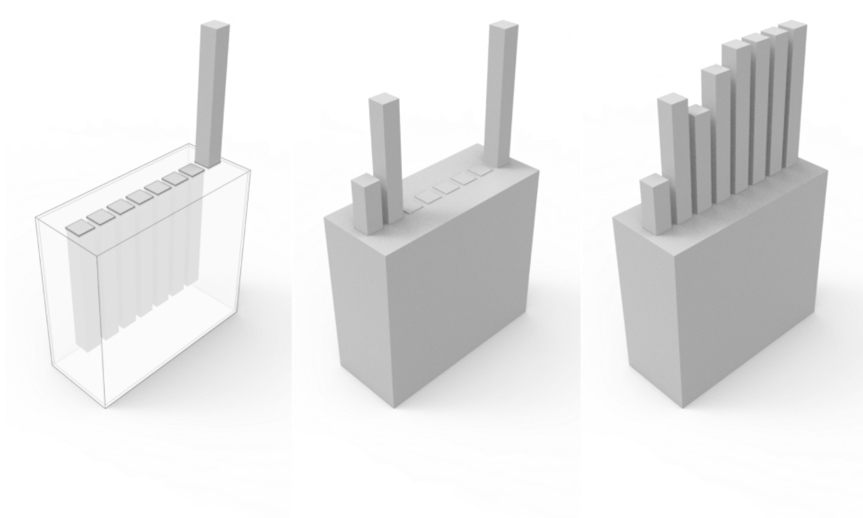

Figure 42: Data communication

At the beginning of the tracking, the eight bar – which represents the step goal, is risen. As the steps are registered, in certain time intervals a disposition of the corresponding bar is noticed. The total length of the bar corresponds to the step goal. When a certain value (step count) is reached, the bar moves up to communicate the change in the step count, proportionally to the bar that represents the step goal. To calculate, depending on the total number of steps, the length of the bar is divided and requires a certain degree of disposition at certain moments of tracking. The prototype communicates the step count seven days of the week, respectively.

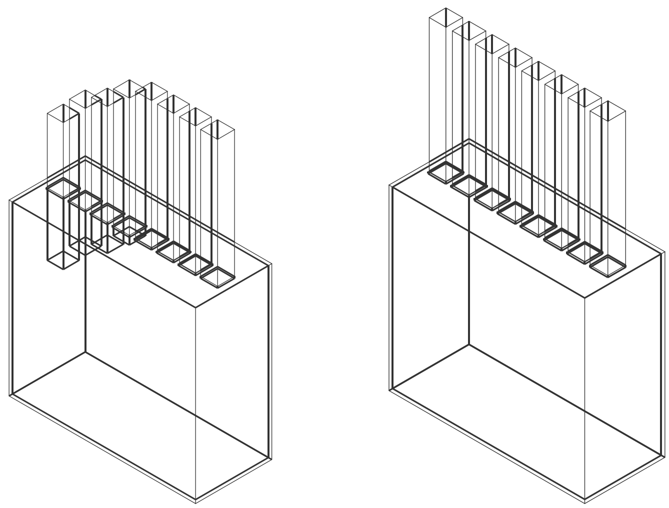

Figure 43: Materialization

To provide details regarding the idea's viability, the bars are nested in a shell compartment, in a manner that allows them to achieve a linear disposition by being linked to an electronic component, from the likes of servo motor. The servo motors are connected to a physical programmable circuit board (microcontroller) and through the use of the software, the relation between step count and step goal is mapped to correspond to a certain degree of movement. The materials used can be from the likes of 3D-printed parts or laser-cut wood. In the role of the microcontroller, the beforementioned Arduino or Adafruit can be mentioned as possible contenders to be used.

Group B concept 2:

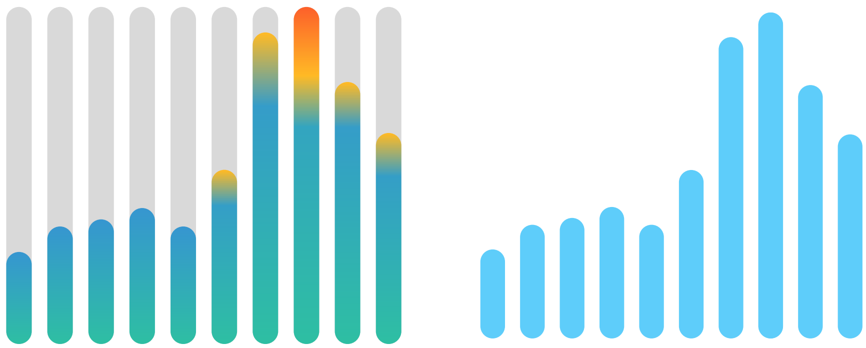

Figure 44: Reference for the fourth concept

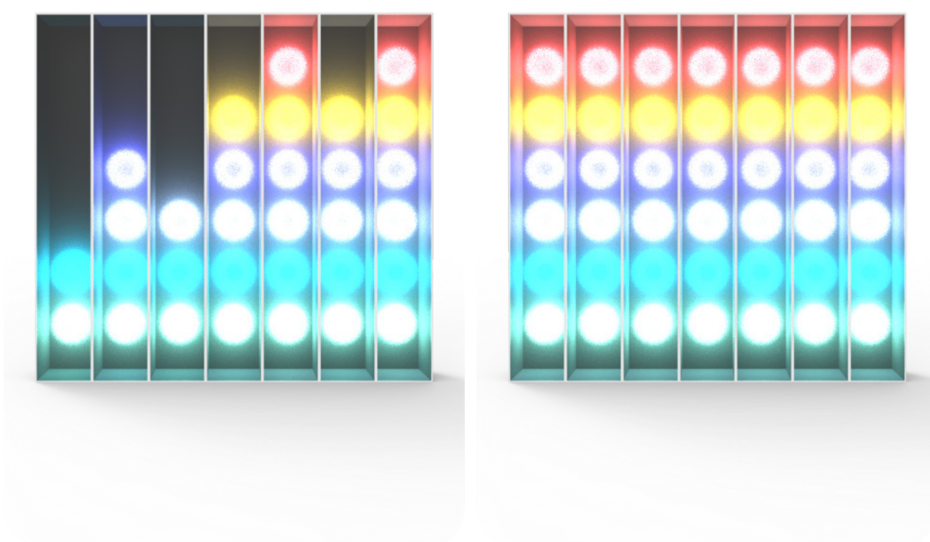

Figure 45: The fourth concept

Here the idea is to use a phygital representation of the data inspired by the visualization provided by Xiaomi particularly. Mainly, grey bars are noticeable, which accommodate the height of the bar corresponding to the step goal, which displays through the use of gradient communication the progress of the step count. In this manner, the prototype mimics the dedicated sections that will showcase the change in step count while the user is reaching its step goal. Different colours are used to emphasize the intensity of the steps, as seen in the reference, where cold colours are changed to warm colours as the step count increases.

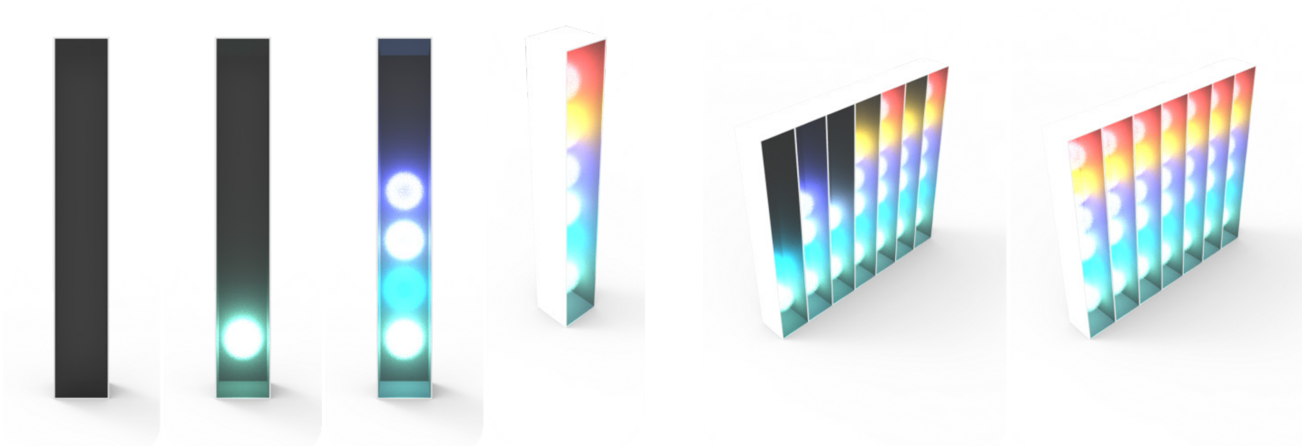

Figure 46: Data communication

For each bar respectively, the light segments correspond to the step count of a specific time instance. The step goal, represented with the value m, is divided depending on the number of led lights, with the value n. Therefore, depending on the number of lights, when a certain step count is reached, the action is emphasized with the corresponding led lights being lit. When the step goal is reached, the whole section of lights is lit. The seven bars showcase the corresponding seven days of activity tracking.

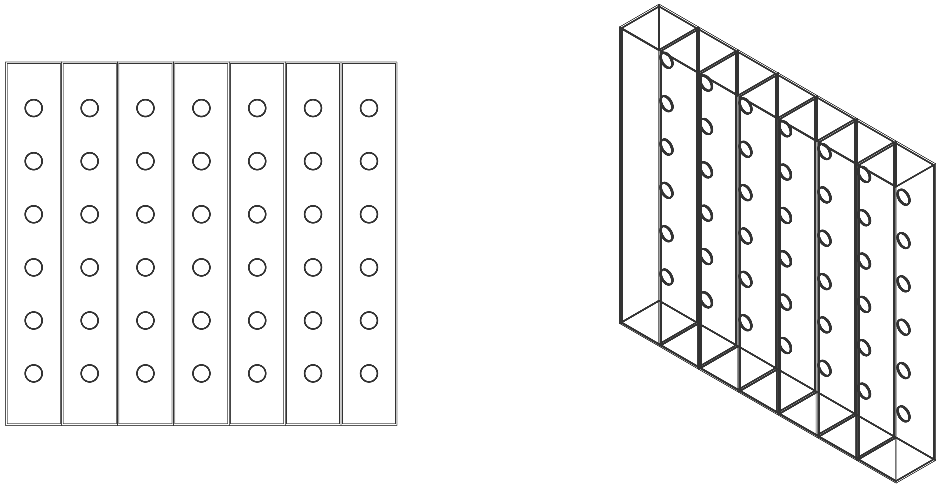

Figure 47: Materialization

To elaborate on the feasibility of the concept, shell compartments for each day of the week will store the led lights that form the bars. As the steps are registered, in a certain time instance, when a certain number of steps is reached, the corresponding light turns on. With the help of the software, the aforementioned relationship between the quantity of lights and step count is established. The led lights are connected to a physical programmable circuit board (microcontroller). Within a 3D-printed shell compartment, the led lights are placed. The shell's lid has a certain amount of transparency so that the emitted lights can be seen through it. In the role of the microcontroller, Arduino can be pointed out as a possible contender as well in the case of this concept, while for what concerns the lights portion of the electronics, the beforementioned neopixel led lights stripes can be mentioned.

Having the concepts illustrated, the next step is to understand which one has the biggest potential to be realized as a presentable functional form of personal data physicalization. The idea of the prototype is to explore the feature of communicating data through physical representation that will counterpart the visualization, in a way that validates the experimental quest of this research project in understanding whether the physicalization can come off as more efficient. Moreover, the prototype should showcase full functional simulation and is constructed by techniques that allow for easy implementation (Floyd, 1984).

By examining the concepts that have been put forth, we can see how those that call for the use of led lights for implementation fall more on the "ambient display" side and, as a result, fall short of meeting the criteria for an artifact that can be considered a physicalization in its purest form. Additionally, they are still contenders that are characterized as novel ways or fresh methods with which to represent personal data, but they heavily rely on the use of flat displays to communicate data.

Nevertheless, the idea based on the disposition of bars is the most promising because it comes the closest to illuminating the idea of converting the most popular visualization into a 3D physical artifact. The discussion of creating the data physicalization is continued in the section that follows by outlining the subsequent actions.

7.4. Develop

It's time to get started on building a working prototype now that a promising idea has been found. It is necessary to determine the prototype's technological and material specifications in order to support the overall goal of conveying data through the geometry and physical characteristics of the proposed artifact.

The answers to these questions can lead us to bring the prototype to fruition:

1) What elements are required to create the data physicalization?
2) How to connect the elements?
3) How to establish the link between the hardware and software aspects?
4) How can the geometry and material properties of the physicalization be used to realize and communicate data changes?

We elaborate on the following steps that lead to the realization of the prototype by responding to the questions posed.

1) What elements are required to create the data physicalization?

The components that will enable us to realize the selected concept are identified as follows:

Adafruit Huzzah Feather Board

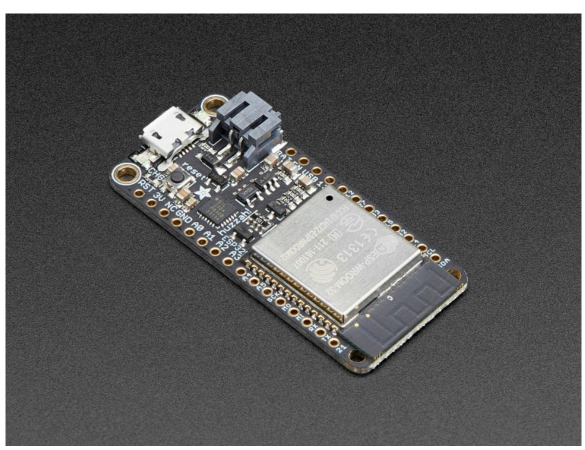

Figure 48: Adafruit Huzzah Feather Board

The cornerstone or foundation of the project, which serves as the central hub to which all other components are connected, is the Adafruit Huzzah Feather board. It provides the essential connectivity and processing capabilities that permit the prototype to function; thus, the board plays a key role in the success of the physicalization. The Adafruit Huzzah Feather board is a compact device, convenient to use in order to easily build a wide range of projects. It features a USB-to-Serial converter for easy programming and debugging and is compatible with the Arduino IDE. The board is available with preassembled stacking headers, which is convenient for stacking other components without using a breadboard as an intermediate.

Adafruit Servo FeatherWing

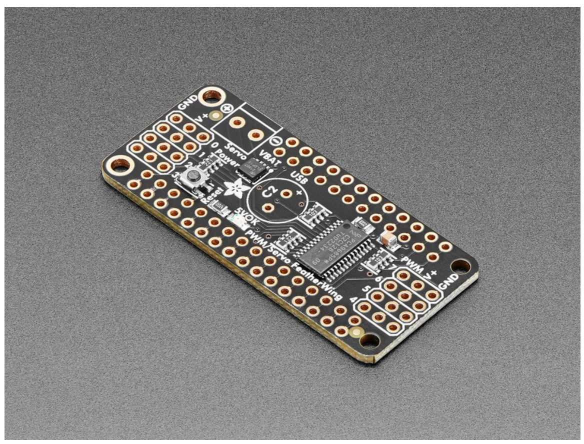

Figure 49: Adafruit Servo FeatherWing

The Servo FeatherWing is an accessory that expands the functionality of the Adafruit Huzzah Feather board. It has eight channels of pulse width modulation (PWM) that allow to control eight servo motors. It is convenient for the data physicalization prototype, as precise control of eight bars that showcase data change is required.

Servo motors

Figure 50: SG90 9G Servo motor

A servo motor is a kind of rotary actuator that enables precise control of angular position, velocity, and acceleration. Small hobby projects and robots frequently use micro-sized servo motors, such as the SG90 9G servo motor, that can rotate to a precise angle within the range of 0 to 180 degrees.

It is a low-cost, light, and simple-to-use motor that can rotate to a specific angle in response to a pulse signal from a control device. The designation “9G” stands for its torque, which is 9 kilogram-force centimeters. The movement of robotic arms, grippers and other similar devices is frequently controlled by it.
For controlling the position of the bars based on the values that will represent the step count, it is convenient to connect the servo motors to the aforementioned accessory Adafruit Servo FeatherWing.

Bars

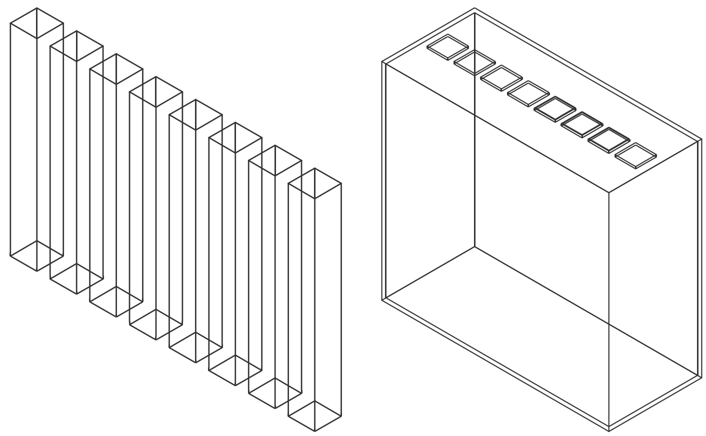

Figure 51: Bars and container – to be 3D modelled and printed

The linear adjustment of the position of the bars will be carried out by the eight servo motors. A test version should be created in order to figure out how to design and fabricate the bars, primarily to comprehend how to guarantee to achieve the linear disposition, and which construction would permit doing so.

3D-printed parts make sense for the concept in order to address the material question. While addressing the query of how to produce the overall physicalization, the exploration of the appearance and feel of the bars will be detailed and explained in continuation.
To accommodate the assembly, which is made up of the aforementioned components, it is appropriate to design a box-shaped container that will store the parts and allow the intended disposition of the bars.

The appearance and texture of the bars and the container must be examined, as was already mentioned, in order to determine which construction would allow for the best implementation of the concept and its materialization, which will be discussed in more detail later.

After identifying and gaining a better understanding of the components, we can now answer the following query:

2) How to connect the elements?

The Adafruit Huzzah Feather board comes fully assembled with a USB interface that allows us to quickly use it with the Arduino IDE. From the available options, the board can be purchased with preassembled socket female headers in order to avoid soldering and to attach the FeatherWing very easily (Industries, n.d.-c).

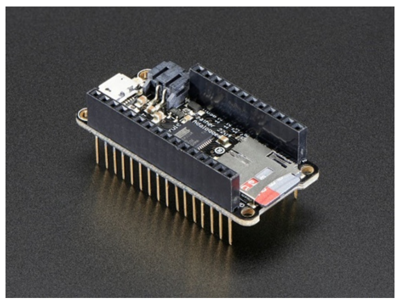

Figure 52: Adafruit Huzzah Feather board

In order to assemble the FeatherWing, a little light soldering is required, for the purpose of attaching the desired headers and the terminal block for power input, respectively. The FeatherWing contains eight pairs of three pins that are used for driving the servo motors (Industries, n.d.-a). The pins are as follows: GND pin (power and signal ground), V+ pin (5V power from the terminal block for powering servos), and signal pin (3.3V logic signal).

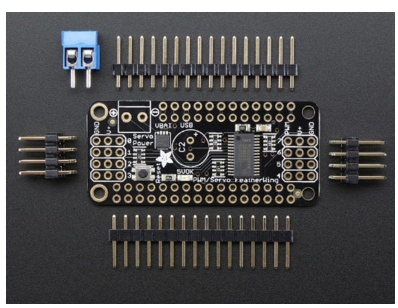

Figure 53: Adafruit FeatherWing with headers and terminal block

It is important to solder the header strips in a way where all pins are soldered properly for reliable electrical contact. Next, there is the need to solder in the larger header blocks, that are used to plug in the servo motors into the FeatherWing. There are two blocks, each are 3×4 headers in size. Lastly, the 3.5mm terminal block that is used for power is soldered. This is how we will provide the large amount of current that driving the servo motors require. With that being done, we can now plug in the FeatherWing into the Feather board.

A single servo should be plugged into each of the eight PWM ports, starting with the PWM #0 port, which is the first one. Each servo motor is plugged by connecting it to the three corresponding GND, V+ and signal pins on the FeatherWing. The wings of the servo motors will be connected to the 3D-printed bars and will allow them to move up and down. This will be explained in continuation, when the test assembly will be prepared in order to understand which construction will allow us to achieve the linear disposition of the bars.

To summarize, the following flow is produced in order to link the hardware components:

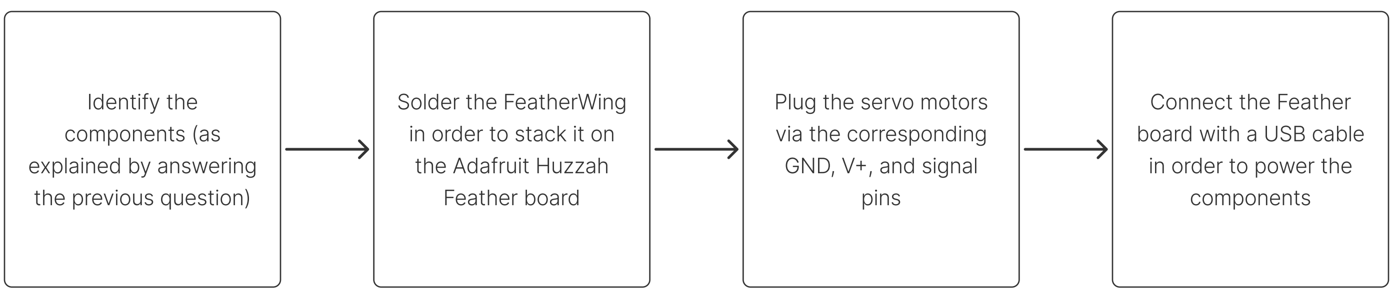

Figure 54: Connecting the hardware

The following step entails comprehending how to control the servo motors in relation to the numerical value that denotes the step count.

3) How to establish the link between the hardware and software aspects?

Having identified the components for the physicalization and successfully connected the hardware, it's time to delve into the software aspect. The servo motor's movements will be controlled by the code, which will cause correspondingly the bars to move in order to visually represent the data change. This will be made possible with the use of the Arduino Integrated Development Environment (IDE). The Arduino IDE is a software application for writing, compiling, and uploading code. It will be used as a platform for writing, testing, and debugging the code for the Adafruit Huzzah Feather board.

Setting up the environment is crucial before moving on to the coding portion. This involves installing the corresponding library for the specific feather board and setting up the parameters for the prototype. Establishing the environment will allow us to move on with understanding the FeatherWing's requirements, which will be essential to building a successful and useful prototype.

Once the beforementioned is concluded, the Adafruit Huzzah Feather board can be found and selected through the board manager. The next step involves setting up the necessary library for FeatherWing. This is essential to the functionality of the prototype because it will let us communicate with the FeatherWing and the servo motors. The servo motors' movements, which are essential for physically displaying the data, will be controlled by the servo motor functions and commands that can be accessed through the said library.

Defining the minimum and maximum angles for the servo motors as well as the frequency at which the servo motors will be updated is crucial before mapping the step count to the angle of the wing. These parameters will guarantee the prototype's proper operation and enable us to precisely adjust the servo motors' movements to suit our needs.

The main goal after installing the library and tuning the servo motors is to translate the values, which represent step counts, into corresponding angles. In response to the changes in the data, the servo motor wing will be able to move in a manner consistent with those changes. The servo motors will be able to physically demonstrate the data changes by moving the bars up and down by converting the step counts into angles. The step count at any given moment is represented by a numerical value, which is then translated into a corresponding angle to move the servo motor's wing. The value can be translated to correspond to a value that ranges from 0 degrees to a maximum of 90 degrees, which is the maximum height that can be achieved for the bar. In doing so, two functions are declared to steer the servo motors to a particular angle. The first function converts the step count to an angle value and modifies the angle of the servo motors to raise the bar. The bar is lowered by the second function, which modifies the servo motor's angle in the opposite direction.

To sum up, the following flow is reached in order to link the hardware and software dimensions of the data physicalization:

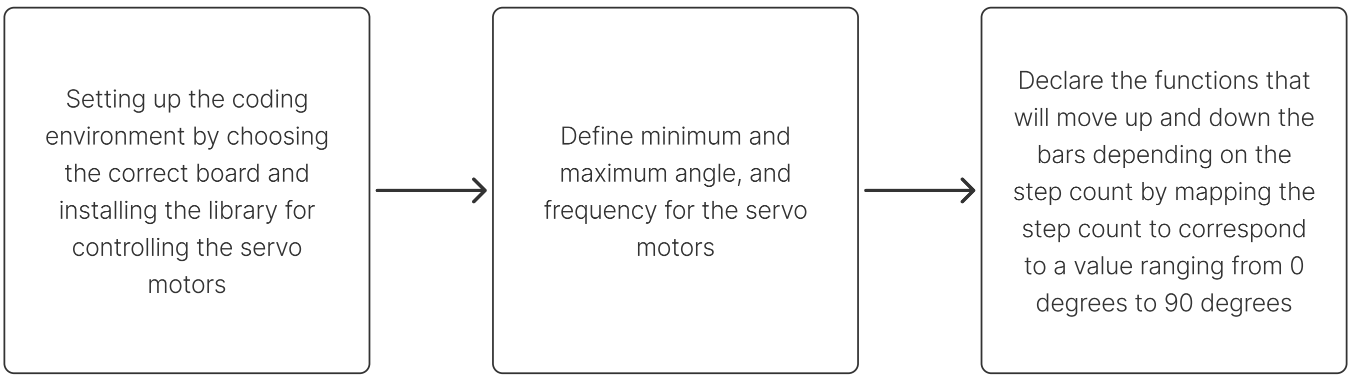

Figure 55: Establishing a link between the hardware and software dimensions

In this endeavour, the step count is inputted manually in order to test the running of the functions that map the values. The next step entails gaining an understanding of the look and feel of the bars with the structural elements that will enable to materialize the data.

4) How can the geometry and material properties of the physicalization be used to realize and communicate data changes?

As previously teased, we need to understand how to design and fabricate the bars and the environmental parts that will help to constrain them, as to understand how to guarantee the achievement of the linear disposition and which construction would permit doing so.

Therefore, we created a test 3D assembly in order to understand whether the angular movement of the wing of the servo motor will translate to the linear disposition of the bar. The following elements were identified:

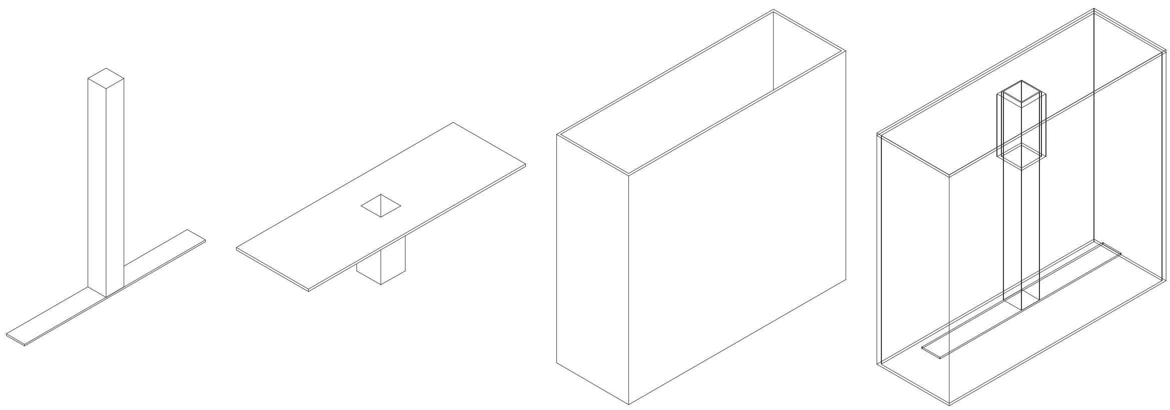

Figure 56: 3D printed parts

The bar is the element that will be moved up and down accordingly to represent the data change physically. The disposition is enabled by the beforementioned and explained hardware and software dimensions. The bottom part of the bar is a structural element that allows for contact between the bar and the appropriate servo motor and it is used to enable movement.

The lid element covers the elements and with the central cut allows for the bar to move up and down. A crucial structural element is the constraint structure, which allows to position centrally the bar and fixes it. This is because once the contact between the bar and the servo motor is established, there is a necessity to constrain the bar itself, so when the wing of the servo moves, the bar is constrained to produce a linear disposition.

The premise of having a wall constraint serves to visually declutter and hide the corresponding components inside, as well as to furtherly constrain the bar to move in this dedicated space. The servo motor is positioned outside this shell construction, where one side and the top are empty, in order to allow for the disposition of the wing of the servo motor and the positioning of the previously mentioned lid part with the constraint structure.

With 3D modeling and printing the respective elements, we reached an assembly that allowed us to test the geometry and materialization in correlation with the hardware and software elements.

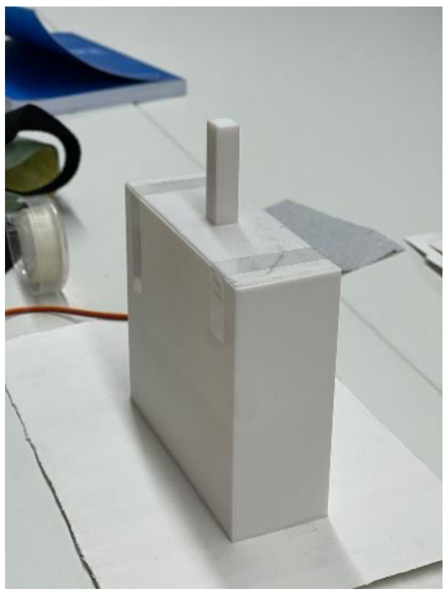

Figure 57: Testing the construction

The test consisted of inputting the step count, which is the numerical value, and mapping it accordingly to correspond to the specific angle of the servo motor. With this, we could understand that these elements could be used for the final prototype, although certain improvements and insights from the testing can be implemented. Moreover, the bottom part of the bar, which allows for the contact between the servo motor and the bar itself, can be enlarged to occupy a bigger area, making it to correspond to the dimensions of the wall structure, to allow for a more robust connection.

Another insight is to take into consideration how the constraining structure on the bottom of the lid should be smaller in height, as we need to take into consideration that it affects the overall height of the bar, and we want to optimize these dimensions in order to design and 3D print elements with compact dimensions. In this endeavour, the dimensions of the bar, moreover the square section, is one centimeter by one centimeter, with ten centimeters of height, which comes off as a bit small, which prompted us to think to increase the section dimensions to correspond to two centimeters by two centimeters. With this being said, having validated these structural components of the materialization, we can continue with defining the look and feel of the overall data physicalization, that will be used in the study.

7.5. Deliver

In order to deliver the data physicalization for study purposes, the following questions arise:

1) How to create the overall physicalization?
2) How will the data be delivered to the prototype for the user study's purposes?

We start by answering the first question. Following up on the answer to the previous question, we started envisioning the overall look of the physicalization that counts eight bars. The first seven bars are used to represent the step count of seven consecutive days, whereas the eighth bar is used to represent the step goal, which serves to establish a proportional connection amongst the step values of the consecutive days. The data physicalization will be materialized through the following elements:

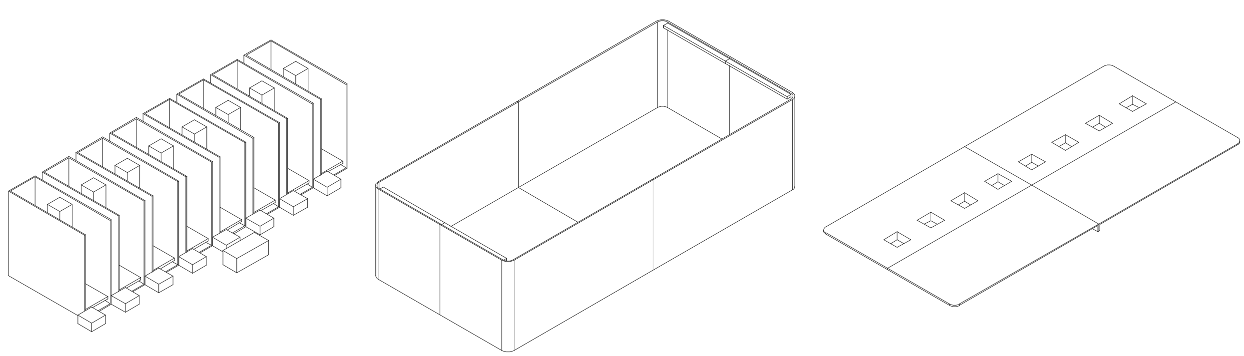

Figure 58: Elements that make up the data physicalization

Apropos the initial test 3D print, it is appropriate to design and 3D print the eight bars with their corresponding wall construction where they will be nested. This shell wall construction comes with emptied top and side walls, as to accommodate the corresponding lid on the top and allow for making the connection point between the servo motor and the bottom part of the bar on the side.

The lid comes with the corresponding constraint structures that are needed to assure the linear disposition of the bars and to be used as a fixing point for each bar. The purpose of the lid is to provide a visual declutter of the data physicalization itself. As the mode of materializing is through 3D printing, in order to assure proper 3D printing, the lid is made up of four parts that need to be joined, as to provide parts with appropriate dimensions for 3D printing.

The container, or the box, is designed to accommodate the bar assembly and to support the lid through the designated support structural points. In the same manner, as when designing the parts for the lid, the box is made by connecting four parts respectively, in order to assure proper 3D printing with dimensions that are appropriate for smooth completion.

To zoom in on each assembly, the bar assembly follows the logic of the tested 3D printed assembly, whereas the lid and box assemblies are designed with the following considerations in mind. Moreover, when designing the respective parts that need to be joined in order to shape the lid and box themselves, merging points were taken into consideration, as to have points that contain appropriate structures on the surface that allow us to establish a proper connection.

By joining the hardware elements with the 3D printed parts, the assembly, that is the data physicalization is illustrated here:

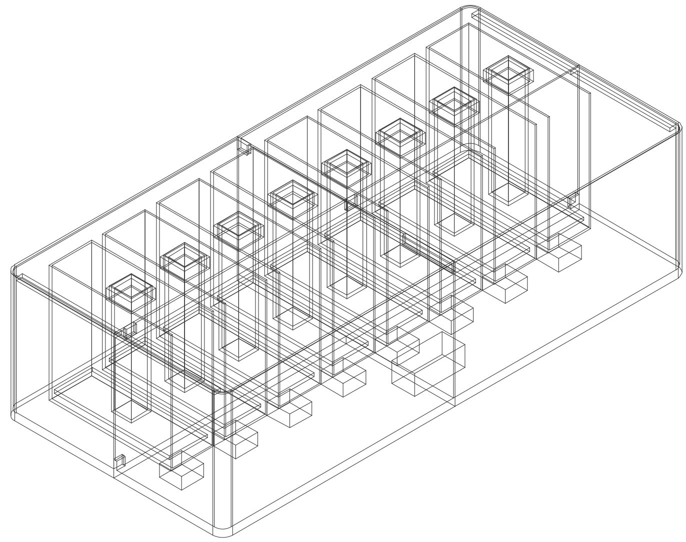

Figure 59: Schema of the assembled data physicalization for user study

Moreover, for the study purposes, we decided to incorporate two sets of data physicalizations, which will allow us to simultaneously test with two users and downgrade the overall time spent on conducting the study. The question that remains unanswered is to understand how the data will be inputted into the physicalization.

6) How will the data be delivered to the prototype for the user study's purposes?

With the design and 3D print of the corresponding elements to build the data physicalization, the next question refers to how the data, consisting of the step count numerical values, will be communicated to the prototype. In order to simulate the dynamic aspect of the physicalization, we can define an array that will store the value of the step for the eight consecutive servo motors. The first seven values will represent the step count of seven consecutive days of the week, whereas the eighth value will correspond to the user's step goal. By inputting the eight values in an array, the values will be parsed and mapped respectively.

7.6. Conclusions

This personal data physicalization is intended to support a dynamic type of personal activity data, which is a dataset that derives from a dynamic stream and is updated through local sensing with the help of self-tracking technologies. The information is represented by physical movement, which also demonstrates how the data has changed. This physicalization incorporates implicit indirect interaction, where users might not be aware that their actions are used as input for the physicalization, and uses sensor data as its input. In this manner, the steps count is communicated to the physicalization, which repositions the bars in a given time interval to communicate the change to the user.

The physicalization purpose, as needed for the comparative study, is to showcase data change over a period of the current tracking week. That being said, we are not concerned with the physecology within which the physicalization takes place, such as dedicating an appropriate graphical interface in order to obtain more information. To elaborate more on this, the study will incorporate visualization that is isolated from a graphical user interface, and its goal is to showcase weekly overview of the data for the current tracking week. Therefore, the physicalization does the same. It showcases the data for the current tracking week, and a fair basis of comparison is reached.

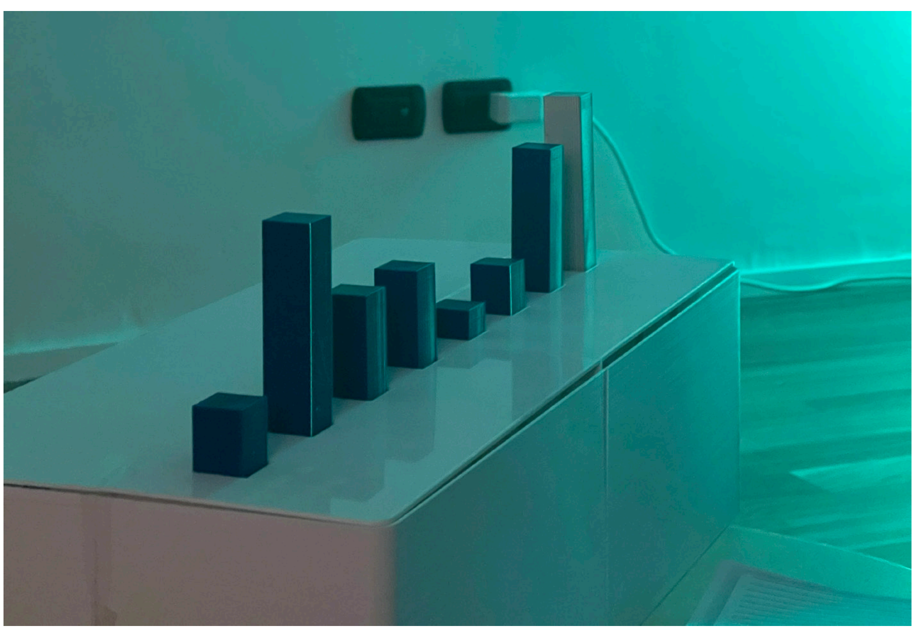

Figure 60: The data physicalization

The interaction's output revolves around the user, where self-tracking technologies pick up on their movements and feed that information into a physicalization that is private and intended for use in a domestic setting.

Although for the sake of the user study, the data is communicated manually, the physicalization is designed and enabled to retrieve the data automatically, by allowing for serial communication between the self-tracking technology and the Adafruit Huzzah Feather board. This communication requires a deeper understanding of programming knowledge or additional resources, such as smart watches, and the data communication aspect on its own is not the objective of the research, as it does not correspond with the competencies that are intended to be acquired with this research. During the testing phase of our physicalization project, we discovered that certain hardware components, specifically the servomotor wings, were not consistently aligned with the 0-degree angle position. As a result, we had to manually adjust these components to ensure that they conveyed the correct data values. This additional adjustment process was required to optimize the physicalization device's functionality and performance. Based on our observations that the hardware components required manual adjustment to accurately communicate data values, as well as the complexity of the serial communication, we determined that the study activities should include manual data update. We were able to improve the accuracy and reliability of our physicalization system by implementing this manual adjustment process. This aspect is taken in consideration and elaborated on when crafting the user study itself, as can be seen in the next chapter The eighth bar represents the step goal of the user, which is the fixed step goal that requires memorization, and representing this step goal in the physicalization enables relative and absolute estimations about the value of the data showcased through the rest of the bars.

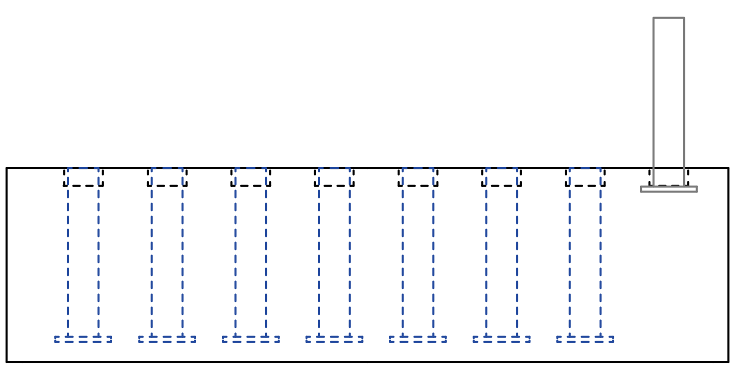

Figure 61: The starting point of the physicalization with the eight-bar representing the fixed step goal

Over the course of time, with step data being communicated to the physicalization, the rest of the bars for seven consecutive days of the week take a position to represent the step count proportional to the fixed step goal.

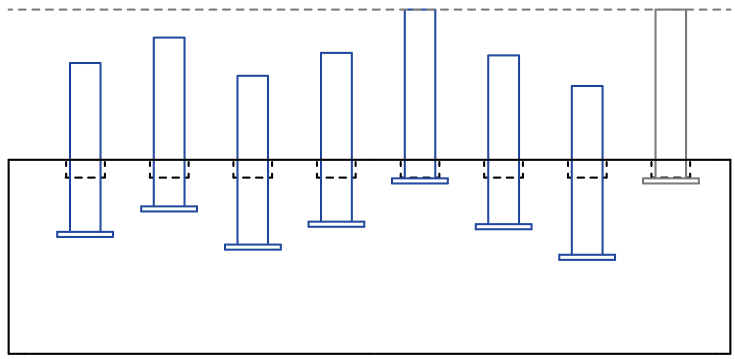

Figure 62: The data physicalization over the course of time

In case when the daily step count is greater than the fixed step goal, the bars are repositioned proportionally to communicate this information.

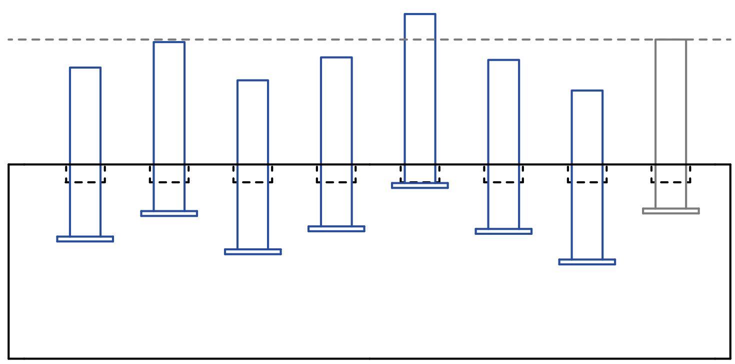

Figure 63: The data physicalization when daily step count is greater than the fixed step goal

Chapter 8: The study

8.1. Foreword

In this chapter, we will explain how we created the user study to address the research purpose, after establishing the research premise and crafting the data physicalization, respectively. The user study incorporates identifying several elements that would help for its successful conducting, where the creation of the protocol is a pivotal point. Therefore, in continuation, we will explain the parameters of the user study, starting with the context, that recalls the research question and the objective.

8.2. Context

The study is being conducted in response to the growing interest in data physicalization, personal informatics, and data management, such as acquiring and processing of personal data. Getting a deeper understanding of the abundant contexts and data types that the physical artifact can embody was helpful in order to determine the setting of the study, which lead us to the environment of data representations that deal with expression and self-reflection, which are frequently driven by data practices represented by the quantified self-practitioners. Despite the current availability of self-tracking technologies, more comprehensive and engaging methods of visualizing personal data are required. Our research aims to fill this gap by comparing different types of data representation and investigating the potential benefits of using physicalizations, as we are aware that the current primary challenge in producing physicalizations is identifying benefits that outweigh the cost of doing so.

As previously stated, we will focus on activity-based data, specifically linked to goal-oriented tracking, because it is thought to be an appropriate specimen for introducing novice learners to the field of data work. The research will include a data representation that will materialize and physically represent the appearance of data visualization within graphical user interfaces, allowing for a fair comparison of modalities.

The study’s goal is to gain a comprehensive understanding of the participants’ experiences with visualization and physicalization in order to determine which representation is best suited for managing and improving the quantified self. As a result, they must reflect on their step count at specific times while tracking their personal data in order to meet their step goal. In order to manage and reflect on their data, it is necessary to understand which responses the representations elicit. We believe that the findings of this study will be useful in inspiring future design efforts in the field of data physicalizations, with the goal of developing tools that can be integrated into daily life, communicate information in an engaging manner, and facilitate personal growth by providing a better basis for reflection.

8.3. Type of study

This study can be classified as (mainly) experimental, while at the same time, it incorporates some elements of research by design.

In an experimental study, an independent variable is changed or manipulated in order to see how it affects a dependent variable, which is measured to see how it is affected by the independent variable. In accordance with this, in this study, the independent variable is represented by the two different types of data representation models, data visualization and data physicalization respectively. The dependent variable is the effectiveness of each data representation model, which will be assessed by collecting both qualitative and quantitative data based on the participants' experience and preferences for each model. This will allow us to draw conclusions about which data representation model is more effective at eliciting better responses for data reflection and management.

Research by design, on the other hand, is an approach that integrates design activities with research to generate new knowledge and solutions to practical problems, which in this case would be the problem that the communication through the graphical user interface is coming up short. Another incorporated research by design element is designing and creating a new type of data representation model, which is the physicalization itself, and then testing it, in order to gain insight into its effectiveness.

By combining the experimental and research-by-design approaches, the study not only tests hypotheses but also generates new design knowledge and insights that can inform future design decisions.

8.4. Participants and ethics

Given the time constraints, it was critical to find participants for this user study as soon as possible. It was also critical to find users who were willing to participate in the “quantified self” movement. Due to time constraints, identifying and recruiting actual members of the “quantified self” movement was not possible.
As a result, convenience sampling was used to find participants willing to portray the persona despite not being personally involved in the “quantified self” movement. The convenience sampling method was used because it is a non-probability sampling method in which participants are chosen based on their availability and willingness to participate.

It’s also worth noting that the participants were thoroughly briefed on the persona they’d be playing, and were asked to act it out as if it were their own. The study’s procedure involves participants acting as members of the quantified self-movement who are tracking their step data in order to meet a daily step goal. The goal is for participants to act and respond as if they are tracking their step data in a directive manner in order to achieve a specific goal. For addressing this, the previously generated persona (see figure 24 and figure 25), George, was able to illustrate the characteristics of what they are intended to portray.

As beforementioned, the persona was created based on highlighting the potential lack of the current tracking technologies, mainly in the way in which the personal data is communicated to the users, by uncovering the series of problems that the quantified-selfers experienced while tracking, managing, visualizing, and using their own personal data (Rapp et al., 2016), which due to a variety of lacks in the standard visualization tools’ features lead the quantified-selfers to build their own tools for tracking or create their own visualizations (Choe et al., 2014), while self-tracking for self-awareness, optimising and improving their lives (Lupton, 2015). At the same time, for providing more information and setting the mood of the persona, a customer journey map was also available to give more context, if needed. The adapted persona and customer journey map for the user study are as follows:

NEEDS

- gaining awareness of his own actions and routines
- enhancing his general health and wellbeing
- make more informed decisions about his own life
- eager to use data and technology to further these objectives

PAIN POINTS

- the lack of efficient tools for managing and visualizing personal data, which makes it difficult to think about the said data
- the challenge of finding a self-tracking technology that meets all of his requirements and preferences
- it is difficult to integrate and bring the data closer to him because it is scattered across several platforms
- disappointment and annoyance from devoting more time and effort to data management than to decision-making and self-improvement

Figure 64: Persona used for the user study

In accordance with this, we stress the inspiration behind the lack of current self-tracking technologies, as it would be interesting to investigate whether data physicalizations could serve as a platform for improving how individuals interact with their own personal data. Instead of relying on conventional data visualization techniques, George might be able to understand the data more intuitively and directly by interacting with physical representations of it, which is also automatically updated and do not require a lot of effort from his side. With this being said, it is interesting to explore whether the physicalization can rise above the visualization as a medium that better serves the purpose of reflection and management of data. Hence, the need to evaluate the effectiveness of data physicalization is therefore reinforced.

Additionally, we can explore what the customer journey for the majority of “Quantified Selfers” can look like.

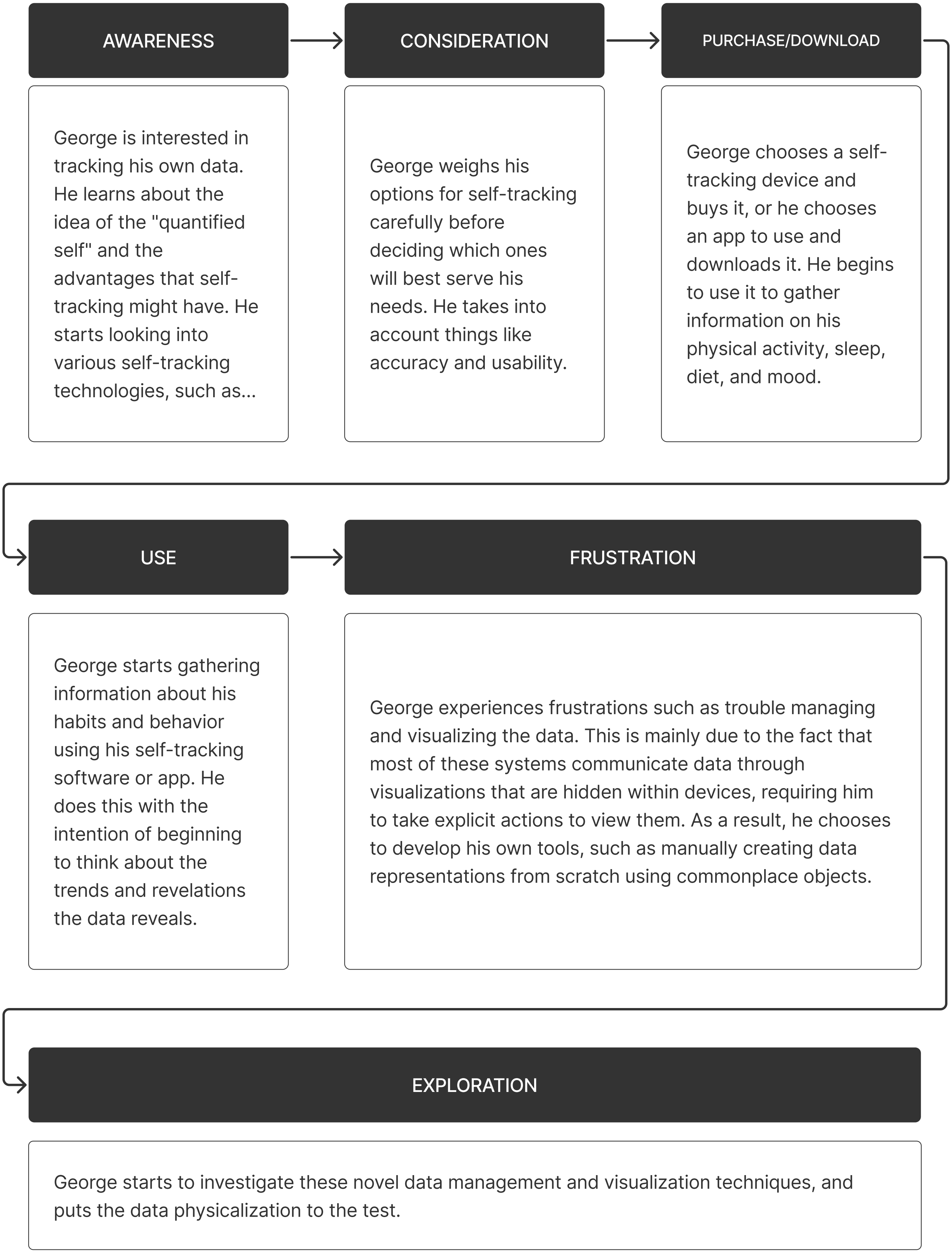

Figure 65: Journey map used for the user study

Despite the limitations of the recruitment method, this helped to ensure that the study's results were meaningful and representative of the target population.

Here we created a pre-study questionnaire, that can help us better understand the participants' current experiences and perspectives on data visualization and physical representation, which will help us design our study and interpret our findings. We also want to include some demographic questions, such as age, gender, and occupation, to better understand the participant group's diversity.

It is important to note that informed consent forms are used to conduct the study in order to protect the participants' privacy and the handling of sensitive information, such as disclosing their personal data in order to interact with the physicalization.

8.5. Procedure, timing and resources

In this section, we will elaborate on the activities that are included in the study itself. During the five-day study, participants will alternate between using data visualization and data physicalization to acquire and process, and therefore reflect on their step data.

The participants will use the visualization at a specific time on the first and second days, and the physicalization on the third and fourth days. The participants will be introduced to the graphical user interface before their interaction with the visualization, and the physicalization will be introduced before their interaction with it. It is important to stress that the participants are to be concerned with the current data, such as in the past seven days, therefore they are interacting with that specific visualization, and their insights are to be based on the current tracking week only. Similarly, the physicalization is also designed to support the display of data for the current tracking week, as previously discussed, in order to reach a fair basis for comparison.

In order to understand in a deeper manner, the impact of the data representation models, we will be asking participants to use each representation for two consecutive days. While dedicating one day to each representation model may provide some initial insights, using two consecutive days will allow us to gather more in-depth data on the effectiveness and limitations of each representation and to better understand any potential changes in behavior or attitude over time. We believe that a longer duration of exposure to each representation will provide a more comprehensive understanding, though due to time constraints, we will try to demonstrate that a four-day study can also provide credible and valid results, that can be strengthened by conducting a longer study.

The graphical user interface chosen for this study is an app that visualizes steps taken, while the physicalization is the one described in the previous chapter.

It should be noted that the physicalization is intended to support automatic updates of the step data communicated from the self-tracking technology to the physicalization. However, as previously mentioned, due to time constraints and the intricacy of achieving this communication, as well as our observations that the hardware components required a manual adjustment to accurately communicate data values, in order to improve the accuracy and reliability of our physicalization system the physicalization data changes will be simulated in this study. This is because the primary goal of this study is to understand the impact of different data representation techniques on the user's ability to manage and reflect on personal data, rather than to investigate the communication aspect. Therefore, the corresponding activities for the study were crafted with taking this limitations in consideration.

During the first and second day of the study, the participants interact with the data visualization, which is introduced to them before the first day of the study and they are briefed on how to access the said visualization. The visualization portraying the data for the current tracking week is accessed through the graphical user interface of the app Google Fit, and it is required from the participants to reflect on their personal data at a specific time, as to understand which responses the visualization elicits, in terms of managing their data, such as acquiring and processing of the said data, and reflecting upon it. The participants are reminded to interact with the visualization at the specific time, as that is their quantified self ritual. In the evening, they dedicate certain amount of time and space to get in touch with their data. The visualization itself is isolated from the features provided within the said app, as the participants are required to interact with that one feature in particularly, which is the weekly overview of the data.

Figure 66: The graphical user interface with its respective data visualization used for the user study

During the third and fourth day of the study, the participants interact with the data physicalization, which is introduced to them during the third day of the study. The participants are briefed on how the physicalization works, and are required to disclose where would they like the physicalization to be positioned.

For the designed personal data physicalization, the participants are asked to share their personal data in order to update the step count and display it physically, without their presence. The update of the personal data is achieved at a specific time, after which the participants are required on their own to understand which responses the physicalization will elicit, in terms of managing their data and reflecting upon it. The participants are reminded that once their data is physicalized, they will dedicate time to engage with the physicalization, in their quantified self ritual. The same activities occur as when they interacted with the visualization, such as, in the evening, they dedicate a certain amount of time and space to get in touch with their data. Essentially, the physicalization is used to replace the visualization and the participants interact with it when it is time to get in touch with their data, and this is to ensure that the lack of serial communication does not interfere with the required participation from their side.

Figure 67: The data physicalizations used for the user study in the homes of the six participants

Participants are encouraged to keep track of their thoughts, feelings, and any insights they may have while interacting with the data representations throughout the study. They are allowed to write down and return to their thoughts during the post-study questionnaire and interview, which will provide both qualitative and quantitative data on their experiences and preferences.

To summarize, the protocol of the study includes the following steps: introduction to provide the context of the study to the participants, ethics to provide the consent form to the participants, pre-study questionnaire, the study, post-study interview, and post-study questionnaire.

The protocol consisting of the aforementioned elements was provided in a printed form to the participants during the first day of the study, with a dedicated space for journaling.

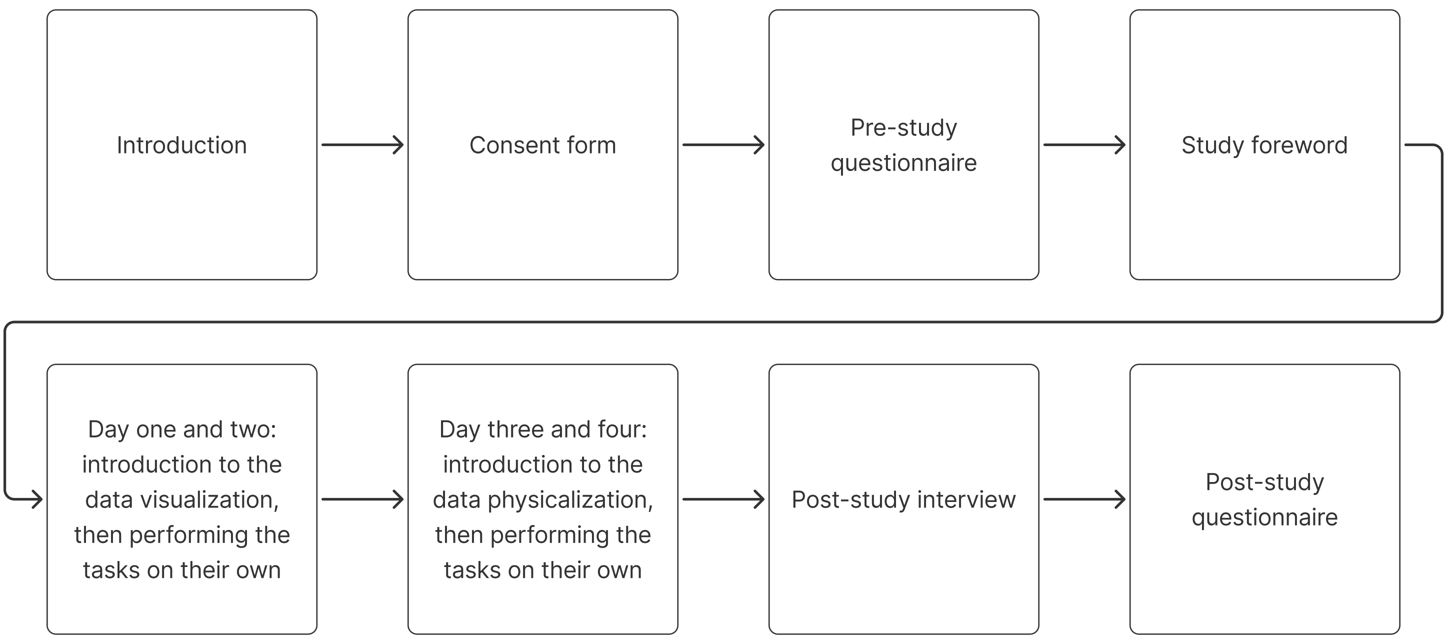

Figure 68: Elements of the study

Moreover, we can create the following map, showcasing the activities from both involved sides.

BEFORE

RESEARCHER ACTIONS	Provide the pre-study questionnaire	Introduce the study to the user
USER ACTIONS	Fill-in pre-study questionnaire	Observe and comment on the introduction and the foreword of the study and the persona brief

DURING

	DAY 1		DAY 2	DAY 3		DAY 4
RESEARCHER ACTIONS	Introduce the visualization	Remind the user to go through with the ritual	Remind the user to go through with the ritual	Introduce the physicalization	Update the data and remind the user to go through with the ritual	Update the data and remind the user to go through with the ritual
USER ACTIONS	Get introduced to the visualization	Interact with the visualization at the specific time as it's their ritual and keep a journal	Interact with the visualization at the specific time as it's their ritual and keep a journal	Get introduced to the physicalization	Interact with the physicalization at the specific time as it's their ritual and keep a journal	Interact with the physicalization at the specific time as it's their ritual and keep a journal
USER GOALS		Understand which responses the visualization elicits in terms of managing and acknowledging their personal data and reflecting upon it, as well as ease of use, level of engagement and establishing emotional response	Understand which responses the visualization elicits in terms of managing and acknowledging their personal data and reflecting upon it, as well as ease of use, level of engagement and establishing emotional response		Understand which responses the physicalization elicits in terms of managing and acknowledging their personal data and reflecting upon it, as well as ease of use, level of engagement and establishing emotional response	Understand which responses the physicalization elicits in terms of managing and acknowledging their personal data and reflecting upon it, as well as ease of use, level of engagement and establishing emotional response

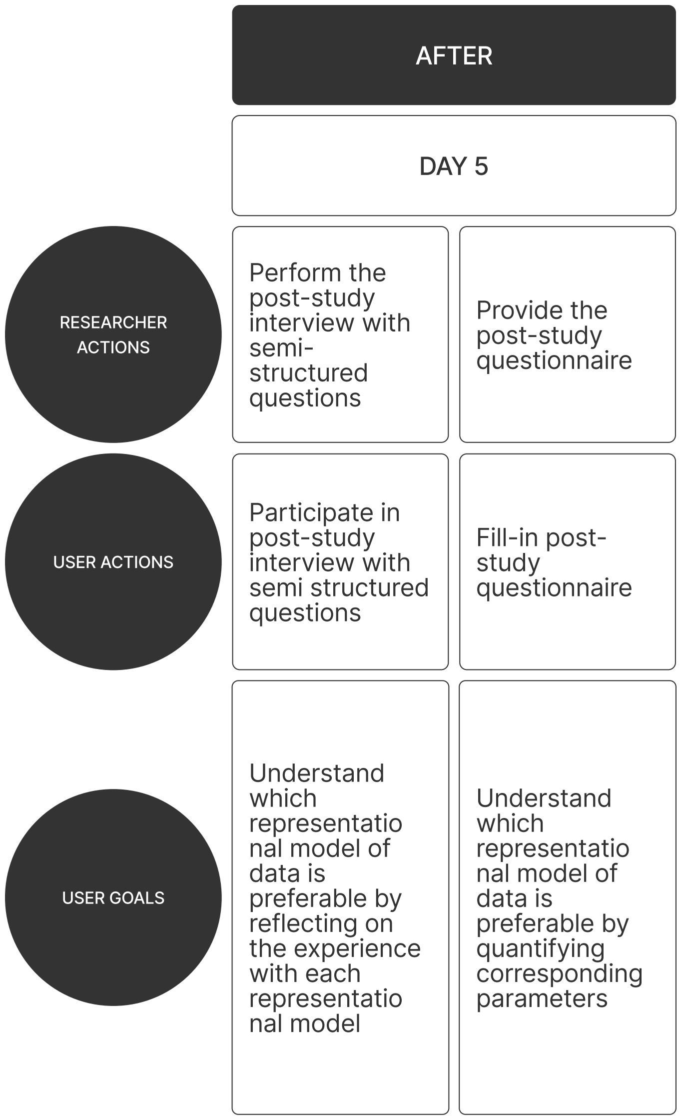

Figure 69: User study map

8.6. Data collection

Through conducting the user study, the data collection process consists of gathering quantitative and qualitative data through the means of post-study questionnaire (quantitative from the likes of interpreting specific parameter and its' efficiency on a Likert scale and qualitative from the likes of connecting the respective experiences with the both representational models with adjectives that best summarise the participants' experiences) and post-study semi-structured interviews, that commenced on the fifth day of the user study, after the participants successfully finished the four day study.

The six participants met the study without any relevant concerns, in the context of what is intended to be done from their side.

To decide on the final set of questions for both activities, a study pilot was conducted with two participants in order to understand the quantity of the questions and their relevance.

Both the interview and the questionnaire are critical in collecting a comprehensive and well-rounded set of data that will provide valuable insights into the experiences with the data representation models and their efficiency.

It is important to note that in order to talk more about numbers, it would be appreciated to explore the questionnaire results from a bigger number of participants, which in this user study wasn't the case, since the answers to the post-study questionnaire are heavily dependent and based on the experience of the participants that participated in the lengthy user study. We believe that the in-depth semi-structured interviews with the six participants allowed us to encounter a rich and complex dataset for thematic analysis, which contributes to more profound insights. The semi-structured interviews in their nature can be perceived as an opportunity to gather in-depth descriptions and an occurrence in which the participants can attribute meaning to their own experiences (Braun et al., 2013).

The interview with semi-structured questions is designed in order to gather qualitative data and provide insights into the thoughts, feelings, and perceptions of the participants.

Subsequently to this, this type of data collection is more open-ended and allows for a more in-depth exploration of the experience of the participants.

The crafting of the structure of the interview included generating a bigger number of promising questions, then clustering them to understand which ones to focus on. This is mainly due to the fact that the nature of the semi-structured interview allows for flexibility to ask follow-up questions in order to explore the subject in more depth and gather more detailed and nuanced answers.

The semi-structured interview covered all areas of interest in order to understand what makes one representational model more efficient compared to the other, while answering questions that tackle how each representational model helped them in order to get in touch or acknowledge, visualise and manage their personal data, with the ultimate goal of eliciting the process of reflection, while gaining broader understanding of the engagement and interest that the models sparked in the participants.

Another opportunity was to understand how the physical representation affected the relationship with their personal data and the difference in the emotional response to the two representational models.

After concluding the questions whose responses are based on the current experience of the users, we wanted to delve also in exploring questions about the future experience, where it is necessary for the participants to envision how interacting with the physicalization can be helpful.

The qualitative interviews indeed helped in the generation of a more nuanced understanding of the experiences the participants experienced while interacting with both representational models, in order to define which model was more efficient.

The efficiency was interpreted through understanding which data representation model was a better representation model of their personal data, in supporting their goals of acknowledging, managing and visualising their own data, furthermore contributing to them feeling more engaged with their own data, in order to reach the state of eliciting self-reflection during those quantified-self rituals. Those goals are deducted and dependent on the specific use case of the data physicalization, which in this study, was the use of physicalization for self-reflexive purposes, and the goals themselves deal with the aforementioned tasks of acknowledging, managing and reflecting, while in the previous case of conducting a comparative study, the physicalization was used for analytical goal, where the task of low-information retrieval was put to the test (Jansen et al., 2013).

The interview started with the opportunity for the participants to overall share their stories by discussing the overall experience they had with the both representational models, whereas the aforementioned set of questions were not followed strictly, as depending on the answer the participants were giving to a certain question, a question would be implicated, in order to produce data in a more natural flow.

The interview's duration ranged, as well as the length of the participant's answers to the specific question in mind. It is interesting that the length of the interview and the length of the answers were not that detrimental for forming the conclusion that the length would implicate the gathering of richer and more important records of the participant's experience, as at a certain moment, some answers that were perceived as shorter and more straightforward, would implicate to spark a very promising code that leads to generating a clearer theme during the thematic analysis.

The questionnaire, on the other hand, is used to gather quantitative data, which provides a more structured and numerical representation of the experience of the participants. It includes a set of questions adapted from the likes of standardised questionnaires, exploring the assignment of numerical values in order to understand which representational model of data is preferred, by quantifying numerous parameters, such as: the effectiveness in understanding (their) personal data, effectiveness in managing and visualising (their) personal data in order to elicit reflection, ease of use, level of engagement, and effectiveness in establishing emotional response to (their) personal data. With this, the quantitative half of the questionnaire is covered, while the qualitative half was represented through the requirement for the participants to associate all the adjectives that best describe their experience with the both respective representational methods.

8.7. Data analysis

After conducting the study, we can elaborate more on the data analysis process. The pre-study questionnaire was used in order to gather data that will describe the participants themselves, with gaining understanding of their level of technology usage, as well as understanding of data representation models from the likes of bars and graphs, and whether they themselves indulged in self-tracking activities in the past.

With this, we create the following table, portraying the demographics of the six participants:

Age of participants	25-29 years
Gender	Female 5 (84%) Male 1 (16%)
Background	Studying or working in the field of UX/UI 6 (100%)
Technology usage	Intermediate 2 (33%) Expert 4 (67%)
Familiarity with traditional data visualizations	Intermediate (50%) Expert 3 (50%)
History with activity tracking	Yes 6 (100%)
Frequency of self'-tracking	Every day 1 (17%) Around three times per week 2 (33%) Once weekly 1 (17%) Once monthly 2 (33%)

Table 3: Participant's demographics

The participants for both questionnaire and interview were predominantly well familiar with traditional data visualisations and expressed a good level of technology usage. All of them have history with indulging in self-tracking activities, such as step count in particular, while the frequency of doing so was met with differences, ranging from every day (17%), around three times per week (33%), once weekly (17%) and once monthly (33%).

The idea behind the post-study questionnaire was to gather straightforward data that can be easily illustrated in order to point out potential contrasting parameters about the two representational models and design a graph that connects each of the quantified entity in order to produce a comparative graph which represents how the experience with each representational model differs in its effectiveness, by producing two respective graphs to represent each representational model. This is prepared for each participant.

Moreover, the graphs are followed by the mapping of the selected adjectives that correspond to the experience that the participants had with the both respective data representation models, in a style that indicates sections that cover adjectives of neutral, positive and negative connotation.

In this manner, we could create a summarised graph of the quantified experience and mapping of the selected adjectives, in order to provide a straightforward quantified summary of the participants' experiences.

This covers the data analysis part that is concerned with the data gathered from the post-study questionnaire.

The data collected from the interviews were analysed by using reflexive thematic analysis (Braun et al., 2006). With this reflexive thematic analysis, the intention was to identify patterns across the data, which would help to better tell a story about the preferences and the quest of determining which data representation model was labelled as the more efficient model, by reminiscing the experiences the participants had while interacting with the respective representational models.

The reflexive thematic analysis was conducted by undergoing through the following six respective phases, which will be explained in continuation:

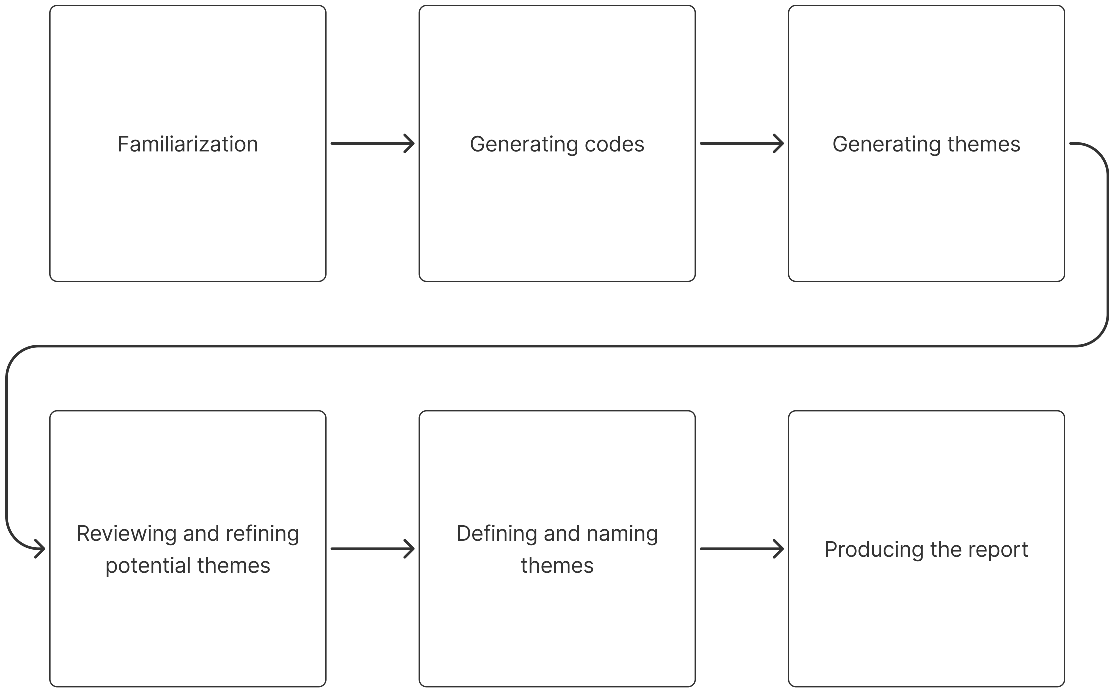

Figure 70: The process of doing reflexive thematic analysis

Familiarisation:

Prior to the start of the familiarisation phase, the interviews were audio recorded and then transcribed by using Otter AI, which required additional re-listening in order to sort out the transcripts and have them ready for data analysis. The correction of the interviews transcribed with the software was helpful in reinforcing initial opinions about the dataset, onto which to furtherly generate some initial familiarisation notes.

Given that all aspects of the data collection were carried by myself, starting with the generating of the questions themselves for the semi-structured interviews, to carrying the face-to-face interviews and engaging with the dataset while transcribing the said interviews, I was quite familiar with the gathered data. Conducting the interviews was a process that let me engage with the participants in an in-depth manner and gather an understanding about their respective stories, so I felt immersed in the data from the very beginning, although the additional re-listening to the recordings during the transcribing process, allowed me to digest the data in a more word-by-word basis, which made me notice points of interest that were not that obvious while having the role of asking questions and actively listening to the participants themselves.

Once transcribed, the scripts were re-read multiple times, where some notes could be crafted as a response to the data, such as things of potential interest, ideas that implicate for further exploration during the next phase, as well as personal reflection holding the responses to the data encountered, based on what was familiar, what was unfamiliar or surprising, and the why behind it. For me it was also important to not be quick to identify patterns in this familiarisation phase, as I wanted to read the data as data, without trying to identify trends, but more to carry the role of observer. That being said, numerous notes were created, and the following ones are pointed out as an example:

After participants expressed their overall experience and what they liked or disliked about both representation models, which was tackled with the interview opener, it seems as they already define their preferred representational model, hence it is their obvious choice when facing the further questions that deal with making a comparison between the pixels and the third dimension in order to choose one as a 'winner' in the corresponding circumstances.

It was interesting that the same parameter that the participants would point out as the why behind why they would put one representational model before the other, would actually be the same parameter to resurface when discussing why they would find the certain data representation model more engaging, more interesting, or would help them face their personal data and enter the mode of reflection more easily.

The participants generally found the physicalization of their personal data to be more engaging, motivating and reflexive than the traditional data visualisation on a screen. The physical model provided a novel and interesting experience for the participants, and they appreciated the ability to interact with their data easily and without distractions, because of the ability of the physical models to blend seamlessly into their living spaces.

One participant noted how they felt how they met the physicalization with a feeling of 'exaggerated data', as they couldn't sense much of the difference between the step data alongside the tracked days within the visualisation, as they wouldn't necessarily feel a lot of difference while observing data on their screen.

Something that is worth mentioning is that one participant found how the physicalization provides more simplified experience and it narrows down the data on 'good' and 'bad', meaning it was visible through the height of the corresponding bars in correlation to the bar representing their step goal whether they did good or bad in terms of reaching their step goal, while noting how for them numbers don't meet a lot.

Similarly, other participants felt that they preferred the more abstract representation which the physicalization showcased.

It was interesting to understand that both visualisation and physicalization were met with clear understanding from the participants' side, as for most of them, the physicalization was something new and never experienced before, which meant that the visualisation was converted in the physical space effectively. Moreover, the participants envisioned future use of physicalizations that are more artistic and personalised, as based on their current experience, that the comparative physical artefact is the better choice.

When defining favourites, it is interesting to note that the participants didn't express concern with the manual nature of the updated data on the physicalizations, which could have been considered as a concern. The participants approached the physicalization as it was automatically updated and based their judgement on this scenario. Moreover, the participants appreciated the dynamic nature of the physicalization, and found it to be visually appealing and engaging.

This selection of notes includes personal reflection that tackles what the familiarity with data reminded me of, as well as what the data made me think about at a certain moment, and what I could notice about the participants, in the way how they enclose their experiences through their observations. The notes themselves were created less systematically, which leads us to the next phase, that deals with the systematic nature expressed through the process of coding.

Coding:

After getting familiar with the dataset, the next step follows the coding of the transcribed interviews. As a result, codes are generated, represented through their labels. The so-called codes are used to capture what is analytically interesting about the data. When thinking about what could constitute as code, I was dealing with pieces of information that could be potentially useful to answer the imposed research question in mind, as well as generating meaningful codes that capture the key ideas and concepts. It was important to understand whether the clusters of codes have a central idea that drives them together, and whether the generated themes consist and are supported by enough meaningful data.

This required going through the transcribed material by zooming in, line by line, and paying attention to every part of the data. In doing so, it was important to identify both representational samples, from the likes of semantic codes, that are sticking close to the explicit understanding which the participants verbalised in terms of their own experience, as well as trying to produce latent codes, that look below the surface level meaning of what the participants had expressed.

The process of coding can be explained as being a rather lengthy and slow one, as it was required to re-read the transcripts in order to understand if there is something that was overlooked, which was also discussed with the supervisor of the process. With a little below 11000 words, it was quite lengthy to identify all the interesting codes. While generating the codes, I was concerned with generating codes that are brief, yet offer sufficient detail, as the idea of properly generating codes relies on generating the ones that can be perceived as standalone pieces of information, which can inform meaning (Braun et al., 2012).

This was done by highlighting relevant data, such as phrases, sentences, or paragraphs, that stand out as relevant or interesting, while staying close to the data. At the same time, it was important to be overinclusive, as to end the phase of coding with a list of codes and all the data that is relevant and connected to each of the codes. In this way, any excessive code could be discarded during the next phase. In order to generate the said list of codes, I found it useful to connect the corresponding code to the piece of information of the actual dataset, from where it was deducted, and include notes that will elaborate more depth and be useful to cluster the codes and reveal potential themes behind it. Over 110 codes were identified.

Examples are as follows:

DATA ITEM	CODE	REFLEXIVE NOTE
P1: "I forgot that I have it [the visualization]. And it started to not get useful."	Forgetfulness as a barrier	The participant shared the observation that they tend to forget about the phone-based visualization, suggesting a barrier to engagement, which is not present with the physicalization.
P1: "...like I enter the room, I see this [the physicalization], and I see my data... and I can't avoid seeing it."	Embodiment of data in the environment	The participant shared the observation that since the physicalization allows their data to be embodied and present in their environment, it makes it more salient and difficult to ignore.
P2: "And then once you leave your phone, it's not visible anymore, I guess."	The limitations of digital visibility	The participant shared the observation that the data is no longer visible once they leave their phone, which suggests a potential drawback of digital interfaces, whereas the physicalization provides a certain level of persistent physical presence.

Table 4: Examples of generated codes with corresponding label and reflexive note

Having the coding finalised, the next step encountered generating initial themes from the codes, in a manner that seeks to collate codes that deal with similar connotations. In this way, codes were combined to form a theme itself, which tackles the commonality between what the participants had expressed.

Generating initial themes:

In this process of coming up with initial themes, the corresponding reflexive notes accompanying each of the code was vital. It served as a reminder to find recurring patterns through related codes. In this step, certain codes were discarded, as they were more of a standalone observation and were put in a miscellaneous category.

Some ideas about what can constitute a theme were let go as it was important to remain open and to not become too fixated on limited ways of seeing the data. Similarly to the observation upon the familiarisation notes, it could be noticed how when asked to compare the both representational models, the participants would be eager to disclose more information about the model that they preferred, in a manner that emphasises on why they found that specific model to perform better, as opposed to the other.

In this step, after blending themes and trying to emphasise on their connection, an initial connection from the initially developed themes is formed, emphasising on key ideas and their relations, from where a further refining is required in order to structure the themes better, understand the sub-themes and produce thematic map. The initial connection stresses on the contrasting connotations that could be learned from the experiences of the participants, as seen in the following map:

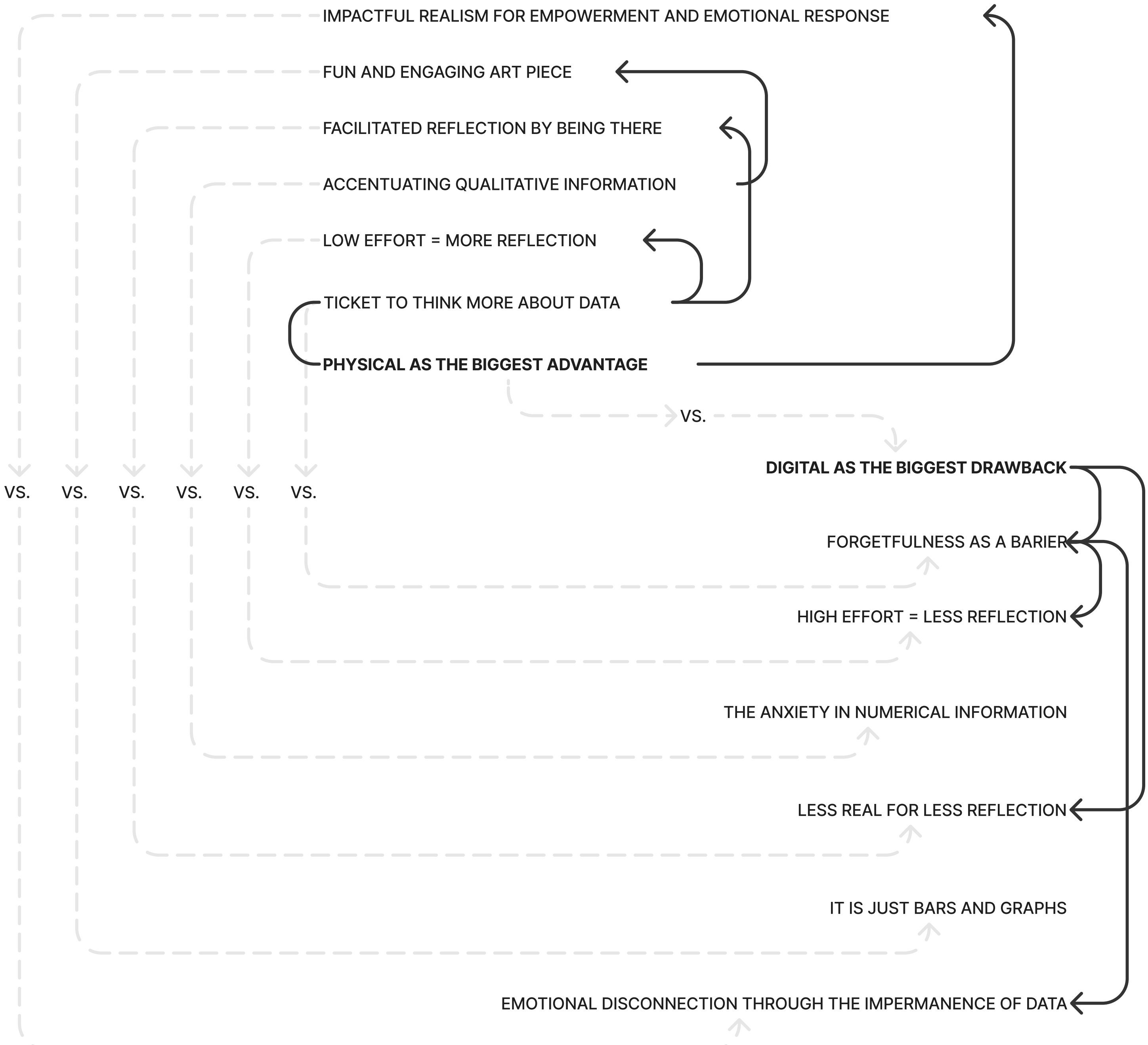

Figure 71: Generating initial themes

Reviewing and refining potential themes:

In the next step, the initially generated themes were reviewed, in order to apply another iteration in this theme generation journey, by staying close to the extracts of data.

Namely, the themes could be categorised depending on the topic of which the participants shared their experience, such as on the topic of eliciting reflection, motivation and acknowledgment of their data, among the others. It was important, for the sake of the comparative study, to generate themes that would form a contrasting story one to another, in a way that certain codes hold expressions about one representational model, whereas other codes elaborate about the second. It was a lengthy process to understand how to overcome the overlapping connotations, in which categorising the themes was found usable. It was important to handle the manner in an iterative process and with time dedicated to process the generated themes.

This included stepping from the data and returning to it. Moreover, two distinctive themes could be proclaimed as overarching ones, such as generalising the experience with the two representational models, and gaining understanding on which was crucial in the choice of the participants to be more efficient model of representing their personal data, which required additional refinement in order to reach one theme with comparative connotation. This process made use of a preliminary map, in order to correlate the different themes and uncover patterns in order to make them connected.

The map is as follows:

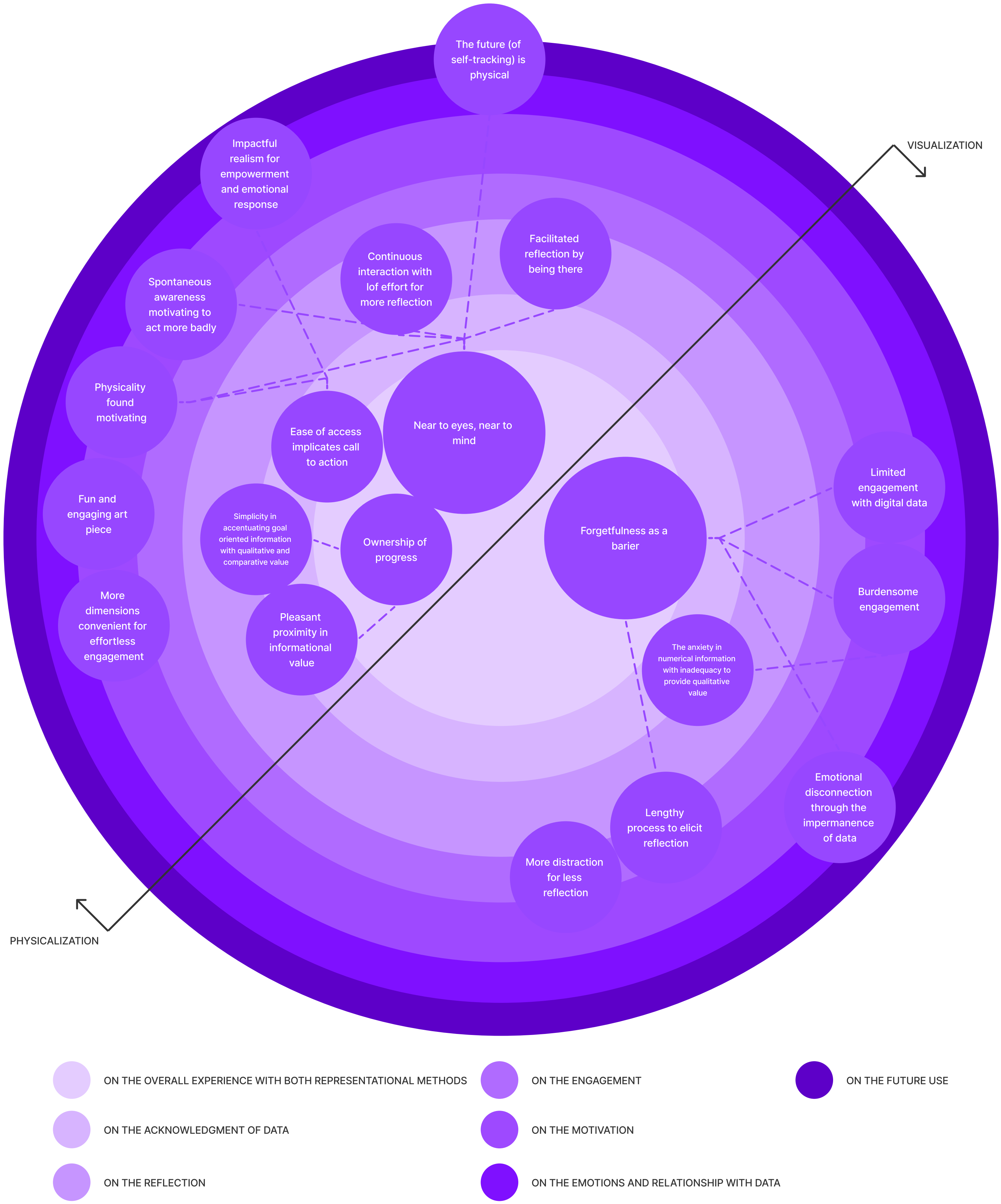

Figure 72: Refined map of themes

Producing the report:

Finally, after understanding the connection between the themes and the hierarchical and relational aspects between them, it was a necessity to define the final themes and name them. Through the refinement step, areas of overlap were better distinguishable, hence it was important to understand in which way the data could be described, through defining and articulating narrative. The names were developed once the clear differences between themes was finalised, by keeping the nomenclature close to some labels of the codes, in order to emphasise the link between the labels of the themes and the dataset itself.

When the themes were definite, the next step involved writing about each of the themes in a communicative manner that elaborates on the relevant findings and illustrates the corresponding ideas through the use of multiple quotes from the participants. It was important to retrospectively revisit the previous steps in this preparation of thematic analysis in order to assure that the ideas elaborated on with the data illustrate the research aims. Furthermore, it was important to select vivid and compelling examples of data to illustrate each theme, demonstrate patterning, and to be sure to select extracts from different participants.

The finalised thematic map and the corresponding findings are elaborated on in the following chapter.

Chapter 9: Conclusions

9.1. Findings

In this chapter we present the findings of the data analysis from the data collected during the user study, the post-study questionnaire and the post-study semi-structured interview, respectively.

As beforementioned, the findings from the post-study questionnaire are based on quantifying respective parameters and qualitative from the likes of assigning adjectives within the experience the participants had with the both respective data representational models of their own personal data.

Namely, the graphs are as follows, for each participant respectively:

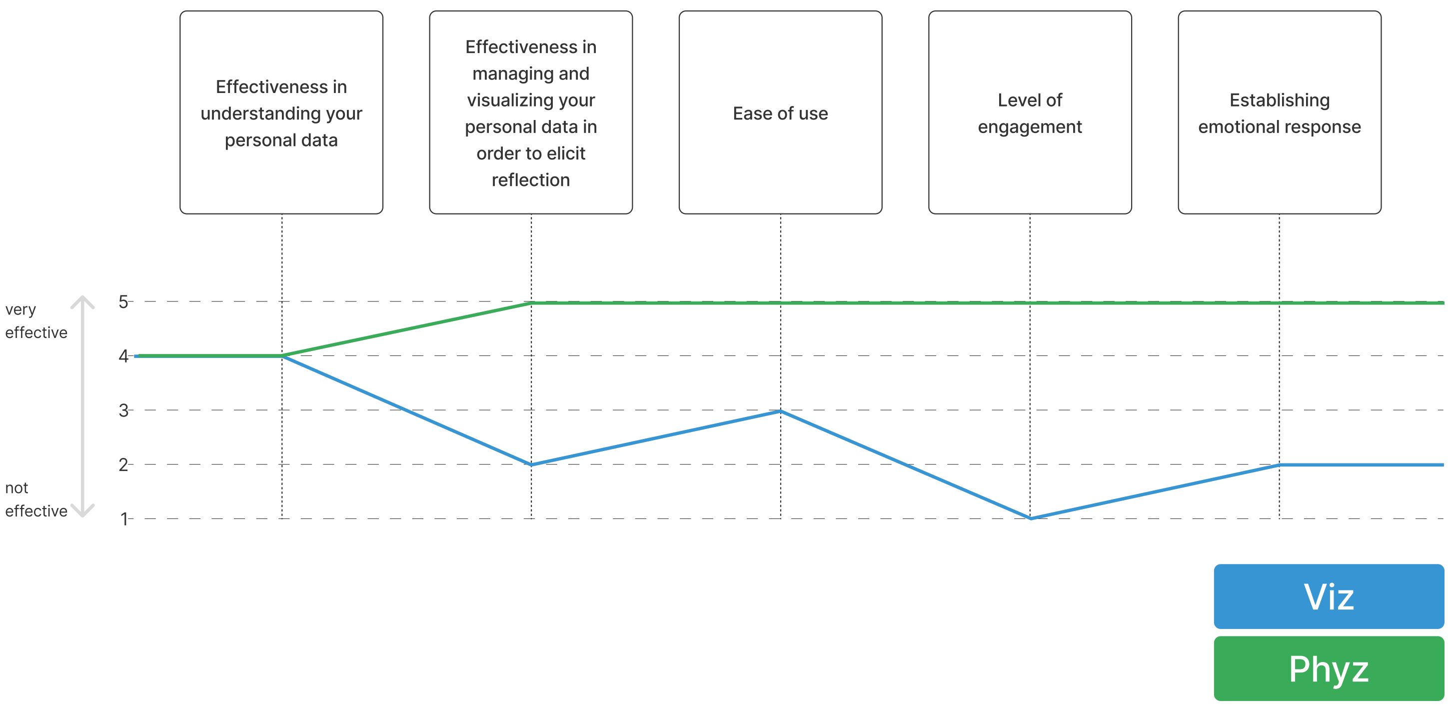

Figure 73: Results from participant number one

The first participant found the data physicalization to be more efficient and effective while quantifying their experience in correlation to the specific parameters asked for, based on the experience with the two representational models. There is a noticeable gap in terms of which representational model helped them to elicit self-reflection, was more engaging and effective in establishing emotional response towards their own personal data, where the data visualization underperforms. The data physicalization was met with a level of understanding that doesn't interfere with the abstract manner in which it communicates the information, even though they haven't used physicalizations before.

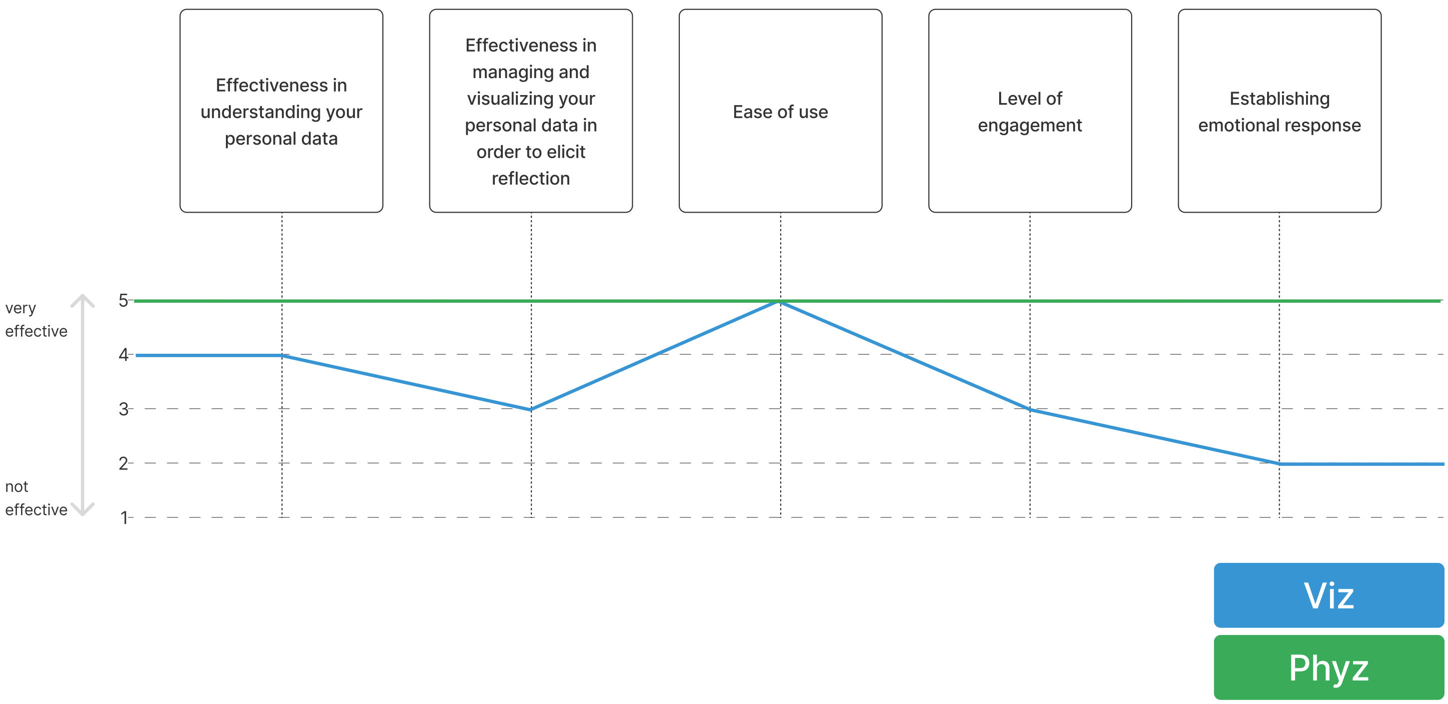

Figure 74: Results from participant number two

For the second participant, the data physicalization was met to be highly effective in all the questioned areas. The data visualization was found effective in communicating the data to the user, although the data physicalization performed better in eliciting self-reflection, was found more engaging and helped to establish emotional response to their own personal data. The data physicalization was met on similar level in terms of communicating the information to the user, and it was as easy to use as the visualization, which means the abstract side of the physicalization was met with ease, given that they didn't had experience with interacting with data physicalization prior to the study.

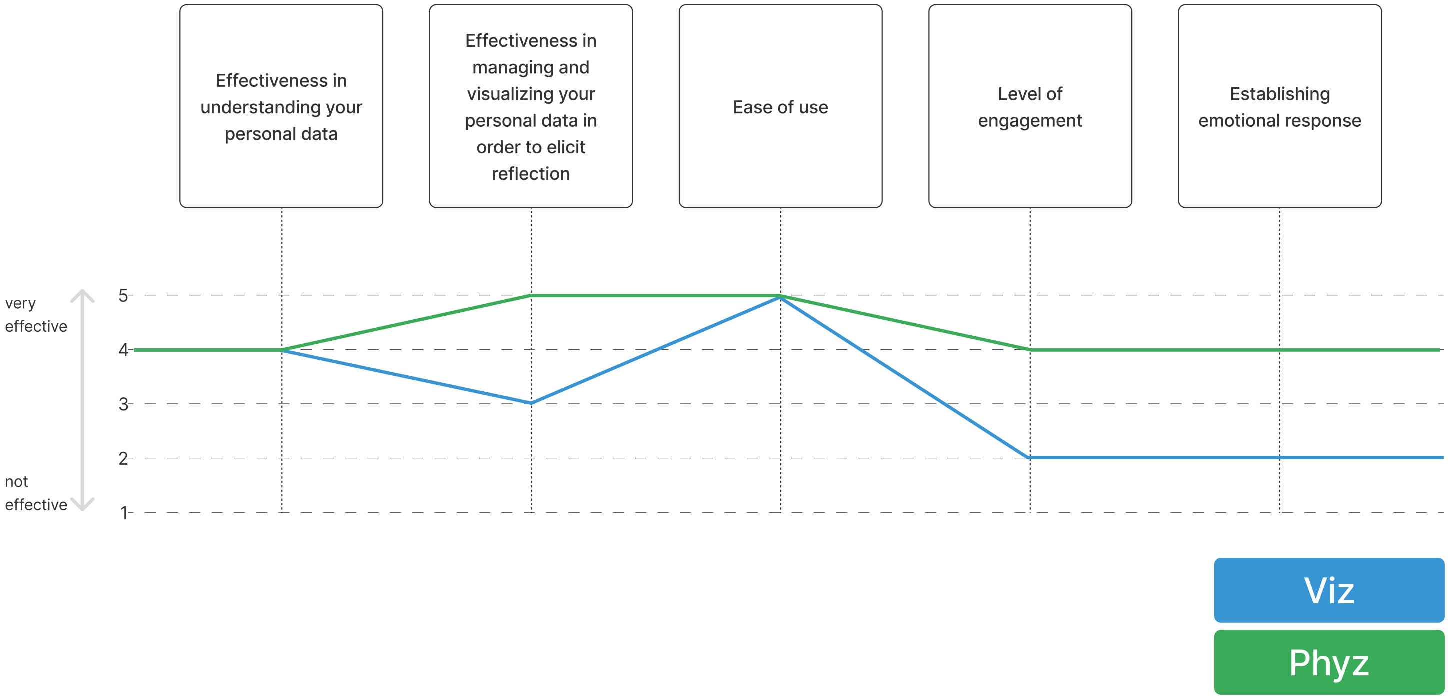

Figure 75: Results from participant number three

For the third participant, the data physicalization was the preffered model when thinking about which experience helped them to elicit self-reflection more effectively, as well as they found the physicalization more engaging and helped them to establish emotional response to their own personal data. The data physicalization was met with similar level of understanding of the communicated data and ease of use with the data visualization, which means that they didn't encounter any problem with the physicalization in terms of how the data is communicated, in correlation to its abstractness, even though they haven't been introduced previously with data physicalizations. They found the data visualization to lack in helping them to establish emotional connection to their personal information, as well as finding it overall less effective in their level of engagement.

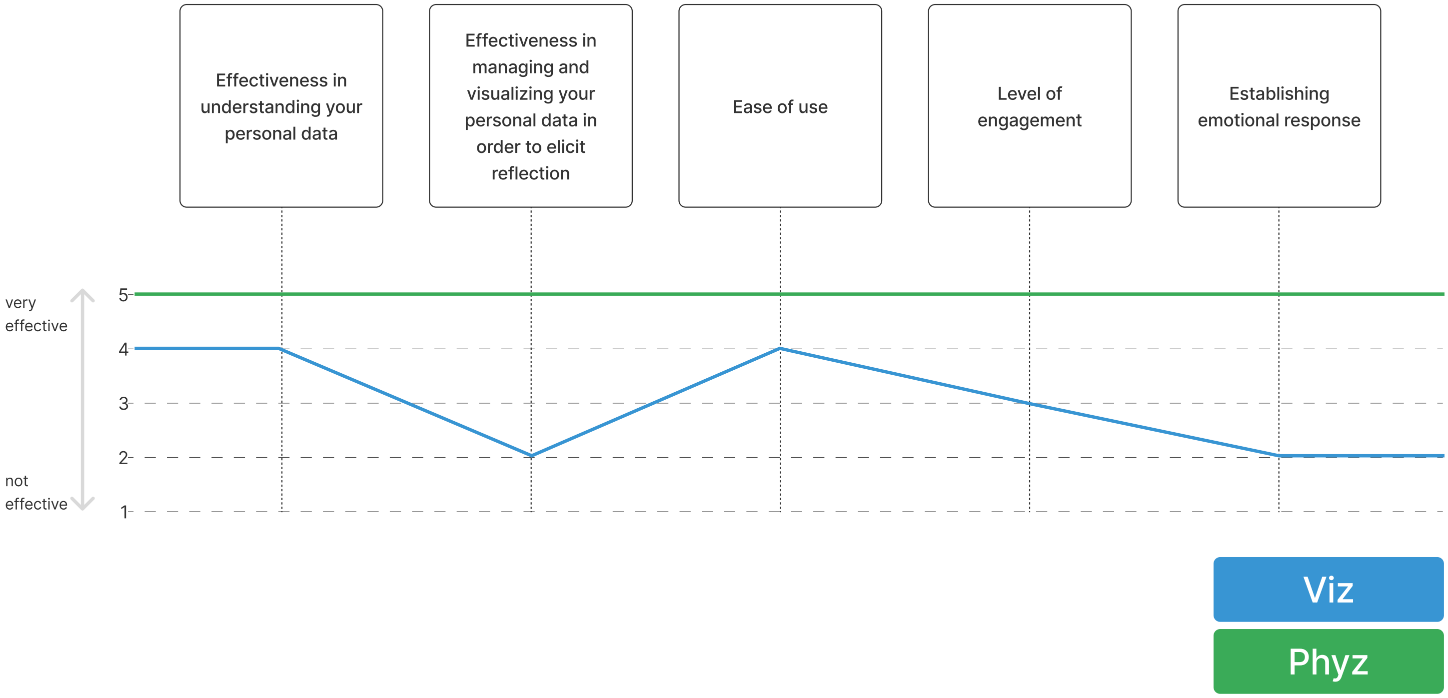

Figure 76: Results from participant number four

For the fourth participant, the data physicalization was marked with highest scores across the respective questioned parameters. Moreover, the data physicalization was seen as easy to comprehend and effective in communicating their personal data on a similar level with the data visualization, although they're novice users when it comes to physicalizing data. The data physicalization was found to be more effective in eliciting self-reflection, they felt more engaged with this data representation model, and overall found that the data physicalization helped them to establish emotional response to their own personal data. The data visualization was marked as less effective across all parameters, with noticeable difference in performance in terms of eliciting self-reflection and establish emotional response to their personal information.

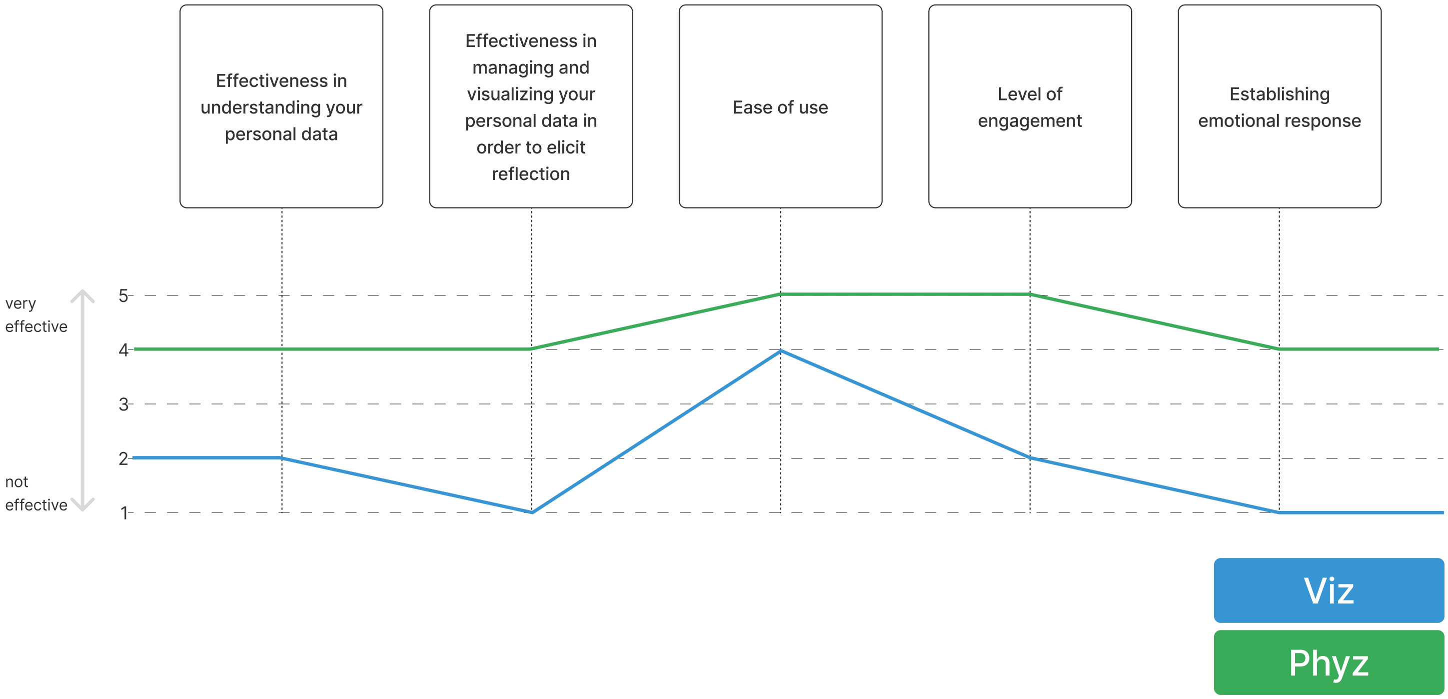

Figure 77: Results from participant number five

For the fifth participant, the data physicalization was more effective when understanding their own personal information, as well across the other questioned parameters, such as effectiveness in eliciting self-reflection, ease of use, level of engagement, and establishing emotional response. This novel data representation model was met on a similar level of ease of use as the data visualization, to which they were well acustomed previously. They expressed their opinion of finding the data visualization the least effective when it comes to eliciting self-reflection and establishing emotional response to their own personal data.

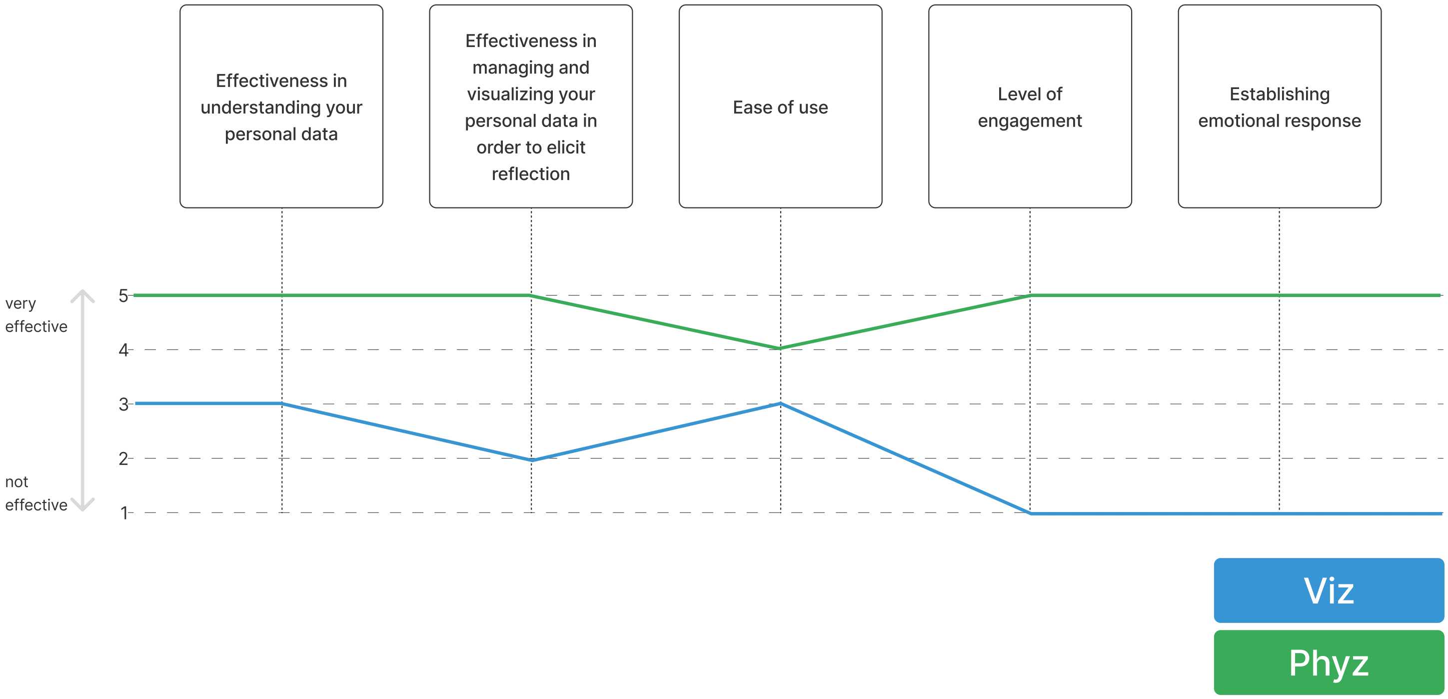

Figure 78: Results from participant number six

For the sixth participant, the data physicalization tends to be the preferred data representational model. Namely, they found the data physicalization to be very effective across all questioned parameters, such as finding the data physicalization more effective in gaining understanding about their own personal information, eliciting self-reflection, and establishing emotional response to their own personal data. Moreover, the data visualization underperformed to elicit self-reflection, establishing emotional response, as well as being the data representation model they found to be very ineffective when it comes to their level of engagement.

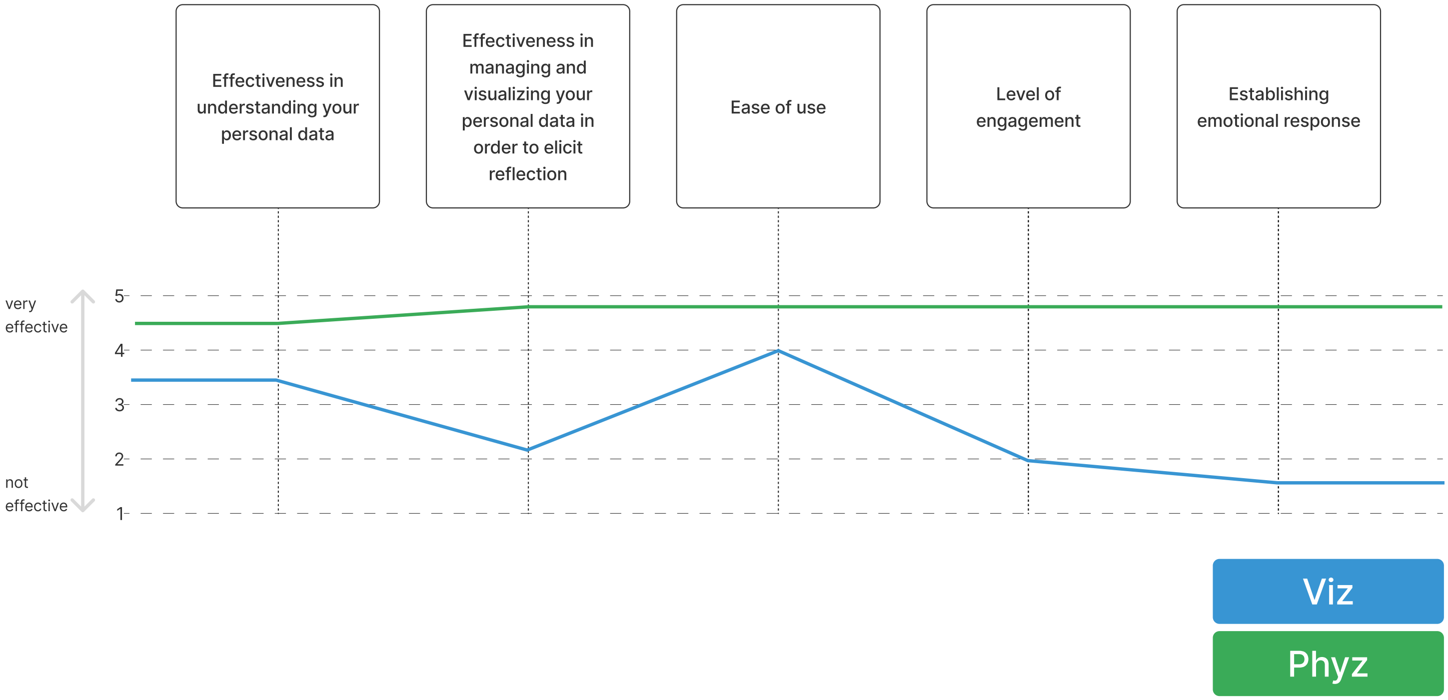

Figure 79: Collated results from the six participants

Summarizing the marks given from the six participants, on this cumulative graph, we can understand how the data physicalization positioned itself on top, with performing better than its visual counterpart across all questioned parameters, such as gaining understanding about their own personal infromation, eliciting self-reflection, and establishing emotional response to their own personal data. When it comes to the parameters from the likes of ease of use, the data physicalization and the data visualization were met on a similar level, respectively, which is a good indicator, since the data physicalization was a novelty to all six participants in the user study.

With this graph, the quantifying half of the post-study questionnaire are wrapped. In continuation, we showcase in illustrative manner which adjectives each participant associated about their experience with the both respective models used in the user study, as well as a summarization of their associations.

Figure 80: Associated adjectives from participant number one

For the first participant, the data physicalization of their personal data was able to produce experience that can be associated mostly with positive connotation, such as they found their experience to be rewarding, interesting, fun, helpful, engaging and efficient, amongst the others.

On the other hand, the data visualization was met as disappointing and unsatisfying, which contrasts the beforementioned experience with the physicalization.

Figure 81: Associated ajdectives from participant number two

When associating adjectives that best describe the experience the participant had with the data physicalization of their personal information, it can be said that the physicalization overall performed well, since it has been associated as exciting, satisfying, stimulating and helpful.

The second participant found the data visualization less efficient and rather unsatisfying, without pointing out adjectives of a more admirable connotation.

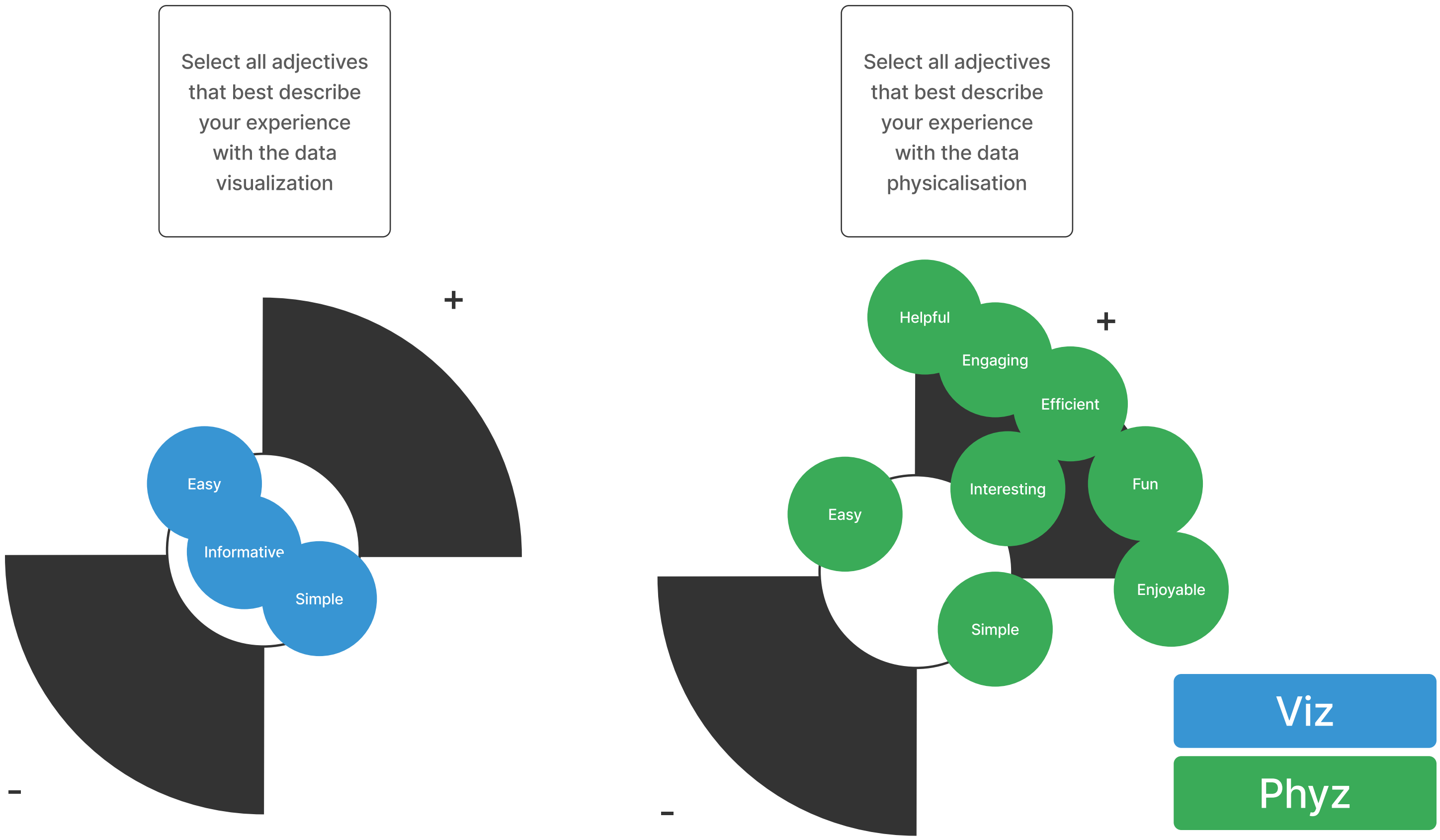

Figure 82: Associated adjectives from participant number three

While associating adjectives to best describe the experience the third participant had with the both data representation models respectively, the data physicalization was linked to advantageous adjectives, such as helpful, engaging, efficient, and interesting, amongst the others.

The data visualization was found easy and simple, likewise for the data physicalization, which confirms that both representation models were on a similar level in terms of gaining understanding of the manner in which the data is communicated.

Figure 83: Associated ajdectives from participant number four

For the fourth participant, the experiences with both data representational models share contrasting connotations. Namely, the participant found the data physicalization to be fun and efficient, whereas the data visualization left the impression of experience that is boring and inefficient.

Moreover, the adjectives that furtherly describe the experience that the participant had with the data physicalization of their own personal information are stimulating, engaging, and enjoyable.

Figure 84: Associated adjectives from participant number five

When asked to select all adjectives that best describe the experience that the fifth participant had with both representational models of their own personal data, the physicalization was met with a more competent note, linking it to the adjectives from the likes of exciting, rewarding, efficient, engaging, and satisfying, amongst the others.

The constrasting adjectives were found fitting when describing the participant's experience with the data visualization, such as boring, challenging, inefficient, and unsatisfying, amongst the others.

Figure 85: Associated ajdectives from participant number six

The sixth participant found the experience with the data physicalization best described with the following adjectives: exciting, satisfying, interesting, rewarding, and engaging, amongst the others.

On the contrary, the participant described the experience with the data visualization as inefficient, boring, and unsatisfying.

Both representation models were met on a same level in terms of ease of use and simplicity, which means the novelty and abstractness that the data physicalization brought to them wasn't discouraging.

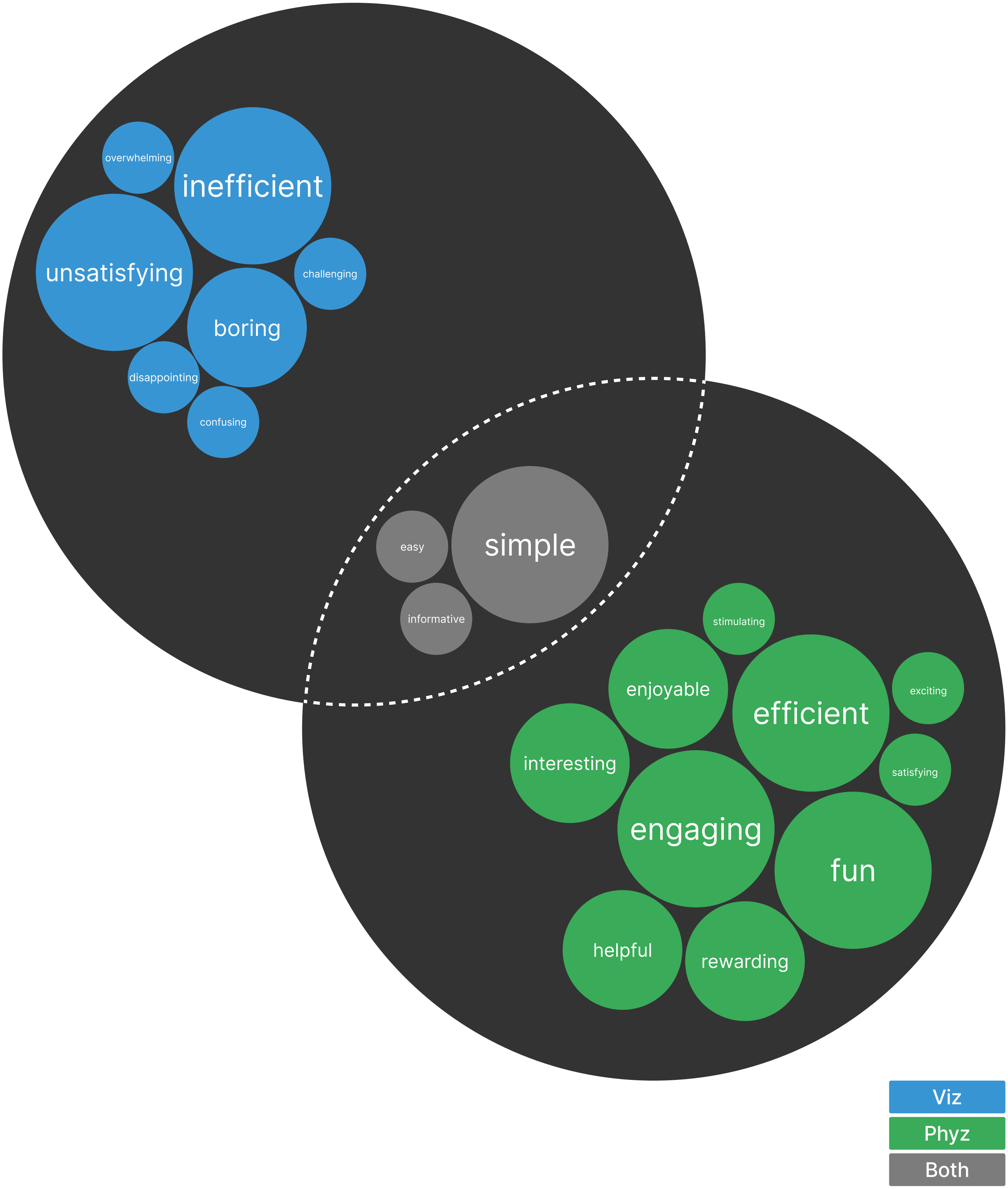

Figure 86: Collated associated adjectives from the six participants

Following the quantified graphs, we showcase the mapping of the selected adjectives that correspond to the experience that the participants had with the both respective data representation models, in a manner that stresses the most frequently used adjectives for each representational method, in a Venn-diagram manner.

Summarizing the associated adjectives from the six participants, on this cumulative map, we can understand how the data physicalization was associated with mostly admirable connotation, such as being the representational model of data that helped the participants achieve mostly efficient, engaging, fun, interesting, helpful, and enjoyable experience.

On the other hand, the data visualization was met with quite the contrary negative connotation, by providing experience that can be best described as inefficient, unsatisfying, boring, overwhelming, challenging, disappointing, and confusing.

In this way, we establish the contrasting comparative experience the participants encountered while interacting with the both representation models of their own personal data, while what the models shared in common is the ability to portray simple, easy, and informative experience, which shows how the participants grasped the abstract communication nature of the physicalization without encountering problems, as the abstractness was as clear as seeing numerical values.

The comparative graphs and the associated adjectives reveal the data physicalization to be the preferred model for acknowledging, managing personal data, moreover, eliciting self-reflection, providing more engaging experience, and establishing emotional response to the participant's own personal information.

They serve straight-forward findings through illustrative purposes, while in continuation, with the reflexive thematic analysis of the semi-structured interviews as a dataset, we will delve deeper to understand the meaning behind finding the data physicalization more efficient, in a more elaborative manner, which complements the post-study questionnaire's findings.

The data analysis was helpful to generate the development of overarching theme, which emphasises on key ideas about the performance of the two respective representational models of data, which are intertwined and recalled upon in the subsequent (main) themes and sub-themes, as shown in the following table:

Overarching theme: Close to eyes, close to mind compared with the forgetfulness as a barrier				
Theme 1: Pleasant proximity in informational value against the anxiety in numerical information	Theme 2: Facilitated reflection by being there as opposed to 'take a look, and, move on'	Theme 3: Ease of access implicates call to action in comparison with explicit actions through burdensome engagement	Theme 4: Impactful realism for empowerment and emotional response in comparison to the emotional disconnection through the impermanence of data	Theme 5: The future (of self-tracking) is physical
Sub-theme 1: Simplicity in accentuating goal oriented information with qualitative and comparative value in comparison with the inadequacy of numerical values	Sub-theme 1: Continuous interaction with low effort for more reflection in comparison to explicit interaction with forgetfulness	Sub-theme 1: More dimensions convenient for effortless engagement		
Sub-theme 2: Ownership of progress		Sub-theme 2: Physicality and spontaneous awareness motivating to act more badly		

Table 5: Themes generated through reflexive thematic analysis

Overarching theme: Close to eyes, close to mind compared with the forgetfulness as a barrier

This overarching theme captures the moral of the story of the whole data set, as once the main patterns were identified, it was clear how participants found one particular representational model of their data - the physicalization itself, to overperform its visual counterpart, mainly due to its nature to represent their personal data embodied in their own respective environments.

They found the physicalization to be more effective mainly due to its physicality, which resulted for the physicalization to be their go-to representational model of data when talking about the topics of data acknowledgement, data processing, eliciting self-reflection, the topics of motivation and engagement, as well as establishing emotional response to their own personal data, and envisioning future use.

Similarly, they found the screen barrier to be less effective, greatly due meeting its biggest disadvantage to be its digital nature, which is noticeable and spoken loudly about in all aforementioned topics of participants' experiences.

To elaborate more on this comparative matter, we can take a look at what the participants had to say about their experience interacting with this physical representation of their own personal data. The sense of embodiment of data in the environment was of an important advantage, as it was found as a great factor to facilitate to the self-reflection state of mind, by having this model that allows their data to be embodied and present in their environment, which makes the physicalization salient and difficult to ignore: "... like I enter the room, I see this [the physicalization], and I see my data... and I can't avoid seeing it" (P1), which was met with attentional bias and perceptual experience in the way how the physicalization captures the participants attention and makes it more engaging, as opposed to the static image on a phone screen. The importance of the physical presence was furtherly strengthened with recognizing the benefit in having physicalized data, which is for it to be always present and suggests a deeper appreciation for the role of physical artefacts in shaping attention and behaviour: "...the difference, like, physicalization of that data is seeing it always being there present in your physical space, rather than on your phone" (P2). On a similar note, there is the observation that emphasises the role of materiality in the way people perceive and engage with data. The physicalization of data makes it more tangible, real, and perceptible to the person, which can enhance their engagement and understanding of it: “If you translate [the visualisation] into a real thing that you can touch, or you can actually see, it’s more real to me” (P3). The physicality was met with a way to enhance the participants active perception and engagement, as the physicalized data is more visible and impossible to ignore, which can make people more aware and conscious of it. There is a certain degree of persistence or continuity that the participants could associate with the physicalization, noting that the physicalization is always on and does not require explicit actions to be turned on like a screen, which suggests a higher level of permanence associated with the physicalization: “...having the prototype itself in a physical way and always on, like, I mean, I don’t have to turn it on. I mean, it’s not a screen, so it’s not turning off.”

On the other hand, we can elaborate on the experiences the participants had with the visualisation. For starters, the visualisation was met with forgetfulness as a barrier, as the participants noted how they tend to forget about the phone-based visualisation, suggesting a barrier to engagement, which is not present with the physicalization: “I forgot that I have it [the visualisation]. And it started to not get useful... With visualisation on the phone... it’s like I can forget about [it]” (P1). In another effort to emphasise on what made the visualisation underperform on the topics about which the participants were asked to share their opinions, it was noted the limitations of digital visibility. Moreover, the data is no longer visible once the participants leave their phone, which suggests this potential drawback of digital interfaces, whereas the physicalization provides a certain level of persistent physical presence: “And then once you leave your phone, it’s not visible anymore, I guess” (P2). In correlation to this, the limitations of engagement with digital data were raised, as the data its not that visible and the participants wouldn’t necessarily bother to check it: “...it’s [the physicalization] not the same as the digital data, because when I think about that [the steps], okay, today, I did a few steps, or I didn’t even go out, but I will never open the app” (P3). The recurring lack of engagement was expressed in the observation how the act of seeing the visualisation wouldn’t prompt the participants to take any action: “...I’m actually not engaged at all, when viewing the charts of my steps, like it’s just, it’s just there [the visualisation]. Like it’s just, I just see the graph. And I’m like, okay, it doesn’t prompt me to do anything else” (P6), which is opposed to the realisations about the physicalization, that was found motivating by just being there.

The following narrative was constructed following in detail the experiences the participants had in terms of acknowledging their own personal data. The main theme emphasises on the most pivotal idea when talking about forming understanding of their own self-tracked data, while the sub-themes illustrate additional interesting points of interest.

Theme 1: Pleasant proximity in informational value against the anxiety in numerical information

While illustrating their respective experience with acknowledging their own personal data through the both representation models, participants shared contrasting opinions in terms of the abstractness of the physicalization compared to the concreteness of the visualisation. Namely, the physicalization was met with generating a less pressurised experience, given its nature to blur the data. This proximity was met as pleasant and reducing pressure, due to the absence of exact numbers, which is contrary to the way the visualisation communicates the same information: "As I look at the physicalization, you have like a proximity of how much you're doing [steps], and it's kind of, in a way, it's kind of nice, because it's, it's not giving you a lot of pressure in the way yeah, like, the visualisation does" (P4). This pleasant experience was linked to be able of cultivating a sense of mindfulness, while bringing awareness to the participants about their personal data: "So definitely the physical way or the physicalization of my data made me more mindful and acknowledge it [the personal data]" (P6), while stressing on how at first there were initial doubts about questioning the effectiveness of the physicalization in displaying detailed information about the step count, which were debunked by coming to appreciate the simplicity of the physicalization, and the fact that it didn't overwhelm with too much information, but rather with goal-oriented and qualitative nature, which will be discussed in more details while tackling the next sub-theme: "At first, I was like, okay, it's another type of visualisation, but it's not telling me the exact number [of the steps]. But then I realised that we have an app for that... At the end of the day, I changed my mind. And I was like, I actually like it this way. It's more minimal" (P6).

Opposed to the pleasant experience in the abstractness, contrasting connotation was met while interacting with the visualisation. The participants shared how they felt pressured by the numerical nature of the data visualisation: "...it's [the physicalization] not giving you a lot of pressure in the way yeah, like, the visualisation does [because of the number]" (P4). A certain degree of anxiety and numerical data was expressed, about feeling anxious when presented with exact numbers of step count: "But it will even make me more anxious, probably knowing the numbers, rather than just seeing the bars go up and down" (P6).

Sub-theme 1: Simplicity in accentuating goal oriented information with qualitative and comparative value in comparison with the inadequacy of numerical values

As a sub-theme in this topic, the following discussion complaints the (main) theme and stresses furtherly the differences in acknowledging the same personal data. The participants expressed how the physicalization communicated goal clarity which was met with higher awareness of their data in this goal-oriented self-tracking, which affected their engagement with their personal data, whereas the visualisation was met with lower awareness as the goal is less evident: "And I think it's more evident in this one [the physicalization]. Because here, I have the goal. And I know that this is the goal... But instead, on the phone, I think the goal is on a dotted line. And it's not so evident... And then I checked the visualisation on the phone, and I saw it. But before I didn't know I had the goal" (P1). The participants felt that they are more interested in knowing whether they are on track to achieve their goal, rather than knowing the exact number of steps taken, which suggests a goal-oriented motivation: "Well, I can think of how like the prototype itself right now might not tell me the precise number [of steps] for each day. But I don't need to know, anyway. I mean, if I want to know, like, I just log into the app. But overall, I want to know, like, if I'm on track, or if I achieved my goal, basically" (P6). This correlates also to the next sub-theme, where the participants' experiences about feeling a better ownership of their progress is elaborated on in more detail.

The qualitative and comparative value of the information communicated through the physicalization was met more efficiently, contrary to the inadequacy of the visualisation to provide qualitative value. In this manner, the participants expressed their interest in comparing data rather than knowing the exact number of steps taken, in which the physicalization was found more effective, in facilitating comparisons between different days: "I'm interested more in comparing the data, which I think is more effective than the physical one... for me, just to compare [the data] is enough" (P5), "While here [in the physicalization], it's different, so this comparison between bars maybe is what makes the experience more engaging" (P5).

On the other hand, the numerical nature of the visualisation was met to underperform in providing qualitative value, as the participants felt they aren't concerned with knowing the exact number of steps, and feel how the visualisation fails to provide any explanations or understanding of the data beyond the exact numerical value, as they are inclined to know information of more qualitative nature, like whether the amount is good or bad: "And actually, at the end of the day, I'm not really interested [to know] if it was 1000, 2000 or 3000 [steps]... for me, the number actually doesn't mean anything... like you can't understand whether it's good or bad. That's it" (P5). Subsequently to the qualitative nature, the participants felt how they had better ownership of their progress through the likes of the physicalization, which is the next sub-theme.

Sub-theme 2: Ownership of progress

On par with the qualitative manner of the information communicated from the physicalization, which the participants met with appreciation, another interesting point can be stressed when talking about processing their own personal data, as in the case of the physicalization, they felt to have a better ownership of their progress. Namely, they expressed on the importance of emphasising the change in the data, in which they found the dynamic nature of the physicalization to allow for the changes in data to be more noticeable and potentially more impactful, as it also allows for better ownership of their progress, contrary to the changes in visualisation, which are not that evident: ...it's interesting, because [the physicalization] every day is changing. So every day I will see the difference as it is not something that is static. So something with movement is more catching the attention" (P1). Moreover, the physicalization was found to place a greater emphasis on the progress made, particularly with regards to steps taken, compared to the visual representation in the app, as well as to be able to communicate more clarity and emphasis on small or big number of steps, without having the specific number: "...it [the physicalization] would give me a little bit more of reference and understanding of the progression in comparison to the visual representation" (P5), "...because I had such a big difference between the steps. It was clear that, okay, this is a small number, this is a big number of steps" (P2).

The step goal was found more encouraging in the physicalization, as well as feeling accountability to make some progression in the data, as the physicality served as a constant reminder and motivator to reach the step goal, through creating a sense of accountability: "...it makes the goal more attractive and makes me more motivated... every time I glanced at it; it's telling me: 'You got to go here [reach the step goal]. You got to stick to it" (P3). Similarly, the physicalization was met to provide a clearer representation of the progress and achievement in tracking steps, as it provides a clearer emphasis on what is a bigger amount of data compared to what is not, as well as how the data visualisation does not provide adequate feedback or a sense of accomplishment, whereas the physical representation allows for a greater sense of achievement: "...there is really a huge emphasis on the steps in the case of the physical one, with the bars there is really a huge emphasis on what is really a huge amount of steps and data and what is not... In the application, you couldn't just feel that you actually did good there" (P5). The ownership of progress and performance was highlighted through the continuous feedback on the physicalization, with expressing feeling of control: "So having it [the physicalization] on all the time, and seeing it [the data] change dynamically, all throughout the day, I think it's a very, I don't know, it's a very interesting thing to experience at the end of the day" (P6).

Theme 2: Facilitated reflection by being there as opposed to 'take a look, and, move on'

In continuation, this theme tackles the topic of reflection, by analysing the experiences the participants had in eliciting self-reflection through interacting with the both representational models of the same personal data.

Apropos to the label, to elaborate we can illustrate by sharing the experiences of the participants. Namely, the physicalization was met with increasing awareness and prompting the action of self-reflection, through making the participants to consider or think about their data and its meaning, finding it impossible to not reflect and think about their data once they see the physicalization, in their personal space: "...I think with this representation [the physicalization], it was more, I was more aware, and I was more prone to reflect over my data... this one the physicalization], I feel it makes me reflect a bit more, or more times, also, because if it is in the room, and I'm in the room, and I see it, and it's there, it's like impossible not to think about [the personal data]" (P1), "... [the physicalization] it was there, non-stop visible for me, in my personal space, so it kind of required my attention in that way" (P2), "Having eight physical bars definitely helped me to do more reflection" (P3).

The physicalization was seen as a helpful tool for reflecting on the participants' behaviour and progress towards their goal: "In terms of whether it [the physicalization] helps me to reflect on my data, I think yes... It helps me think more to think about my behaviour from the previous day and the goal I set for myself in the first place and how I'm achieving it on the day-to-day [basis]" (P3), emphasising on he fact that the physicalization is constantly present and visible in the environment: "...going back to the fact that the physicalization is always there" (P4), which made it altogether easier to reflect, because it simplifies the experience and requires fewer steps to access the data, which was found vital for reflection: "...it's easier to reflect with the physical one. Because it also simplifies the experience in general... I just gave a glimpse of it [the physicalization]. And I'm already ready to start reflecting on it" (P5). This prompts on the idea of ease of access and continuous interaction, which will be elaborated on in greater detail in the continuation. The act of self-reflection is easier with the physicalization, due to having the physical model always there: "... the physical model, it's just there. And it's just part of the physical world by being physical. And I can observe it. So, it's always there" (P6).

Contrary to the formed opinions about reflection and physicalization, the participants contrasted in their explanations on why the visualisation underperformed. For example, the participants shared how they found the visualisation to lack in eliciting a response from their side, which implicates that it is difficult to elicit reflection. While the statement 'take a look and think about it' is true for the physicalization, the statement 'take a look and move on' sounds appropriate for the visual counterpart: "...on the phone it's like it doesn't matter. On the phone, I see it. And nothing, I just take a look at it... So, I'm curious and just take a look and close it [the app] and move on" (P1). Another point of the visualisation, less convenient to reflect, is the digital essence, and the explicit interaction to reach it: "... it [the GUI] gives me notification that I'm doing good... And that's it, it doesn't give me anything until I enter it on my own" (P5), which hints on the next sub-theme where the meaning of interaction is furtherly tackled. Moreover, the visualisation was found to lack in eliciting response because of the connection to the digital distractions: "I would choose a physical model, also because it's kind of disconnected from the distraction of the smartphone world... it [the physicalization] makes me be more mindful about it [the personal data] without getting distracted by this virtual phone ambient" (P6), whereas the physicalization was met with mindfulness without distractions, which helped in establishing a habit of reflecting on personal data. With this we sense the observation how it is easier to elicit reflection by a representational model that is embodied in the respective environments and whose presence is noticeable and breaking the screen barrier, due to the materiality and the third dimension, opposed to a pixelated representational model on a screen, which is seen as a barrier.

Sub-theme 1: Continuous interaction with low effort for more reflection in comparison to explicit interaction with forgetfulness

As previously hinted, here we elaborate more on the mode of interaction, and tackle ideas from the likes of calm technology, ambient computing and non-obtrusive blending. The continuous interaction supported by the physicalization due to its inevitable presence was met with participants reflecting more, just because the physicalization would continuously communicate their data, and it was in their environment: "...I like the fact that I can visualise the data all the time, I'm more prone to reflect and it awakens my emotions" (P1). Here the theme of establishing emotional response with your own personal data is hinted at, which will be elaborated greatly in the next themes. The ability of the physicalization to promote continuous interaction with the data was pointed out as pivotal when self-reflecting, as the physicalization was always present and visible, making reflection possible throughout the day, as this perpetual reminder which supports passive interaction with low effort: "And that also makes this interaction possible throughout the days of the week... Yeah, it's kind of inevitable [to reflect] because you can't ignore it [the physicalization] ... like I pass by, and I see [the data]... Like, it's still there all the time. And I'm still interacting with that" (P5). This emphasises how the physicalization simplifies the reflection process and requires less effort than accessing the visualisation, which makes the physicalization more accessible and usable, contrary to the visualisation. For example, the visualisation was connected with explicit interaction and forgetfulness, as the participants shared how they couldn't elicit reflection easily with the visualisation, as they needed to take explicit action in order to reveal the data: "The visualisation, it just doesn't call so much attention. I have to remember to open it to reach solid data instead" (P1), which was described as a lengthy process to elicit reflection, contrary to the experience with the physicalization: "...I have, in order to reflect, to read the data, [for which] I have to enter the app, I have to do additional steps...” (P5). The requirement of doing explicit actions for the visualisation was found less effective in eliciting reflection.

The physicalization was connected to calm technology that raises awareness, as the physicalization was found efficient in catching the participants attention and promoting a deeper level of awareness of their own personal data: “So it’s in the background, but also trying to speak to you so you’re more aware... So, every time I look around, I see it” (P4). This observation can be connected to the non-obtrusive blending of the physicalization, through the likes of having the physicalization perceived as ambient computing and integrated with personal environment: “So, since it’s always available for me to see it [the physicalization] in a non-obtrusive way, because it blends into the space [where] I am... I would say it [the physicalization] is some sort of ambient computing stuff, like, it blends with me. And it blends with my environment” (P6). The participants shared the observation how interacting with the physicalization in a non-obtrusive way through a seamless and unobtrusive experience, in which the representational model of data blends in their environment, is important for eliciting self-reflection.

Theme 3: Ease of access implicates call to action in comparison with explicit actions through burdensome engagement

In a quest of forming a contrasting connotation between the two representational models, we can establish the connection between the ease of access supported from the physicalization, as it is always available and does not require any additional effort to use, opposed to the engagement with the visualisation, which is rather burdensome: “...in the UI, because you need to tap there, you have to take a little bit more time” (P5).

Namely, the participants found it convenient to access data through the physicalization as opposed to the digital format. Physicalized data can be easily accessible and allow for passive engagement where individuals can engage with it without any effort, as the participants don’t need to turn it on or access an app to use the physicalization, which is more convenient: “But [with the physicalization], I have things just placed in my home. I like, kind of, like passively receiving. So, I don’t need to open my phone and open the app, things like that” (P3), “The physical one [is more engaging]. Because, as I mentioned before, like, it’s something that I don’t have to turn on every time, or access an app. Like, it's just there. It's just available" (P6).

On a similar note, having the physicalization always present and easily accessible, without needing to open an app or perform any additional actions, served as a constant reminder to engage with the personal data, as well as highlighting the reliability and accessibility of the physicalized data, to provide the information to the participants without any preparation or effort on their part: "...talking about the data physicalization, I think, it's an interesting way. Because like, you don't have to open the app, it's always there" (P4), "...I don't need to prepare, be prepared to get my data" (P3). The participants noted on how the physicalization 'speaks' and engages with them with the data. This type of engagement can be more immersive and compelling compared to the visualisation, which require additional effort to access and interpret the data: "...rather than being a passive way of showing the data, it's an active way, I would say, like, it's trying to speak to you all the time, because it's there" (P4). Comparing the engagement with the physicalization to the engagement with the visualisation, the participants shared how they felt curiosity and increase in their engagement with the personal data through the physicalization, which isn't the case with the traditional screen-based representational model: "I mean, I felt curiosity and more engagement, definitely, than just seeing [the visualisation], even on the screen that we are all used to" (P6).

Moreover, the physicalization was met with ability to prompt or encourage the participants to act based on the communicated information and ticket to think more about their personal data,, such as feeling more mindful about what they're trying to achieve, which suggests a higher level of awareness of their personal data, which was made possible by adding this new dimension of the physicalization: "So when you added [the physicalization] ... it made it more interesting for me to just think about it [the personal data] ... And it's definitely more engaging [the physicalization], and more, I mean, makes me think about it [the personal data] more, and be more mindful about what I'm trying to achieve. Because before that [with the visualisation], it wasn't like that" (P6).

Sub-theme 1: More dimensions convenient for effortless engagement

When asked about which representational model of their personal data the participants found to be more engaging, the idea of unavoidability, which was proven to be a pivotal point for eliciting self-reflection, is applicable also on the topic of engagement and motivation, or overall labelled as more interesting. The participants found the physicalization to be more engaging, because of its state of being impossible to avoid or ignore, due to its persistent presence. They found themselves involved with the physicalization in a way that requires minimal effort: "...the physical representation, for sure, would be more interesting in the, I guess, in this like passive way of engaging... because it was always there because it's physical, it's like something you can't easily avoid, or forget about" (P2). As for the effortless engagement, the participants found the physicalization to require less effort to engage with: "The physical one, it's also more engaging, like it asks for some effort from me, but also not too much of effort. Like, it's an easy effort to do. So. Yeah. I would say in general, still, it's more engaging [the physicalization]" (P5). The effort is not burdensome, as they appreciate the way the physicalization requires some physical interaction to understand the data, as it has been found that touch equals more engagement, as the ability to touch the physicalization was met as detrimental in being more engaged to the physicalization: "...because you can touch it" (P4), and the participants found themselves engaging more with the physicalization, due to its nature, which supports at least two-dimensional interaction: "... there's, like, more dimensional interaction, seeing it, or you can touch it, at least two..." (P3). In the contrasting manner, the visualisation was met with less engagement, due to its screen based nature, which supports one dimensional interaction: ...compared to the page [the visualisation] that is only one dimension interaction" (P3).

Sub-theme 2: Physicality and spontaneous awareness motivating to act more badly

While delving more into the realm of the motivation, the participants were rather straightforward on how they met the physicalization motivating them to act more badly: "... I mean, every time I see that [the physicalization], I know: "Yeah, I got to go out, and I want to make that progress more badly... if I want to go out, that thing [the physicalization] will motivate me to take more steps" (P3). By just seeing the physicalization, they feel more motivated to do better, they are willing to do more steps, in order to reach the step goal. In this manner, by living with their personal data as a motivator, the physicalization creates a more tangible presence in one's environment, forcing them to relate to it more often than they would with traditional visualisation: "...this is actually you living with it [the data] in the physical space. So it's like you have to relate to it more often than you maybe wouldn't do it in other circumstances" (P2).

The participants shared how they would be more motivated to make changes in their personal data because the presence of the physicalization in their environment makes it inevitable that they will notice and reflect on it, even when they're not actively looking for it. This spontaneous awareness prompts them to consider their activity levels and motivates them to increase their steps the next day, and the constant presence of the physical representational model makes it easier to maintain motivation and spark curiosity to reach their goal: "...I would look at it [the physicalization] even though it wasn't the specific time that I was dedicating to look at my data... I would wander around the room and see it [the physicalization]. And it's inevitable that I will think about it [the personal data] and be like: "Okay, maybe I should step it up the next day", or... "Oh, my God, I didn't walk at all, I should do different things tomorrow" (P2), "... [the physicalization] it's there, like it is always in my surroundings. That's why I would say in general, it's much easier to have it [the physicalization]" (P5), "For me it's the case that [the physicalization] is there. So, since it's there, and it blends with my space, and it's dynamic... the bar for this day, like, there's no steps yet. But then at the end of the day, I'll come back and see if I reached my goal or not... Well, I kind of felt more motivated to reach my goal, like, for example, by seeing it physically, to have all the days [the bars] to be on the same level" (P6).

Additionally, by having the goal visible, they felt more motivated to reach their step goal and rise up the respective bars to reach the height of the bar that represents the step goal: "...silver goal, it's there. And it's not only motivating me to do more steps, but also motivates me to raise the bars to the silver bar, up, like day by day" (P3). Moreover, the physicalization was met as subtle and gentle approach in motivating behaviour change, as it's not overly aggressive or confrontational in its approach, it gently nudges the participants towards their goals, making it more impactful and motivating to improve their personal data, unlike the visualisation, which can be pushy or demanding: "...the physicalization, it pushes you in a... gentle way... Because when I look at it, I'm thinking: "Oh, I'm doing good today. Maybe I should walk like that [day]" (P4).

Theme 4: Impactful realism for empowerment and emotional response in comparison to the emotional disconnection through the impermanence of data

Through the discussion with the participant, a point of interest worth exploring arose, namely about the topic of emotions and establishing relationships with their own personal data, as it's something that plays a role in the overall self-reflection. In this quest, a comparative value between the two representational models with contrasting connotations was generated. Moreover, the tangibility of the physicalization was sensed with higher degree of reality, as the participants shared how the physicalization made their personal data more real, and this realism was impactful in forming emotional response, as the experience with the physicalization was more impactful than the visualisation, and therefore has a greater impact on them emotionally: "...it's like, it feels more real [the physicalization] ... my data is here, it's moving, I have the possibility to move it" (P1), "But with the physical things, I mean, it's more like a living thing than the digital visualisations. So, it's more real" (P3), "The physicalization is definitely more impactful, and more raw, in a way. So, it's kind of, because I had some, like, one day when I had like, more than average [steps], and then the other day completely under [low number of steps]. So, to see that difference physically, it's very, like, impacts you more... you feel... negative emotions" (P2). At the same time, the physicalization made the participants feel empowered, by how they have more power over their data: "I feel like I have the power with this one [the physicalization] ..." (P1). The physicalization made the participants form an emotional investment through forming attachment to their own personal data, through experiencing the physicalization itself as being more personal and meaningful to them, compared to the visualisation, through its stronger emotional impact to provide feedback that generates emotions: "...it's more about my emotions. I feel more emotional about my data" (P1), "It [the physicalization] seems more personal... I see if I did good. My emotions are present in a positive way. And if I see that I did bad, they [the emotions] are present in a negative way" (P5).

On the other hand, the participants shared how the visualisation made their personal data feel impermanent, and underperformed in providing emotional connection to the data, compared to the physicalization, which implicated nonexistent impact on emotional level: "This one [the visualisation], when I see it, I know that it's my data, but nothing, I just see it, then it goes away" (P1), "...in the digital visualisation, I don't sense any emotional elements inside, it just tells you the data" (P3), "... [the visualisation] it's less of a personal touch. So, it's like zero emotions" (P5).

Theme 5: The future (of self-tracking) is physical

In the concluding part of the discussion, the participants were asked to elaborate on which representational model they would choose to relay in order to indulge in self-tracking activities in the future, by forming reflections based on the experience they went through while doing the user study. The discussion was with more of an overall generalised self-tracking activity, not excluding the concrete directive goal-oriented style of tracking as experienced in the user study.

The participants shared their opinions while gravitating towards the physical dimension of things. Namely, they shared what for them makes the biggest impact in choosing to rely on physical representational model of their personal data, such as the continuous presence being vital for the future self-tracking, as the physicalization is a model that can't be easily forgotten, and it will be more beneficial for reflecting upon personal data: "Yeah, I would use this one [the physicalization] ... it's there, and it's evident, and I'm watching it all the time. I can't forget about it, that's the benefit of this one the physicalization]" (P1), "Yeah. Because it's fun... I think it's because it's always there, [therefore] maybe it's more effective" (P4). In this connotation, the participants shared how they would prefer to use physicalization in the future, because it requires less effort to interact with, reaching the state of less effort for more efficiency: "Yeah... it's easier to look at it [the physicalization]" (P5).

The physicalization has been met to equal for more impact, as participants shared the observation how they would prefer to use physicalization for future use, as it has more impact and it's more effective, emotionally wise: "I think the physical one for sure. Because, like I said before, it has more impact on me... emotionally I think it will be more effective for me" (P2).

The participants, based on their current experience, shared how they think physicalization would be more effective in helping them identify areas for self-improvement in the future: "I will say it's effective to help you think more about your personal information, that will make you notice some patterns... it will contribute for you to find areas to self-improve" (P3). Moreover, they felt how achieving a goal has never been easier, as the physicalization could be helpful to achieve their goals in the future: Yeah... if I have the goal... and I really want to achieve it... this [the physicalization] could help me more to achieve the goal" (P1).

9.2. Discussion

This research was conducted in order to better understand the experiences with different modalities of the same data, in a comparative manner, as to understand which data representation model performs better as opposed to the other. In doing so, directive style of self-tracking, which is goal oriented, was used as an illustration, where physicalization and visualization of activity data were put to the test.

With this study, we show that the data physicalization outperform its visual counterpart in the context of self-tracking, by gaining understanding how the physical artifact relates to eliciting self-reflection, as well as providing better acknowledgment and management of the personal data to the participants. Similarly to the study where data physicalization was put to the test in the context of low-informational retrieval (Jansen et al., 2013), the tangibility and visual realism played a major role in the outperformance of the physicalizations, which in this case was also found benefitial in wider range, such as increasing engagement and establishing emotional response from the participants, as well as making it easier to self-reflect. The wider range was reached by tackling and reinforcing the active and depth perception of the physicalization, as well as it being interesting for the participants, which leveraged to have them spend more time and effort exploring their own data, which reinforces the statements about data physicalization from the work of Opportunities and Challenges for Data Physicalization (Jansen et al., 2015).

The findings of the post-study questionnaire suggest that data physicalization is a more effective method than data visualization for gaining understanding about personal information, eliciting self-reflection, and establishing emotional responses. The findings also elaborate that data physicalization and data visualization were similarly easy to use, which is a good indicator considering data physicalization was a new concept for all participants.

The associated adjectives used by participants to describe their experience with the data physicalization were mostly admirable, including efficient, engaging, fun, interesting, helpful, and enjoyable. In contrast, the adjectives used to describe their experience with data visualization were mostly dismissive, including inefficient, unsatisfying, boring, overwhelming, challenging, disappointing, and confusing.

This findings were established through illustrative comparative graphs and associated adjectives, and are further elaborated and complemented in a more in-depth manner, through a reflexive thematic analysis of the post-study semi-structured interviews as a dataset, which summary of findings are showed in continuation.

Due to the physicality and embodiment of the data in their surroundings, which made the data physicalization prominent and more engaging, the participants chose physical representations of their personal data over digital ones. The data became more substantial, real, and noticeable because of the materiality of the representation, which also encouraged self-reflection and increased engagement with what was being presented.

The physicalized data was also constantly available and did not need to be explicitly activated, indicating a higher degree of permanence connected with it. On the other hand, visualisation's forgetfulness was a barrier to engaging with digital representations because the data wasn't constantly accessible and didn't encourage the participants to take any action after they were away from their phones.

Due to the lack of precise numbers, it was discovered that the data physicalization was more enjoyable and reduced pressure, whereas the participants' anxiety was raised by the data visualization's numerical character. Goal-oriented information with qualitative and comparative value in the data physicalization was found to enhance simplicity, while the visual equivalent was found to be insufficient in providing qualitative value.

The fact that the participants cared more about knowing if they were on pace to reach their objectives than they did about the precise number of steps walked implies that they were motivated by goals. Additionally, it was discovered that the data physicalization was more useful for making comparisons between different days.

Given that the data physicalization was continually present and visible in their personal area, making it simpler to obtain information and interact with, helped participants reflect on their behavior and progress toward their goals. The visual counterpart, however, was shown to be less effective in getting participants to respond because it required conscious contact and frequently involved digital distractions. It was discovered that the constant engagement made possible by the data physicalization was crucial for self-reflection since it encouraged emotional responses to personal data and allowed reflection to take place throughout the day.

The ease of access supported by the data physicalization was found to be more convenient than engaging with visualisation, which was considered burdensome due to additional effort required. Physicalized data is easily accessible, allowing for passive engagement without turning on an app or device. The data physicalization served as a constant reminder to engage with personal data, highlighting its reliability and accessibility without any preparation or effort.

Participants found the data physicalization to be more engaging, immersive, and compelling than the data visualisation, leading to increased curiosity and mindfulness about their own personal data. The data physicalization was also able to prompt or encourage participants to act based on the communicated information, suggesting a higher level of awareness of their own personal data.

The physicalization of data was perceived as more real and impactful, with a higher degree of tangibility that generates stronger emotional responses, compared to the impermanence of digital visualizations. Participants described the physicalization as a living thing that made their personal data more personal and meaningful, forming an emotional investment and attachment to it.

The data physicalization also provided a sense of power and control over personal data. In contrast, the digital visualizations were perceived as impersonal, lacking emotional elements and failing to establish an emotional connection with the data.

The participants expressed a preference for physical representations of personal data in self-tracking activities for the future. They found the physicalization to be more impactful and emotionally engaging, allowing for a greater attachment to personal data and a better understanding of patterns for self-improvement. The continuous presence of the data physicalization was deemed vital and beneficial for reflecting on personal data, as it is always present and cannot be easily forgotten. Additionally, the data physicalization was considered easier to interact with and more efficient, requiring less effort for greater impact. Overall, the participants felt that the future of self-tracking lies in the physical dimension, as it is more effective and helpful in achieving personal goals.

Based on the beforementioned, the findings suggest that the future of data physicalization is promising, and it may play a significant role in the future of self-tracking activities. Future design decisions could prioritize the physicalization of data in self-tracking activities.

Designers could focus on creating physical representations of personal data that are engaging, immersive, and emotionally impactful, as these representations can be constantly present and easily accessible, allowing for passive engagement without the need for explicit activation.

Additionally, designers could prioritize the emotional elements of data representation, as this is important in forming an emotional connection to the data, increasing curiosity and mindfulness about personal data, which can implicate greater levels of self-reflection. By incorporating these findings into their designs, designers can create more effective self-tracking tools that better support users in achieving their personal goals.

9.3. Limitations and opportunities for future research

The limitations of this study are as follows:

Homogeneous sample

The study involved a homogeneous sample of participants, such as predominantly people working or studying disciplines that relate closely to user experience and user interaction design, which may limit the generalizability of the findings.

Novice users

Given the time constraints and finding available users, the participants in the study were novice users of data physicalization, which may have influenced their responses.

Study duration

Given the time constraints and the availability of the users who could participate in this study, the study lasted for five respective days with each of the six participants. It is possible that longer exposure to data physicalization would lead to different outcomes.

Based on the showcased limitations, as well on the gathered findings of this study, the opportunities for future research are as follows:

Varying sample

Future studies could aim to recruit a more diverse sample to explore how different demographics might respond to data physicalization.

Experienced users

Future research could explore how experienced users respond to data physicalization, and whether the benefits observed in this study persist over time.

Contextual factors

The current study focused on a specific context (self-tracking), but data physicalization could be applied to a range of other contexts. Future studies could explore the potential benefits of data physicalization in other areas, such as finance, or education. In this manner, it will be easier to establish contexts where data physicalization outperforms its visual counterpart, so design efforts can be applied that will leverage the cost of producing data physicalizations.

Longer duration of the study

Future studies can involve conducting a longitudinal study to assess the long-term effects of longer exposure to data physicalization on engagement, reflection, and behavior change.

Investigating the impact of different types of physicalization in self-tracking

The study saw how the materialization of the visualization in this form of a physical artifact outperforms, while future opportunity can be seen in investigating the impact of various forms of data physicalization (e.g. 3D printed objects, wearables, etc.) on self-reflection and engagement.

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