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INVESTIGATION OF A GRAMMAR AND FRAMEWORK FOR NEW FORMS OF DATA EXPLORATION VIA DYNAMIC DATA PHYSICALISATION

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Abstract

The practice and the discipline of dynamic data physicalisation is an emerging research area that utilises several human sensory modalities such as touch, smell, taste, hearing and sight to interpret and interact with data encoded using dynamic physical artefacts. In comparison to the traditional visual-based data representation, dynamic data physicalisation offers significant advantages such as faster and better interpretability and interactivity since data encoding is closer to natural human settings using familiar physical objects and the ability to encode data flexibly due to the availability of multiple human sensory channels for the perception of the encoded data. The domain of dynamic data physicalisation is still in its infancy due to the technological limitations and lack of avid research interest due to the sufficiency of the visual representation. However, recently there has been an upward trend in the research related to dynamic data physicalisation due to the explosion of data causing complex data interpretability and using visual modality alone is challenging. Other contributing factors are the limitations of the visual representation techniques to convey the precise meaning using the available screen real estate and technological improvements in areas such as material sciences using improved manufacturing techniques and information communication technology.

The state of the art related to dynamic data physicalisation studies shows significant gaps in the area, especially related to the grammar and framework. Studies have also shown that the existing visual modality-based grammar is not feasible for dynamic data physicalisation due to multimodal interpretation and interaction requirements even though there are similarities. In this thesis, we use the Design Science Research Method (DSRM) to develop the initial physical representation variable set based on a literature review and a proof-of-concept demonstrator using a pre-existing theoretical dynamic data physicalisation framework developed in the VUB's WISE lab. The contributions of this study are the development of data physicalisation variables associated with the necessary literature backing and a software tool to demonstrate the developed physical variables using a theoretical dynamic data physicalisation framework. Furthermore, the novel software tool developed in this thesis is designed in a modular way utilising a client-server architecture style, enabling flexibility in modifying the tool for future experimentation needs. In the end, one experiment has been conducted to evaluate the software and how much it serves this thesis's objectives.

The presented work has several limitations due to the time constraints and other limitations of a Master's thesis. Firstly, the literature study is done without considering existing systematic approaches. Secondly, the

experiment-based evaluation conducted as a final stage showed significant challenges in using the developed software tool support due to the limitations in the user interface design. Finally, the assessment using a small representative group reduced the validity of the evaluation. In the future, the research can be extended by increasing the number of variables and further developing the literature study using a systematic approach. Further, our study also points towards the need to improve the framework for dynamic data physicalisation utilising the developed physical variables.

Contents

1
Introduction

Dynamic Data physicalisation is an emerging research area that controls the properties of the material dynamically using computer-driven methods to encode data from digital form to the physical one, and it exploits human senses to transfer data from physical shape to human perception system [77]. Although there are not many examples for dynamic physical artefacts used in physicalisation, several physical artefacts such as a 3D-printed item, a piece of knitted scarf or a wearable data sculpture are used to bring digital data to the physical world [73]. Some studies have concentrated on shape-changing interfaces or actuated robots to build the dynamic physicalisation [92, 64, 31]. Moreover, using physical properties of the material in physicalisation [78, 148] as a unit [150] have recently been investigated, which opens a new door in this field. These properties can include weight, volume, temperature, odour, stiffness, or other physical properties that can be updated without any effects on the material identity. The main focus of physicalisation is on *"how computer-supported physical representation of data can support cognition, communication, learning, problem-solving, and decision making"* [77]. Dynamic physicalisation leans on computer-supported methods and technologies which control the material properties dynamically in order to turn data into physical forms and augment the users capacity in data-related tasks [77]. A different range of technologies for controlling the geometry of physical artefacts has been studied. Shape-changing technologies can control and manipulate the shape of user interfaces [122]. Using motorised bars [46, 116] to create the interactive physical display in which users can form the shape is the other thriving technology to create dynamic physicalisation. Shape-memory alloys [127] or hydraulic actuation [45] are technologies with which shape deformation can be achieved. Actuating micro-robots [49, 92] are the other advancement that controls the position of multiple physical objects dynamically. Due to the ability to use all senses in the physical world, employing more than one sensory channel is possible in physicalisation. Therefore, in comparison with a simple flat display that only involves the visual sense to illustrate data [132], a more extensive range of data can be conveyed to the audiences in the physical representation. In other words, physicalisation involves not only visual sensation, it enables other sensations to participate in capturing information due to its physical nature, and consequently, it amplifies the impact of representation [39].

Physical data representation had been used by ancient people in a natural way for various tasks such as information storage, accounting and currency exchange [72], even before inventing written languages [102]. One of the earliest usages of the physical object for storing data is a plaque which is approximately 70000 years old and found in South Africa [128], shown in Figure 1.1(A). Studies show this plaque had been used possibly for a purpose since it is engraved systematically. The pattern on this plaque, consisting of intercepted lines, indicates the intended sequence of choices, and it is considered to be used for storing data. Talking about the more recent era, although there is a limited number of physicalisations in the 19th and 20th centuries [73], the contemporary century is considered to be the flourishing period. The *thermodynamic relationship of properties* model, which James Maxwell crafted using clay and plaster in 1873 [87], shown in Figure 1.1(B), and a brass model of *Myoglobin* built by Kendrew and his coworkers in 1958 [99], are some of the examples for physical data representation in previous centuries. More recent examples show a significant increase in dynamic data physicalisation research [77, 66, 73]. Nevertheless, using dynamic physical artefacts or physical properties of materials to encode data is still challenging with the current technology maturity level. [165, 77].

Similar to data physicalisation, visualisation also has a long history, starting from the cave painting to its state of the art. The last quarter of the 20th century is a thriving time for information visualisation, and it has reached its maturity by presenting new methods and models for generating the interactive and dynamic representation of multi-dimensional data [66].

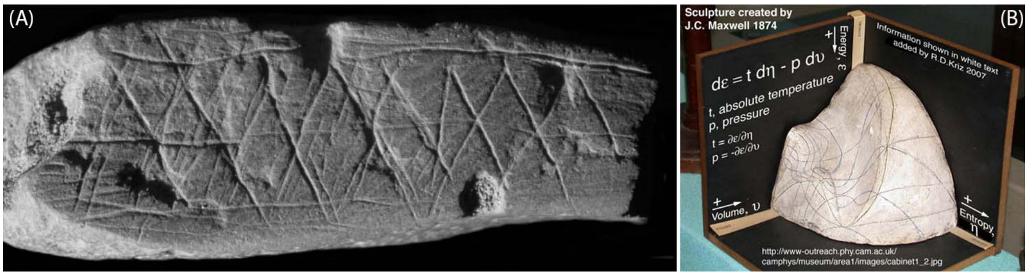


Figure 1.1: (A) The ancient plaque found in South Africa with an engraved systematic pattern [128], (B) The thermodynamic relationship of properties sculpture [99]

Using graphical charts such as bar charts or pie charts in visualisation is a practical approach to convey the multiple characters of data in an intelligible form [28]. In other words, visualisation expands the human understanding of the data and its hidden patterns, and specifically, graphical charts make the visualisation uncomplicated to understand [39]. In the contemporary digital age, since the data is ubiquitous, users require new methods which illustrate abstract data in memorable, interpretable forms [183]. Different methods alleviate the process of representing data to help users fulfil cognitive tasks faster and more efficiently [171]. Information visualisation is the most well known approach in this respect. On the other hand, without visualisation, discovering the messages of data is laborious. Considering the undeniable competence of information visualisation, it does not seem very straightforward to talk about the other methods unless they offer some advantages that visualisation has not proposed up to this time. There are different limitations in visualisation, each of which diminishes the efficiency of visualisation in a specific way. Advanced computers, which can compute more complex algorithms and analytical tasks, are required to manage the increasing amount of data. Current 2D displays are limited in exhibiting complex data, so they make visualisation inflexible and hard to explore. Although interactivity adds flexibility to the visualisation, the displays have a finite capacity to show several aspects of data. Besides display limitation, it is an open discussion of how non-expert audiences can be productively informed or involved in information visualisation [183].

Unlike visualisation, which uses sight exclusively, physicalisation employs multiple human senses bringing the data perception closer to the real physical world. Furthermore, all physical objects have shape and volume, so the physicalisation can benefit from human spatial perception skills no matter if they are an expert in the physicalisation field or a novice [77]. Moreover, recent developments in the physicalisation research area provide new opportunities to encode data in the physical forms [67]. The studies in digital fabrication, 3D-printing, actuated tangible user interfaces (TUIs), shape-changing interfaces, as well as micro-controllers technologies contribute to this filed significantly, which leads to creating physicalisation more efficiently and effortlessly. In the near future, all these efforts promote physicalisation as an appropriate alternative or complementary medium for representing data in the human natural setting [104].

Data physicalisation benefits from engaging audiences actively [166]. Further, it reinforces human perceptual exploration skills by triggering their active perception [77]. Humans have an advanced sensorimotor system that enables them to receive data from the physical world [23]. Physical objects can be touched, manipulated, rotated, taken apart, reassembled, moved, carried and even possessed [165, 166]. These features entail the active perception process, which eventually leads to extracting abstract information from the physical artefact. For instance, the memories symbolised by souvenirs or a piece of art is an example of extracted data from a physical object [166]. Besides, recalling and retrieving the information from a physical object is more accessible because of better user engagement comparison to visualisation [66, 77]. For example, 3D data physical representations perform superior in comparison with 3D on-screen visualisation in terms of information recalling [76]. Furthermore, physical manipulation plays a significant role in learning reinforcement and can address a broader range of audiences, including experts and non-experts [75, 165]. In order to use the people's skills in interacting with the real world [68], Human-Computer Interaction (HCI) researchers have tried to use the richness of the physical environment in the computing and digital information world. They have invented new interfaces which people can talk with, walk through, move, touch and gesture [68]. Wellner et al. [172] proposed to back the physical world to the digital one through tangible objects almost one decade before. For example, tangible interfaces demonstrate how humans are enthusiastic about interacting with digital information using their five senses, namely touch, vision, smell, taste and hearing [72].

Connecting tangible interfaces to visualisations has enhanced the user experience. In other words, tangible interfaces have established a new method to interact with the computational world via physical objects [137, 68]. "Tangible Bits" allow users to grasp and manipulate bits coupled with physical objects, and its goal is enriching digital experiences by adding physical interaction to them [70]. Recent developments in computation and technologies, such as fabrication technologies [141, 153], are significant steps for connecting tangible interfaces to digital data. Moreover, a better understanding of human sensing systems has led to more genuine ideas about encoding data to the actual physical objects and their properties and behaviours. Therefore data presentation can move beyond the desktop in which each sense play the same role, without favouring one specific sense over the others, in interacting with data [75].

There is a flourishing interest in using multi-sensory data representation to show non-visual information. Jansen et al. [73] talk about the idea of turning data into physical form and using it ubiquitously. They can be used as ambient information systems and reinforce casual information perception [100, 118]. In some cases, the visual sense is not available because of disability, or it is already occupied. In this situation, some other stimuli such as vibration, sound, taste or smell can activate the user's other sensory mechanisms [22]. Paneels et al. [111] studied how haptic devices can present information to enable blind or partially sighted audiences to feel and reason the data through touch. It shows alongside visual sense; haptic can be employed to explore more aspects of data. Using haptic can map data onto position, pressure, vibration, temperature, surface texture, or other physical properties. Another sense that can be utilised to represent data is the auditory sense. Some studies such as [107, 26] examine how to use sound to transmit information to audiences with visual impairments who cannot engage with traditional data representation. Data transformation using sound is called data sonification [132]. Sonification aims to convey the data through non-speech audio and acoustic signals [107, 86]. Various sound parameters such as frequency or volume can be used as an alternative way to involve the audience with data [86]. Apart from vision, hearing and tactile senses, humans have the sense of smell, which is surprisingly robust. According to Bushdid et al. [21] humans can distinguish more than 1 trillion different smells. Therefore, Olfaction, the sensation of the smell, is a likely medium to transmit data to the human. Patnaik et al. [113] have developed a prototype, viScent, to convey information through an interactive olfactory interface. Finally, using taste sense as the sensory channel for communicating with data does not have a long history. According to [170, 32], encoding data with the edible materials to leverage taste channels to convey information and design meaningful interaction is called data edibilisation. Figure 1.2 shows a 3D-printed biscuit with edible mushrooms. Users can track their working hours, the temperature besides humidity in their office by monitoring how much the mushrooms grow on the biscuit. Furthermore, they can taste different mushrooms to compare working conditions together [170].

Figure 1.2: 3D-printed biscuit with edible mushrooms topping showing the office working situation in terms of the working hours, the temperature, and humidity [170]

All these examples bring many questions regarding the choice of senses, physical artefacts, physical properties, design and implementing the physical representation. Data physicalisation is successful in sparking users' curiosity and turning data, an exploration into an exciting adventure because of its "always on" nature [148] and human's proficiency in communicating with the physical affordances. But copying with its challenges is still demanding [77, 148, 166]. Data physicalisation, just like visualisation, requires the principled way to encode data from digital form to human-understandable representation [77]. Roberts and Walker [80] discussed the need for a unified approach to use the physical properties of the material, such as resistance, friction, and temperature, in multi-sensory information visualisation. The lack of proper guideline which assists designers to associate the best physical artefact or property with specific data is the other challenge in this research field. How to implement the physical representation effectively is still an open question [77], moreover adding dynamicity and interactivity to physicalisation is a big challenge. This challenge is mainly investigated in this study, and the formalised method (grammar), which uses the set of physical variables to create the dynamic physical representation of data, is explored.

1.1 Problem Statement and Justification

Data physicalisation has started to attract a lot of scientists' interest recently. Since physicalisation translates data to the physical artefacts and material properties, it focuses on the physicality of data [166]. This emerging research area carries out the multimodal physical representation, which engages several modalities, but there are many open research problems [77] to be tackled to achieve maturity in this field. In the following, the problems which are related to this research work is presented:

- Although there have been a lot of studies such as [152, 183, 92] dedicated to the physical representation of data, most of those have tended to concentrate on constructing static physical models. In other words, they created passive and monolithic physical visualisations which do not support interaction and dynamic modification. But creating the dynamic interactive physical visualisation is still a bottleneck [153].

- One of the main challenges of building a physicalisation is to opt for the right physical object or artefact to map data onto based on guidelines [77]. Since the process of making a physical representation is expensive, laborious, and tedious, especially when the data set is large, selecting the right physical mediums is so important.

There are some authoring tools such as MakerVis [152, 153], which facilitate the designing and customising process and create a prototype before crafting the final physicalisation. However, these authoring tools are practical in fabricating physical representation instead of mapping data onto physical properties or artefacts. Although some enabling technologies, such as shape-changing materials [103] and programmable matter [51, 79], have provided new opportunities in dynamic data physicalisation, it is mostly unexplored yet. Some studies tend to discover the well-organised approach, leading to an actuated interactive physical representation [140, 155, 92]. Their goal is creating the physical representation, which is self-reconfigurable, manipulatable and support the data analysis as same as visualisation [140, 155, 92]. Using wheeled micro-robots [92], which gives physical form to the well known visualisations like scatter plot, is one example of these studies. However, there has been no formalised general approach that "democratise" [39] the practice of dynamic data physicalisation. Democratising means developing the physicalisation using free, open and well-supported software development platforms to map data onto the physical properties of materials [165] in order to build the dynamic interactive dynamic data physicalisation.

In information visualisation, the *Grammar of Graphics* was invented to introduce the formal way to transfer data from its basic shape and decorate it using visualised graphical format [179, 9]. Investigating the approach that lowers the barriers in order to transform data to the physical shapes, while the final representation supports interactivity and dynamicity, is required in physicalisation too. The ultimate goal of this approach is digitising the process of information physicalisation from data analysing to final rendering to the physical shapes. In this study, introducing the grammar that translates data to the physical properties or behaviour of materials among a general *physicalisation framework* [140] is investigated. It is believed that this grammar is the first step of building dynamic, interactive physicalisation. Similar to the *Grammar of Graphics*, establishing the grammar that defines the meaningful correspondence between data and physical properties is essential. This grammar should consider the scale, coordination, aesthetic attributes, and legends for physical representation, so the final result will be human-readable. Inspired by the *Grammar of Graphics* [179], the first step in the grammar is defining the variables. In the *Grammar of Graphics*, as the first step, raw data is transformed to the variables that are compatible with the visualisation displays [179]. In physicalisation, the real physical world is being used as a display, so the material's physical properties such as size or shape, their behaviour such as speed or vibration, and the physical artefacts can be used as the variables that depict data physically. In order to define the appropriate physical variables, all mechanical properties of materials and their ability to alter dynamically have been studied. Later the list of potential physical properties is prepared that can be utilised as physical variables. In visualisation, the visual sense is dominant [77], it means the sight is responsible for capturing data from the representation. Unlike visualisation, in physicalisation, a users' entire body and senses can be exploited [75] to capture data from the representation. Consequently, all sensory channels in the human body work together to capture data from physicalisation. So the combination of physical variables is essential. For example, using texture as a physical variable occupies tactile sensation. Selecting the other variable that leans on touch simultaneously can interfere or falsify the process of capturing data from the texture. For example, it is impossible to show two different aspects of data using the same bar in the chart. So that the combination of physical variables is examined in this study, it will determine which physical properties can be used simultaneously to convey as many data dimensions as possible and how users can capture data from them based on psychological studies.

1.2 Research Methodology

The Design Science Research Methodology (DSRM) has been chosen for this study due to its discipline, which leads to the creation of successful theoretical and concrete artefacts [114]. Moreover, it is used due to the lack of existing solutions for building dynamic interactive data physicalisation. The other reason for utilising this research methodology as a heuristic approach is that it helps the writer to design and develop her solution and evolve it to achieve the defined objectives. The DSRM framework proposed by [114] is utilised in this study. According to [114] there are six steps, including *"problem identification and motivation, definition of the objectives for a solution, design and development, demonstration, evaluation, and communication"*. As a short explanation, in problem identification and motivation activity, the specific problem is defined, and the value of related solution is justified. In the next step, as a definition of the objectives for a solution, the quantitative or qualitative objectives of the proposed solution is defined. Then, how the requirements are translated to the system features is discussed in the design and development step. In the demonstration step, the usage of the solution will be demonstrated. In order to observe the performance of the solution and how it can solve the problem, it is evaluated in the evaluation activity. In this principle which is an iterative step, how many objectives are met and the solution merits and demerits are investigated. Finally, the problem which the research is about, its importance, the proposed solution and the evaluation result are all shared in the communication step. These six steps are customised for this study. Figure 1.3 shows these customised steps briefly. This study is in the Design Science (DS) field, and DS involves the process to design and produce the IT-related artefact to address the observed problem [65]. In this work, the artefact is the list of physical variables as a building block of the *Grammar of Physicalisation* which facilitate the process of building dynamic interactive data physicalisation. The six steps of DSRM performed in this study are explained in the following:

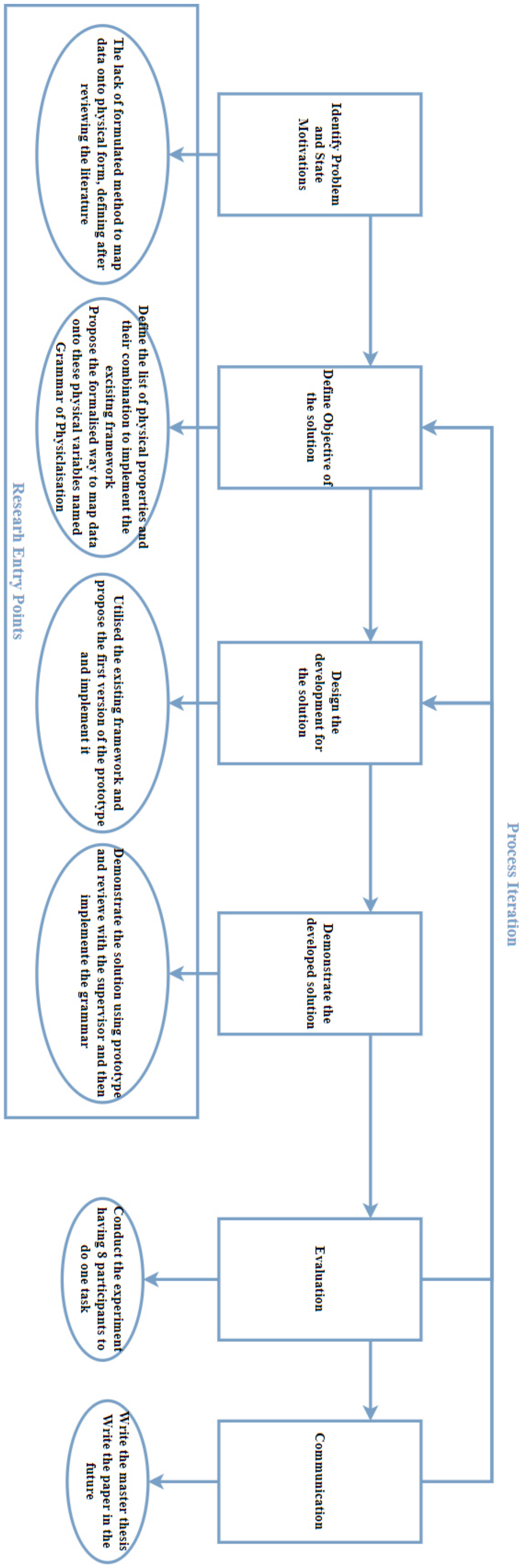


Figure 1.3: Design Science Research Methodology (DSRM) process model

1. **Problem identification and motivation:** The problem this thesis is focusing on to investigate, is the lack of a grammar for building dynamic data physicalisations. In the physicalisation research area, the concentration is mainly on crafting static and passive physicalisation, but this process is tedious and requires advanced workflows [153], and they cannot be modified while the data set changes. Moreover, if the physical representation of data is used for supporting more sophisticated analytical tasks, in some cases, they need to be manipulated mechanically [151], and this procedure is expensive and time-consuming. Dynamic data physicalisation has been less studied, and state of the art in this field shows a significant gap related to grammar which proposes the rules to map data onto physical variables. The development and subsequent dissemination of this grammar lead to building dynamic interactive physicalisation, which is self-configurable while data is changed or interaction happens. The solution for tackling this problem is implementing the framework which is proposed in [140] by introducing the grammar named the *Grammar of Physicalisation* [140].

2. **Definition of the objectives for a solution:** The goal of this thesis is introducing a grammar as the first step of implementing the conceptual *physicalisation framework* introduced by Signer et al. [140], leading to dynamic interactive physicalisation. It is important to know the design space for dynamic data physicalisation, and one of the steps for achieving this goal is investigating the physicals encoding [140]. Physical encoding means transforming data from the digital form to the physical shape. Towards developing the *Grammar of Physicalisation*, defining the physical variables and their combinations as a building block of the grammar are investigated. Firstly, preparing the list of physical properties and behaviours of the material, called physical variables, are prepared. These variables can be used as a unit [150] in the physical representation of data. Secondly, the possible combinations of these variables are discussed. The last goal is proposing the grammar based on the *Grammar of Graphics* [179] which democratise the data mapping onto proposed physical variables. This grammar is called the *Grammar of Physicalisation*. More details about this task are described in Chapter 4.

3. **Design and development:** The primary idea of the proposed solution is based on the conceptual framework for dynamic data physicalisation introduced in [140], as well as the *Grammar of Graphics* [179] which is the main inspiration of designing the *Grammar of Physicalisation*. The

result of the design effort is the first version of a grammar which consists of the list of physical variables and their combinations as the building blocks of physical representation with which data can transform to physical form.

4. **Demonstration:** For exhibiting the proposed solution in this thesis, firstly the prototype for the designed system is prepared, then this prototype is improved by applying the supervisor's comments and eventually it is implemented. This solution is implemented in the application called the *physicalisation framework*. This step proceeds in Chapter 5 which describes the architecture of the system and the implementation details.

5. **Evaluation:** For evaluating the interface of the framework, the experiment is designed with eight participants, and their experiences are examined using the User Experience Questionnaire (UEQ)[1]. One of the contributions of this thesis, which is proposing the list of physical variables, is mainly based on cognitive psychology studies, and it is not tested in the real world. So the designed experiment focuses on evaluating the designed user interface based on measures mentioned in UEQ. More information can be found in Chapter 6.

6. **Communication:** To fulfil this step, this thesis has been written to communicate the problem and the proposed solution based on conceptual *physicalisation framework* [140]. Moreover, the supervisor of this thesis and his team in the Web & Information Systems Engineering (WISE) lab of VUB actively contribute to this research area in terms of proposing the complete data physicalisation grammar, which democratises the process of building dynamic interactive physicalisation exploiting physical variables.

1.3 Contributions

The work undertaken in this research intends to propose some building blocks for the grammar within the conceptual *physicalisation framework* [140], and its ultimate goal is democratising the building process for dynamic interactive physicalisation. This endeavour has begun from an initial exploration into the physical properties of materials to establish the list of physical variables and their possible combination to represent more data at the same

[1] `https://www.ueq-online.org` (accessed 05/08/2021)

time by exploiting all available human senses. Then, the formal approach is introduced as the first version of the *Grammar of Physicalisation*.

To fulfil the purpose as mentioned earlier, the notable contributions of this thesis include:

- This study provides the background which enables non-expert audiences to gain the initial knowledge about information visualisation, human's perceptual systems, properties of the materials, the existing grammars of visualisation and static and dynamic physicalisation besides some examples in this research area.

- The first attempt to implement the "Physicalisation Information Management" is made in this study too. This part aims to gather all the works and studies related to physicalisation to create the physicalisation encyclopedia. This section is implemented as a part of the system, suggesting physical variables for mapping raw data. This system is called *physicalisation framework*.

- The list of physical attributes of the material and their behaviour, called physical variables, is proposed. These variables can be used as an individual unit in a physicalisation. They are chosen because they have the ability to change dynamically without any impact on the material identity.

- The first version of the *Grammar of Physicalisation* based on the *Grammar of Graphics* is proposed, within conceptual *physicalisation framework*k [140], which is used to connect data to the corresponding physical variable.

- The first attempt to implement the simple version of the *Grammar of Physicalisation* is performed, which analyses data and suggests the best set of physical variables to transform from its digital form to the physical one.

1.4 Thesis Outline

The rest of this thesis is structured in 6 other chapters, including:

- Chapter 2 gives the essential background which contextualises the terms used in this presented work, including data visualisation, perceptual and cognitive systems, properties of the materials, the current grammars in the visualisation research area and physicalisation. This chapter will aid especially non-expert audiences to follow this thesis more efficiently and gain the initial knowledge in the mentioned topics.

- Chapter 3 explores the existing studies regarding physicalisation (static and dynamic). At the end of this chapter, some gaps and limitation of the literature are inspected of which this study is conducted to fill the small part.

- Chapter 4 includes the proposed solution for the defined problems of this thesis. This solution consists of proposing the list of physical variables which can be used as a medium for transferring data in physicalisation. Moreover, the combination of these variables is discussed in this chapter in order to enhance the data capturing by the user using all their available senses.

- Chapter 5 provides the details about implementing the solution and introduces the application named the *physicalisation framework* and its functionalities.

- Chapter 6 discusses the evaluation of the application user interface in terms of users' experience. As mentioned in Section 1.1, the proposing and usage of physical variables are based on the theoretical studies, and since the final rendering is out of this thesis scope, the usage of physical variables in the real world is not part of this evaluation.

- Chapter 7 concludes the result of this thesis and discusses the future goals. Defining and implementing the grammar which turns raw data into dynamic physicalisation is a pretty novel argument. Many studies should be carried out to bring maturity into this field, like information visualisation. Some of them have been already discussed in this chapter and some of them will be reviewed in the following chapters.

2
Background

This chapter provides the fundamentals about the visualisation, human's perceptional systems, physicalisation, the brief knowledge about properties of the materials as well as the grammar of visualisation so that the non-expert audiences can read and comprehend the context of this thesis. Firstly, the overview of visualisation is given, explaining the definition, the merits and the challenges. Then, a brief explanation about the human's perceptional system is provided. This system in the human body is responsible for capturing data from the surrounding environment. In the next section, the definition of physicalisation, its benefits, and some relevant studies to static and dynamic physicalisations, besides several examples, are discussed to give the reader a general overview of excising works. Since one of the contributions of this thesis is proposing the list of material physical properties to encode data onto them, brief information about properties of the material are provided in this chapter too. As mentioned in Chapter 1 the *Grammar of Graphics* [179] is the inspiration for the designed grammar in this thesis, so the general overview of the *Grammar of Graphics* and some other existing grammars are provided at the end of this chapter to give the reader a clue about differences between language-related grammars and the grammar of visualisation.

2.1 Data Visualisation

2.1.1 Definition

There are several explanations for data visualisation, all of them have almost the same meaning. According to [84, 165] the process of portraying data in graphics to facilitate understanding and analysing complex data is data visualisation. Moreover, Jansen et al. [78] defines visualisation as an approach that encodes data in graphical marks (e.g. points, lines or areas) and their graphical attributes (e.g. x/y position, size, colour, texture, orientation or shape) in two-dimensional space. Jacques Bertin, the French cartographer, formalised the method of turning data into graphical forms for the first time [9]. Graphics are an excellent approach for investigating data and depicting the result, especially in the informtion age when data is ubiquitous; however, using graphics for presentation and exploration are different. Generally, the graphics which are used for data exhibition are static. They are used to summarise data and display the main pattern hidden in it along with supporting the conclusion. However, exploratory graphics are used to investigate the result [9]. Most visualisations are fast, informative and interactive, which means they can be employed to show various and extensive data and depict ad-hoc changes in data stream [28]. Visualisation helps humans to surpass the limitation of their cognition system and consequently augments their abilities to make the best decision [104]. Visualisation is the impassive and unbiased tool which caters for the solutions to particular tasks, and namely, the primary purpose of it is focusing on analytic tasks optimisation [165].

Since the data is ubiquitous from finance to science, and the demand for comprehending and analysing it is dramatically increasing, visualisation is getting more importance. The visualisation creates the mental model of information, which aims to interpret data efficiently, and it is an increasingly powerful way to address the glut of information [14]. The process of converting data to the visualisation has four rounds which are indicated in Figure 2.1. In the first step, data is collected from the physical environment. Afterwards, data transformation occurs, which focuses on turning data into a form which is easier to manipulate. The next step is mapping selected data onto the visual presentation. Due to the developments in computing algorithms, this step is conducted using computers quickly and efficiently these days. Ultimately, the human perceptual and cognitive system is accountable for perceiving data from the final visual representation. All these steps are combined by feedback loops [171].

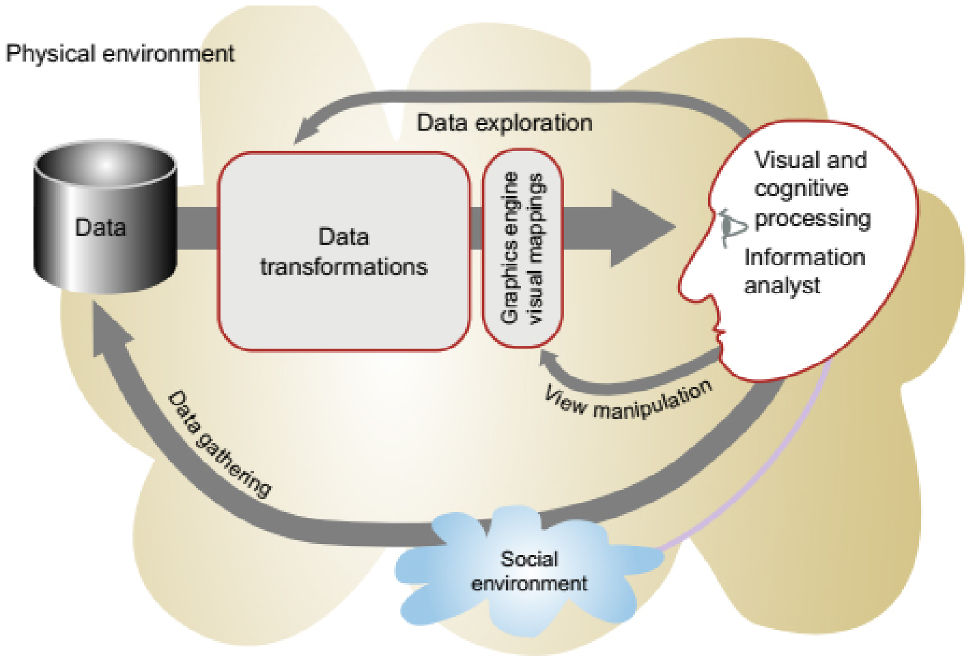


Figure 2.1: The process of converting data into visualisation [171]

2.1.2 Data Visualisation Challenges

There are numerous advantages for data visualisation such as a "better data analysis, pattern identification, error detection, grasping the trends or providing a better approach to find the innovative solution" [56, 37, 53, 84]. But it is not easy to develop a perfect visualisation due to some technical challenges. These challenges can be categorised into five major groups including "*usability*, *visual scalability*, *integrated analysis of heterogeneous data*, *visualising the stream of data* and *errors and uncertainty of data sets*" [94]. The users are involved in visualisation, which profoundly impacts the effectiveness of visualisation. Therefore, some studies such as [10, 52] have investigated an effective method for designing and developing the visualisation. Usability challenge stems from all the difficulties in providing effective visualisation. Besides, visualisation uses flat screens to decorate data in visual form; using 2D displays to show large data sets is challenging. On the other hand, scalability is a significant trial for Information Visualisation (InfoVis), especially with the big data boom. This limitation is one of the motivations to consider the other alternative, which uses the more scalable channels or other mediums for transforming data rather than being limited to 2D screens. In visualisation, the visual sense is dominant [77], and it reinforces this challenge. One of the approaches to alleviate this hurdle is to use channels that involve all human senses, including audition, gustation, olfaction, tactition, and vision. Multi-sensory representation of data such as tangible user interfaces (TUIs) and physicalisation are new options that could diminish flat displays' limitation and use physical artefacts or physical properties of the materials to reveal information concealed in data. In Chapter 4, the usage of physical variables to exhibit data in physical forms which involves all human senses is discussed in detail.

2.2 Human Perceptual and Cognitive System

2.2.1 Definition

Being depicted in Figure 2.1, the human perceptual and cognitive system plays the key role in interpreting and comprehending what is exhibited in visualisation. To define perceptual and cognitive systems and how they function, the perceptual mechanism provides complex and abstract descriptions of reality, and its presentation is not limited to the specific modality. These features establish the connection between perceptual and cognitive systems, which leads to information extraction and tasks performing [82].

In the last century, scientists investigated the geometric relationship between physical and perceived space [109]. Nevertheless, "geometrical perceptual illusions" demonstrate that the relationship between physical reality and perception may not be as simplistic as it looks [109]. In neuroscience, scientists are interested in studying how humans perceive the surrounding world using their channels of sensation [48]. It is said that perceptual systems are the source of knowledge, and the conscious qualities stems from senses [48]. Perception is a multi-sensory phenomenon, it means human senses are designed to work together. Then, the brain is responsible for organising and synthesising the information derived from the senses in order to enhance external environment detection [23]. Regardless of the modality, the brain sorts the stream of information captured by senses and couples the signals. Simultaneously, it differentiates the information derived from the perceptual events to decode them, and finally, the decision is made. The perceptual systems, as *orienting system*, are categorised into four groups which are basis of all other systems including "*auditory system*, *haptic system*, *taste-smell system* and the *visual system*" [48].

2.2.2 The Perception Process and Psychophysics

Perception includes all five human senses; touch, sight, sound, smell and taste. Besides, it has proprioception, a set of senses responsible for detecting body position and movement changes. Unlike other senses, proprioception is personal and absent from conscious perception [161]. As mentioned in Section 2.2 there is some primary type of perceptions, including auditory, haptic, taste-smell and visual systems. Other senses support humans to perceive balance, body position, acceleration, and the perception of internal states [169, 83]. Perception is a process and varies for every individual and every sense. In this process, the sensory information received from the external environment is selected, organised, identified, and interpreted by the human brain to understand the external surrounding world. The stimulus extracted by the sensory mechanism is filtered by perception and enables humans to observe everything nearby without being overwhelmed. There are three steps in the perception process:

1. The enclosing world is full of stimuli that can draw attention through several senses. These stimuli are called "attended stimuli". Step one includes noticing attended stimuli such as light, sound or taste through one or more senses.

2. The perception system works as an organiser to prevent humans from being confused by the tremendous amount of data received from the external world. Step two entails organising the stimulus elements, called "transduction". It means translating stimulus information from electrical signals into neural processing and structuring them into patterns that make sense to the human's brain. The neural processing depends on the signals received from the sensory channels.

3. The patterns extracted in the previous step are interpreted based on different individual properties such as attitudes, experiences, expectations, or physical conditions. Eventually the *percepts* is formed.

The recognition of an object or event is the consequence of the perception process. Gaining knowledge is the other outcome of this process [83]. The action is the motor response that is done due to the perception process. In other words, the perceptual process aids the human to experience the external world and interact with it. The relation between body and mind in this perceptual process is modelled mathematically to enable scientists to study this process more efficiently. This model is called "Psychophysics", originated in the 1860s by Gustav Theodor Fechner [154], a German experimental psychologist, philosopher, and physicist [8]. He also modelled the result of conscious experience of a sensation that stems from an external physical stimulus [154]. This model has used studies related to neuroscience and computer science. Consequently, the perception and cognition system is indispensable in data physicalisation. Physicalisation leverages perceptual exploration skills. It means physicalisation exploits the active and spatial perception skills in order to transfer more data to the audience [77]. In the next section, physicalisation is defined in depth.

2.3 Data Physicalisation

2.3.1 Definition

Through the investigation in the physicalisation domain, several definitions for data physicalisation have been found. Most of these definitions describe physicalisation as computer-supported mapping or encoding data onto and physical artefacts, attributes of physical shapes or physical attributes of different things such as size, volume, length, colour, texture, temperature or stiffness, instead of pixels of a flat display or ink on the paper [153, 76, 77, 78]. Surprisingly, physicalisation is not a novel way of showing data, and for millennia, the physical form of data has been employed by different motivations, even older than inventing the written languages [102]. By modern advances in computer technologies, especially in recent years, computer screens took over as the preferred and convenient method of presenting data; however, due to the big data boom and data presentation on flat screens' limitations, mentioned in Section 2.1.2, academia has lately started to formally concentrate on physicalisation again [146, 78]. Latterly, a wide range of physical representations of data is crafted and used in particular contexts such as art and entertainment, business analytic, and scientific research [73]. They are more captivating, expressive, and in some cases, even more, effective than visualisations on 2D flat screens. In addition they follow diverse missions varying from infotainment to goal-oriented tasks [166, 76, 73]. Data physicalisation is a multidisciplinary field which uses arts, design, media and sciences, so there are different kind of physicalisations for serving different purposes.

2.3.2 Data Sculptures

A large number of existing data physicalisation is monolithic namely data sculpture [166, 165, 183, 149, 141]. It means they are static and made in one piece, mostly from one material [92] which possess both artistic and functional qualities [66]. They display data in the physical embodiment in a tangible form [165]. Zhao et al. [183] proposed the first data sculpture domain model, which was split into information visualisation, TUIs, visualisation art and interactive art areas. This model focused on artistic-functional and virtual-physical attributes. A scale-model of the slave ship Brooks is an example of showing information physically to highlight the inhumane conditions that African slaves were encountered [29, 174]. The physical model of this ship and its diagram is shown in Figure 2.2. Data sculptures may or may not involve computer-supported processes and can be crafted by artists and designers [78] or they are the outcomes of some devices such as 3D-printers. Figure 2.3 (A) and (B) show a data sculpture installed in Germany, crafted by hammering the nails into wooden cubes, which represent the COVID-19 deaths [60]. Figure 2.3 (C) and (D) show a 3D-printed cup which depicts the temperature in Sydney over 150 years [175].

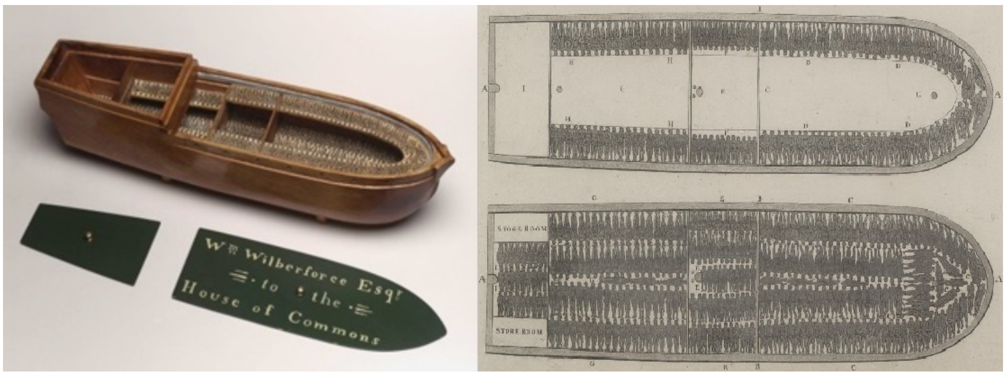


Figure 2.2: Physical model of advocacy for abolition of African slave trade (left) and its diagram (right) [29, 174]

2.3.3 Multimodal Physicalisations

Different studies focus on representing data using specific senses. *Visualisation*, *Sonification*, *Tangible User Interfaces* (TUIs), *Edibilisation* and *Olfaction* are terms which are originated for these purposes. While vision sense in visualisation, hearing sense in sonification, touch and visual senses in TUIs , taste and smell senses in edibilisation are dominant, multimodal physicalisation is not restricted to using one specific sense [134]. On the other hand, it relies on all five senses besides proprioception, a set of senses accountable for detecting body position and movement [161], to enhance users' capability to obtain more data from the representation. In this section, first, the precise definitions for sonification, TUIs, edibilisation, and olfaction are provided, then multimodal physicalisation definitions are given.

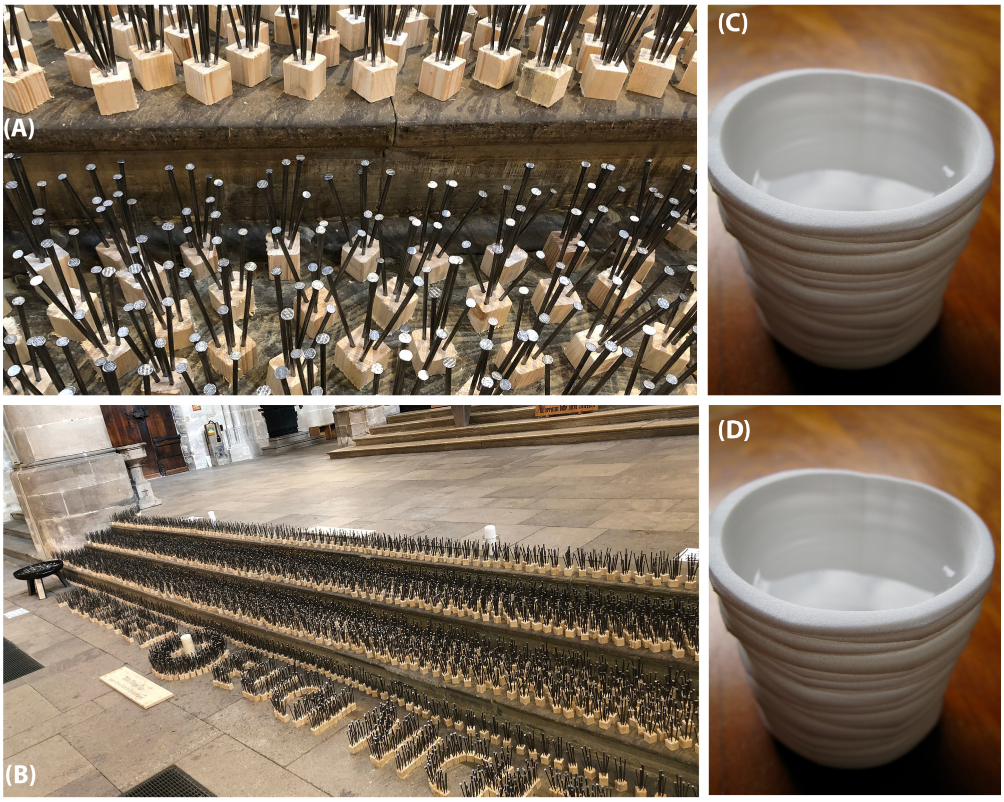


Figure 2.3: (A) and (B) COVID-19 deaths representation by nails hammered in wooden cubes [60], (C) and (D) Measuring cup shows the temperature in Sydney over 150 years [175]

Sonification

Sonification is an interdisciplinary approach to display information and requires expertise across many domains such as *"audio engineering, audiology, computer science, informatics, linguistics, mathematics, music, psychology, and telecommunications"* [85]. To spell out data sonification, it is "transformation of data relations into an acoustic signal" [86]. It means the transformation process maps data onto the sound, and the result can be a stream of waves with changing frequency or an orchestral composition that renders as a sound such as a piece of music. To define it in another way, sonification contributes a complementary approach to investigate the data, and it relies on the idea of listening to a dynamic conversation among neurons during cognitive tasks [26]. The introduction of sonification demonstrates the possibility of using hearing sense in exploring the data. Different audio features such as frequency, pitch, amplitude and location can be exploited to turn data into sound. However, in music contexts, data can map onto sonic dimension as well as different types of instrument sounds, like the violin or piano and higher-order musical dimensions such as tempo and timbre [132].

Tangible User Interfaces

For a prolonged period, the interaction between humans and computers was limited to using a mouse and a keyboard in order to work with windows, icons, menus and pointers (WIMP). Then, many astonishing developments have developed in HCI and provided a broad range of interactions methods that deviate from the WIMP, and one of them is tangible user interfaces [136]. TUIs can be used in different contexts, such as applications for elderly people who have difficulties accepting the new digital technologies [13] or for people with disabilities in a visual sense to enable them to interact with applications using their hands. For example [24] is an attempt to create a tangible user interface to teach Braille. Fitzmaurice et al. took significant steps in the development of "graspable user interfaces" [162]. "Tangible Bits" was one of the most important studies in this field which coupled digital information (bits) with the physical objects and made it tangible in order to enable users to grasp and manipulate the interfaces [70]. They introduced three prototype systems, including MetaDesk, TransBoard, and AmbientRoom. Figure 2.4 illustrates the interaction with the digital world through the objects using the interactive surface and ambient media in the background. Eventually, TUIs' ultimate goal is to use physical mediums to link the digital world with physical objects [181].

Edibilisation

All concepts explained in previous sections follow one central aim: data communication. The other approach, which enables users to communicate with data using taste sense, is data edibilisation. It is a pioneer strategy that proposes encoding data with edible materials in order to bolster taste sensory channel in data conveying process [170]. Data visualisation, Sonification, and TUIs show how to use the advantage of visual, hearing, and touch senses, respectively, in traversing data. However, the design space of data representation can be enlarged to incorporate taste and smell senses to represent data

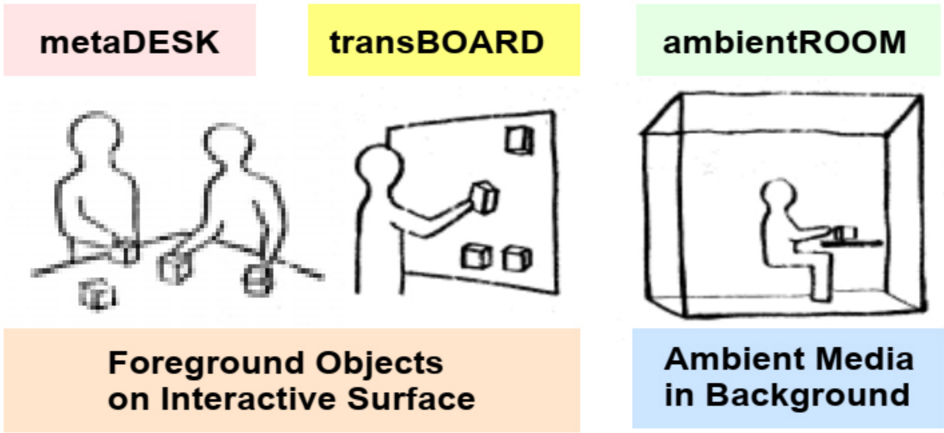


Figure 2.4: Three prototypes introduced by Ishi and Ulmer to interact with the digital world through the objects using an interactive surface and ambient media in the background [70]

in a more evocative and unforgettable way [124]. As it is shown in Chapter 1, a 3D-printed biscuit with edible mushrooms growing on it is an example of displaying the working hours, temperature, and humidity of the office using edible materials, Figure 1.2 [170]. Moreover, *Data Cuisine* is the name of the project performed by data visualisation expert Stefaner and Jaschko, to represent the local data by the local food through some qualities such as colour, form, smell, taste, nutrition and origin [144]. Figure 2.5 shows some plates made in this project.

Olfaction

The last piece of the multi-sensory information representation puzzle uses olfaction to represent data. Information olfaction is fragrant information visualisation. In other words, information olfaction is a complementary approach whose mission is expanding information visualisation design space to use scent or olfactory stimuli to convey data [113]. Due to the smell sense strength, which enables humans to distinguish between more than one trillion olfactory stimuli by one estimate [21], it is an extraordinary sensory channel to be used in multimodal visualisation. Olfaction is chemoreception, the process by which organisms react to chemical stimuli in their environments [88], that induce the sense of smell. It is a compelling stimulant and can be used to amplify cognition [41]. There are roughly 1,000 various sorts of odorant receptors capable of detecting molecule structures. The sensor neurons are

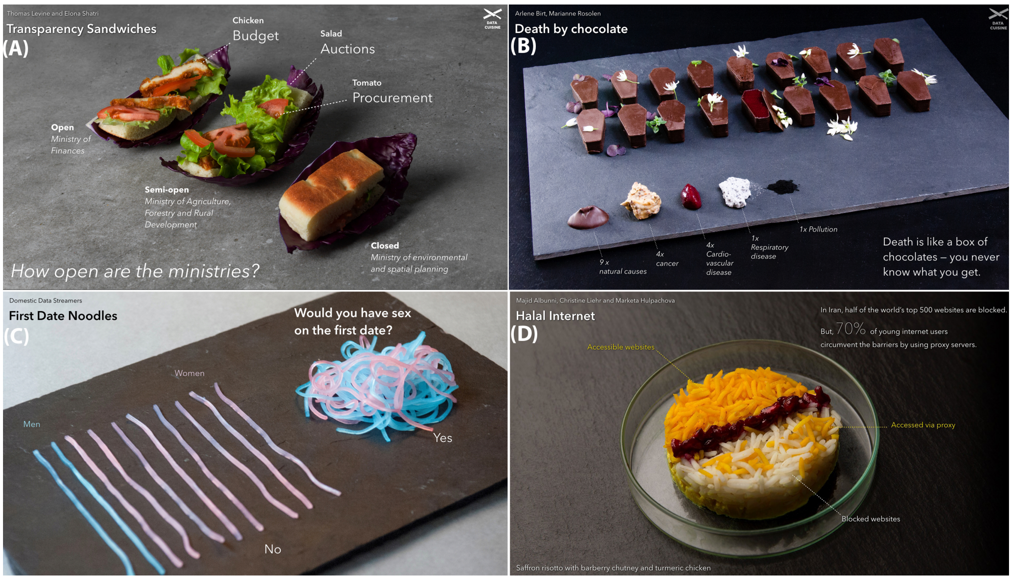


Figure 2.5: (A) shows Transparency Sandwiches, cooked based on a transparency report from the Kosovan Democratic Institute (KDI) [93]. (B) shows a plate named Death by Chocolate represents the most common causes of death in Belgium using dark chocolate and five different fillings [11]. (C) is called First Date Noodles dish, which is cooked in order to display data about the sex life of young people in Barcelona [147]. (D) is the Internet penetration rate in Iran, that is cooked using ingredients representing accessible web pages and filtering data in Iran [98].

all connected to the olfactory bulb in the brain. Through this bundling, the dimensionality of the information is received from the olfactory sensory neurons and afterwards is recognised [106]. All these make the odour receptors very effective in human's body. Moreover, it is believed that olfactory signals that extract information from human memory tend to trigger more intense emotion than other sensory stimuli [50]. Patnaik et al. [113] endeavour to propose the framework to translate information to the olfactory representation; VISCENT. A prototype system consisting of several numbers of hardware as an olfactory display that carries symbols of temperature and direction, a virtual reality headset and a workstation. The software system combines the olfactory display with a traditional visualisation display. Figure 2.6 displays the viSent and its components on the prototype, including "the ultrasonic atomisers, diffusing fan, pneumatic solenoid valves, peltier-based thermoelectric heating system and the accompanying 2D visualisation" [113].

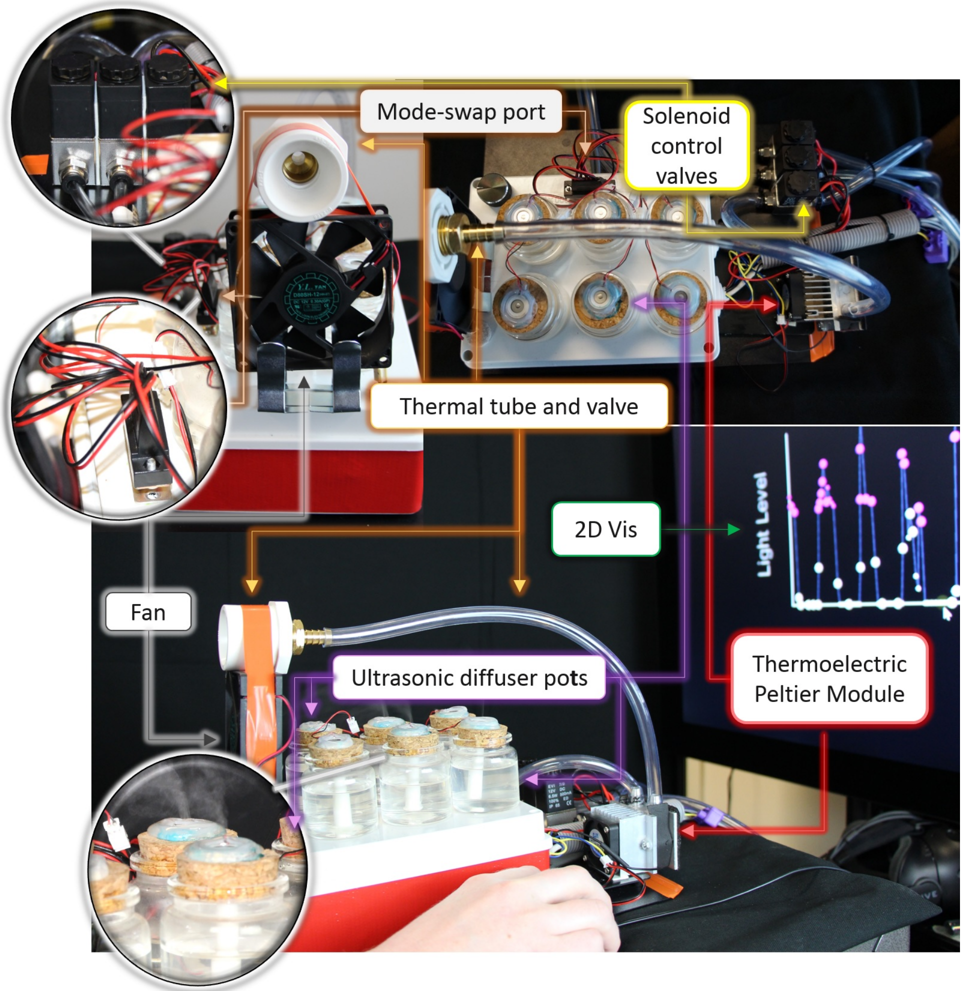


Figure 2.6: viSent and its components in the prototype proposed by Patnaik et al. [113]

Multimodal Physicalisations

Previous sections explained using specific modalities in conveying data, while multimodal physicalisation combines all human sensory channels to expand the capability of transferring data to the user simultaneously. For instance, while using vision sensation assists users to interpret visual variables such as shape, size, length, position, orientation, area, volume, colour, light, opacity, brightness, curvature and some other visual, physical attributes, tactile empowers users to apprehend pressure, vibration, temperature, texture, elasticity, wetness, dryness and stiffness. Sound and all its attributes such as frequency, amplitude (volume), direction or location are perceived by auditory sensation, and the gustatory system and olfaction are responsible for perceiving the flavour and smell, respectively. Combining two or more of these robust sensation systems in multimodal physicalisation augments data perception and enables the data representation to tell the data story from more aspects at the same time. “Edible Bits” is an example of combining vision, touch and taste sensation to map data onto the screen, tangible interface and edible material all together [101]. In the next section, attributes of the materials which can aid to create multimodal physicalisation by participating in it as a unit or block are discussed.

2.3.4 Material Properties

The range of physicalisation is vast, from static monolithic data sculpture to precise physical data models [137, 67], but this thesis concentrates on investigating how to create a dynamic interactive physicalisation explicitly. In order to achieve this objective, it has been tried to survey the different attributes of materials, which are flexible and can alter without exerting an influence on the material identity. These properties can form different pieces (units or blocks) of physicalisation. In the following, a short description of the general categories of the material properties is provided.

2.3.5 Classes of Material Properties

There are thousands of materials, and most of them are categorised into one of three categories. These categories are defined based on the material atomic bonding forces. These three classifications are metallic, ceramic and polymeric. The materials in these classes are further organised based on their chemical compositions or different properties [163]. There are seven different classes of material properties. In the following, these properties and their short definition are given [164].

- **Physical Properties**: These properties are observable, and they do not have any impact on the identity of the material. These properties include density, colour, size and shape, the specific gravity of the material or porosity [164].

- **Chemical Properties**: The chemical composition of the material has a direct impact on the chemical properties. When one material interacts with the other, and some changes happen in their compositions due to the contact, the chemical properties will change [164].

- **Thermal Properties**: Thermal properties are related to the material's conductivity of heat. It means they appear while the heat is passed through the material. In other words, they refer to the material behaviours under thermal load. These properties are thermal conductivity, thermal expansion, specific heat, boiling point, melting point, and thermal diffusivity [164].

- **Electrical Properties**: These properties are related to the materials ability to conduct the electrical current. They include some different properties such as resistance, electrical conductivity, temperature coefficient of resistance, dielectric strength or thermoelectricity [164].

- **Magnetic Properties**: These properties determine the material ability in terms of particular magnetic application. Some of these materials are the ratio of magnetic flux density called permeability, magnetic hysteresis, coercive force [164].

- **Optical Properties**: Transmission, reflection and absorption, which are related to material response to the radiation, are called optical Properties [164].

- **Mechanical Properties**: Mechanical properties have a direct relation with material response to the load and how much deformation happens in it by applying the load or pressure [164].

As explained, excluding physical properties, the rest of the properties are related to the material identity. Later in Section 4.2, it is clarified how the specific type of properties, which can be used as a unit or block in a physicalisation, is chosen among these properties. In this thesis, these properties are called physical variables. As a quick simplification, the physical property of the material, which is not a part of material identity, is a good candidate for being used as a block in the physical representation of data by considering its ability to change dynamically. Some other material properties are dependent on the material identity and are not as flexible as physical properties; for instance, the boiling point, which is the temperature at which the liquid changes into a vapor [115] depends on the inter-molecular forces (IMFs) between the atoms or molecules in that liquid [173]. It means the boiling point of the specific liquid does not change during the time at the same atmospheric pressure [25]. Hence, using these types of material properties is out of this thesis scope. However, this kind of material properties can participate in the physicalisation to represent the scenario which does not need dynamicity. The proposed solution to create dynamic interactive physicalisation using material properties is limited to physical properties in this thesis. The final physical representation of data is composed of different units, each of which corresponds to one data aspect and one physical variable. Creating physicalisation as a composite of several units makes it possible to parametrise, produce and control each block separately and fast [150].

2.4 Grammars for Visualisations

A grammar is a set of general structures and rules of a language that aids to generate the statements following predefined laws [179]. The aim of the grammar is *"bring things together in a coherent way that previously appeared unrelated and which also will provide a basis for dealing systematically with new situations"* [33]. Grammar is used in any language such as natural languages, programming languages, or even a language that leads to describing some graphics' components. This last type of grammar was called the *Grammar of Graphics* for the first time by Wickham [177]. Additionally, as illustrated in Chapter 2, visualisation is the process of decorating data using a graphical representation that enables users to interact with them and get the message of data more easily [165]. Recently computer-supported tools and libraries have provided a powerful mechanism for creating graphics in order to address the problem of converting data into captivating data visualisation [69]. They can create visualisations at different levels of abstractions. Some of these tools, such as Tableau, Looker, Qlik Sense[1] are well known. D3 [16], Processing [123], Raphael [180], Prefuse [63], Protovis [15, 62] or Charts.js [34] are the examples of the visualisation libraries assisting "skilled" users to design the visualisation from scratch. However, designing visualisation using these programming libraries requires specific skills, and non-expert users usually require programming expertise to visualise data using them. But learning the grammar, which generates graphics from data, eases creating the predefined, creative and expressive graphics [178].

Wilkinson [179] proposed the *Grammar of Graphics* describing statistical graphics. This grammar is an abstract approach to think, reason and interact with graphics. Later building upon these notions, Wickham [177, 178] introduced the *Layered Grammar of Graphics* named ggplot2, which is built based on the initial grammar. It is a composite of several independent components which work together in different levels of abstraction to generate the final powerful interactive graphics. This grammar is very powerful because

[1] `https://www.geeksforgeeks.org/10-best-data-visualization-tools-in-2020/` `(Accessedon05/07/2021)`

it does not force the user to have predefined graphics, and they can even innovate new sort of graphics [178]. The main goal of ggplot2 is to prioritise layers and adapt it within R. For more clarification, this grammar describes how the data is mapped onto aesthetic attributes (colour, shape, size) of geometric objects (points, lines, bars) to create the statistical graphic. However, both of these approaches concentrate on visual specification, and they do not truly propose the method for interaction. Moreover, this latter grammar is weak in area plots, including bar charts, spine plots, histograms or mosaic plots. There are some other declarative visualisation grammars, which are a popular means of generating visualisations. They focus on facilitating turning data into several visual forms, namely Protovis [62], Vega [131], Reactive Vega [130], Vega-Lite [129] and ggvis [27]. All of these grammars mostly focus on accelerating the development process and language-level optimisations. Still, most of them suffer from the lack of first-class support for interaction. Protovis, D3 and Vega are low-level grammars that support explanatory data visualisation. Due to their fine-grained control, they are the foundation of analysis tools [129].

Satyanarayan et al. [131] proposed a model of declarative interaction design for data visualisations in 2014 and called it Vega. In this model, the higher-level semantic signals are formed from data streams. In the next step, predicates and scale inversion are generated from signals allowing the interactive selections generalisation at the geometry level. This model extends the specification of visual representations with interaction design support, and it is a significant step towards enabling interaction in declarative languages for data visualisation. Moreover, it follows the declarative JSON syntax, which makes the programmatic generation of visualisations easier. Eventually, it makes the programs that output the high-level reasoning about visualisation. Vega is easily integrated with graphical design tools, statistical packages, and computational environments. However, this model needs improvement in terms of performance optimisation. Also, getting accustomed to this grammar is not easy for novices.

In 2015, Satyanarayan et al. [130] provided a robust implementation for Vega grammar using event-driven reactive functional programming. This streaming data flow architecture is called Reactive Vega. It makes the data flow graph with three first-class streaming data sources: input data, scene elements, and interaction events. Reactive Vega has a parser to traverse an input and instantiate the necessary components to render a visualisation. Its architecture, the server-side offloading computation, provides opportunities to investigate scalable visualisation. Figure 2.7 shows the graph which Reactive Vega creates for streaming financial data extracted from the Yahoo API. Reactive Vega supports interaction, and while the user reacts with the presentation, it propagates the update through the graph and triggers an efficient update. The visualisation is re-rendered; however, working with Reactive Vega is difficult for novices, and it still requires improvement in terms of authoring and debugging specification.

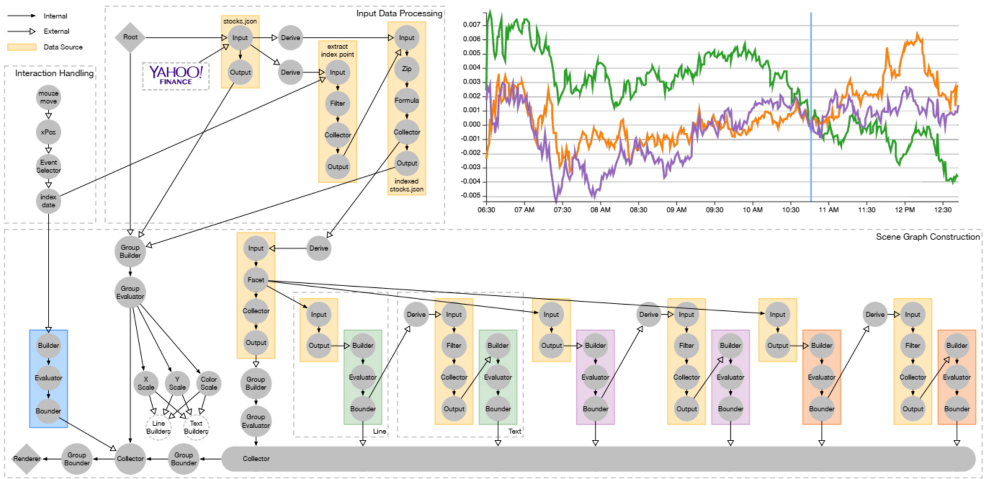


Figure 2.7: The graph created by Reactive Vega for from Yahoo financial data API [130]

Propagating updates through the graph and re-rendering the visualisation is time-consuming. Vega-Lite [129] has been introduced to make this process faster. This high-level grammar enables rapid interactive visualisation by combining traditional rules in the *Grammar of Graphics* with a interaction grammar to provide visual encoding rules with interaction design. Vega-Lite is expressive to propose an interactive visualisation taxonomy. However, this grammar does not support the components manipulation determined in compile time, this limitation affects interactivity. ATOM [112], like D3 [16], is the other grammar based on the *Grammar of Graphics* [179] attempting to fill the gap of existing declarative grammars which does not describe the unit visualisations. Unit visualisation has an objective mapping between each visual mark and data item. ATOM can generate any arbitrary unit visualisation, and its advantage is reducing the need for programming knowledge. However, this grammar is implemented to support *unit visualisations*, and its further versions are supposed the additional visual marks, and interaction.

Beyond these declarative general-purpose grammars that support almost all visualisations, there are some domain-specific grammars for specific visualisations. Wickham and Hofmann [176] proposed the grammar, which combines a few primitives in order to generate statistical graphics. Moreover, a domain-specific grammar is presented for generating Mosaics visualisations that slice and dice data sets into mosaics [97]. The other example of the domain-specific grammar research area is a design space of sequential space-filling layout which focus on creating tree-maps and pixel bar charts with five independent dimensions [139, 47]. However, all grammars mentioned above are a formal approach containing general structures and rules to transform data to the visual representation. This thesis is an attempt to propose a grammar in the dynamic interactive physicalisation domain. It means the grammar which has the specification for converting data to physical attributes, the behaviour of materials or artefacts. Through this investigation, no study which proposed such a grammar is found. In the following chapter, the previous and ongoing researches in the physicalisation domain are reviewed. After discussing their limitation, the solution leads to creating the dynamic interactive physicalisation using physical attributes of materials is discussed.

3
Related Work

The identified problem this thesis focuses on is contributing to dynamic interactive data physicalisation design space by introducing the grammar whose goal is aiding to build the physicalisation more efficiently and effortlessly. Since implementing the complete grammar is a complicated task, this goal is separated into two main sub-goals; (1) introducing the list of physical properties which can be used as a unit or block in the data physicalisation and (2) the set of physical variables which can be combined to involve more human sensory channels and transfer more aspects of data to the audiences at the same time. Finally, the first version of the *Grammar of Physicalisation*, which is based on the *Grammar of Graphics*, is introduced. The stated problem stems from the lack of a formalised approach or a grammar in the physicalisation research area, which aims to map data onto physical variables leading to the final physical representation, which provides interactivity and dynamicity. Reviewing existing literature in this discipline and using the expert's opinions, who is the supervisor of this thesis, are the approaches to assure the stated problem. Many studies are reviewed in Chapter 2 and this chapter, which covers different perspectives of the research topics such as manufacturing techniques and methods, cognition pipelines, the efficacy of physical visualisations or static and dynamic physicalisation. For following the purpose of this thesis, the proposed systematic method as a grammar is called the *Grammar of Physicalisation*. Through this grammar, which provides the formalised approach to translate raw data into physical properties or behaviours of materials and artefacts, different physical candidates and their combinations are studied. These candidates, called physical variables [140], can form separate programmable and updatable units or blocks in physicalisation and enhance data exploration in physical form.

Since Physicalisation is a multidisciplinary research area, this thesis uses various sciences and research areas such as visualisation, psychology, psychophysics, human perceptual and cognitive system, and material science. In order to narrow the literature review section, two main topics of this thesis (physicalisation and the physical attributes in physicalisation) are reviewed, and inquiring the literature related to the rest of the topics is left to the interested readers, although in Chapter 2, required information about all these topics are provided which eases following the main goal of this thesis for the novices or non-experts in these concepts. Based on the investigation performed in this research, there is a lack of formalised approach which aids in creating the physicalisation using physical attributes of materials in dynamic interactive physicalisation literature. In order to tackle this deficiency in this research area, a review of relevant researches is provided. Moreover, physicalisation is studied regarding static and dynamic perspectives. Finally, the usage of different physical attributes such as temperature, texture or size is explored in the data physicalisation domain.

3.1 Physicalisations

A broad-spectrum of physical visualisations has been crafted by ordinary people, artists, analysts and scientists for centuries [73]. Each of them follows a specific purpose ranging from storing data to goal-oriented task [73]. Crafting sculptures by humans has a prolonged history, and the most ancient ones belong to 35 000 years ago [74]. Figure 3.1 shows the Venus sculpture, which has exaggerated physical features. However, in the recent century, this research area has attracted much more interest in the academic world [73]. Modern physicalisation, as a recently developing research area, is relatively limited to unique studies. Having said that, available publications cover various aspects of this research topic such as cognition, design and manufacturing techniques, static and dynamic physicalisation, and the effectiveness of physical visualisations. Moreover, these studies not only focus on studying effective modalities used in physicalisation, but they also survey purposes (i.e. casual or utilitarian) behind making physical visualisations and their ability to support live data and interactivity [59]. Hogan and Hornecker [66], after analysing 154 instances of data physicalisations, have presented the classification based on five different categories, including (1) the modalities used in physicalisation, (2) the material mainly used in crafting physicalisation and its relation with data, (3) the purpose of physicalisation, (4) how the user can interact with physical data and (5) weather data is live or archived. Their analysis revealed the following information. Sight and touch and their combination are mostly used in physicalisations (84%) rather than other modalities. Regarding materials and their relationship with data, they did not find any link between material choice and data source. Just one-quarters of physicalisations used live data, and only about two-fifths support interactivity. Three-quarters of the physicalisation follows casual purposes, and the rest are built to fulfil the utilitarian purposes. It means that just 25% of studied physicalisations are tended to make the users exploit more modalities. In contrast, casual physicalisations require fewer modalities to interact, and they mostly use static data without interactivity. Static data physicalisation is made of one piece or one material, it is fixed, and changes in data cannot affect them. It means they cannot adjust themselves regarding new data, and they do not usually involve a lot of computations [78].

Figure 3.1: The Venus sculpture [74]

In Chapter 2, plenty of static physicalisation examples has been discussed. Unlike static data physicalisation, dynamic physicalisation can adjust itself when the updates in the data or the user interaction happens. The process of creating static physical visualisation is laborious [77]; however, it is becoming increasingly efficient since digital fabrication technologies are more accessible.

Swaminathan et al. [153] studied the role of digital fabrication techniques in creating data physicalisation. They focused on the problems of designing and manufacturing that exist in constructing the physicalisation. These problems are *Manufacturability*, *Assembly and Fit*, *Balance and Stability*, and *Strength*. Moreover, they discussed the need for an authoring tool, called MakerVis, in order to facilitate the data physicalisation processes [152, 153]. This authoring tool can be an excellent option for designing and customising the physical representation, leading to easier crafting. However, it is practical in fabricating physical representation instead of mapping data onto physical properties or artefacts that have the potential to change dynamically to produce dynamic interactive physicalisation.

3.1.1 Static Physicalisations

Physical artefacts, such as tools, clothes, kitchen utensils, sculptures or coins, are a human-made objects which can be used for diverse purposes [167]. Using physical objects for keeping data is not something recent [102]. For instance, more than 7000 years ago, the clay tokens were used to store quantitative data or abstract goods by the Sumerians [102]. The other example is using complex assemblies of knotted ropes for data storage by Incas, instead of writing systems, more than 500 years ago [159]. Also, in the contemporary century, the artefacts have been used as a data-based medium [183]. It means they have not only artistic and functional qualities but also carry out the data whose aim is augmenting the audience's understanding of the specific topic [183]. The static physical representation of data follows the same purpose. The specific data underlain in the representation is supposed to be sent to the audience and aids them to understand it more efficiently [183]. Modern developments in digital fabrication and 3D printing promote the process of crafting a physical form of data [67, 58]. To discuss the capabilities and limitation of static physicalisation as an general approach for representing data, several studies are explored in the following.

The early use of static physicalisation was driven mostly from an artistic perspective [183]. On the other hand, driven by the desire to talk about social issues publicly, many artists and politicians have represented their concerns in the physical forms [183]. The arrangements of wooden crosses, which displays the loss of soldiers tragedy in the British wars, shown in Figure 3.2 [121, 142] and the scale-model of slave ship [29] described in Chapter 2 are the examples of talking about social concerns physically. Although these examples are complex and time-consuming to be built, they both have artistic and functional qualities, which can be helpful in engaging audiences' attention, interest and curiosity. As it is obvious in previous examples of data sculpture, no metaphor is used to symbolise underlying data. Using embodiment in physical representation is the other approach to transform data to physical shape [183]. The term 'embody' means expressing the abstract concept in a concrete form [110]. In the static data physicalisation research field, "embody" means abstract data expression using the physical object [183] metaphorically. It means using a familiar representative or symbol to show the other concept which is less known for the audience [90]. The "Of All The People In All The World" project [182] is an example to use metaphor to map digital data onto physical representation. In this project, starting from 2003 until now, the grains of rice are used to represent statistics regarding the populations of towns and cities in comparison by the number of doctors, soldiers, newborn and deceased people in one day. Figure 3.3 illustrates how this data is shown by grains of rice to represent data metaphorically. The mentioned examples show no formalised ways have been exploited to build data sculptures, and it makes the assembling process laborious; moreover, maintaining these data representations is exhausting and needs a great deal of endurance. In addition, they do not support interactivity. It means if the user wants to investigate more aspects of data, they cannot explore the physicalisation by interacting with them. However, there are some dynamic physicalisation efforts with which users are able to interact.

Figure 3.2: Remembrance of soldiers killed in World War I built by wooden crosses and poppy flowers [121, 142]

3.1.2 Dynamic Physicalisations

According to Hogan and Hornecker [66], while the majority of the endeavours in the physicalisation research area are concentrated on building static physical visualisation, it is crucial to dedicate more efforts to study how to build the dynamic interactive physicalisation. Since physicalisation can be

Figure 3.3: Of All The People In All The World project, in which grains of rice are used to show statistics data about people around the world. (A) shows starting project in Birmingham in 2003. (B) represents a part of the project in Tokyo in 2010. (C) is taken from the project in Bonn in 2015. (D) is the most recent one which is taken in Birmingham in 2021 [182].

built from different physical blocks, and each block can be a physical artefact or the physical property of it, changes in data should lead to changes in each individual part [150]. Changes in data can stem from user interaction or the software [140], in both cases, actuating physical units of physicalisation can support changes. So the dynamic interactive physicalisation succeeds when it adopts its representation behaviour by forthcoming changes of data. Furthermore, researchers in the dynamic physicalisation domain [117] believe that if the representation is dynamic, it will be more realistic for the end users. Therefore, shape-changing approaches which aim to provide the actuating interfaces in terms of shape, is a good start to discuss how to augment users' experience by giving them an interface which can change.

Rasmussen et al. [122] explain how shape-changing interface techniques can deliver information to the users by enhancing the physical affordance. Shape-changing interfaces are impressive efforts in the dynamic data physicalisation domain. They are progressively used in building physical user interfaces, which enhances users' interaction with digital information. The dominant senses in this data representation are mostly tactile and vision [122]. Different shape-changing techniques are used to create dynamic physical interfaces. These techniques can be categorised into two different classes; (1) the techniques which change the physical properties of the used artefacts in the final representation and (2) the methods which have an impact on user interaction with these interfaces. For instance, changes can influence the pace, the location, the orientation and the texture of artefacts [117]. So that these changes can lead to direct and indirect interaction. For more clarification, direct interaction can be triggered when the user pulls or push some part of representation directly, and indirect interaction is the result of some changes due to new inputs from an embedded software [122].

The first engaging example of using these interfaces for transferring data is shape-changing mobiles [64] which rotate their chassis to pass some data (interactive feedback, user notification, and ambient display) [64] to the user. In this prototype, one-dimensional tactile feedback allows users to get information about the number of photos in the gallery. As it is shown in Figure 3.4, the phone should be held in the horizontal direction, and the thicker body on one side shows more photos on the same side of the gallery. There are two other applications for this prototype, which is notifying users about download progress and battery level by the thickness of the chassis. This idea is original, and users can capture data through tactile modality while they are using vision and hearing senses to get ordinary data from mobiles. However, with the advances in touch screens, the tactile modality is not available anymore. In addition, using smartwatches enables users to have all their notifications on their wrist, even without touching their phones. Moreover, new advanced technologies have allowed mobile manufacturers to produce thinner and lighter products that satisfy users, and increasing thickness of the mobile's chassis does not seem a genuine idea anymore.

The other example of using shape-changing interface is Surflex [31]. Surflex is a programmable surface which takes advantage of the properties of both shape-memory alloy and foam. It proposes a surface that can be programmed to a new shape. As shown in Figure 3.5, Surflex is built from 1-inch foam besides 2 circuit boards which are connected through 8 shape-memory alloy coils. These coils are made of nickel and titanium and can remember the previous geometry. Coelho et al. have proposed two different applications for this technology, including adaptable interfaces and the real-time computer modelling of objects.

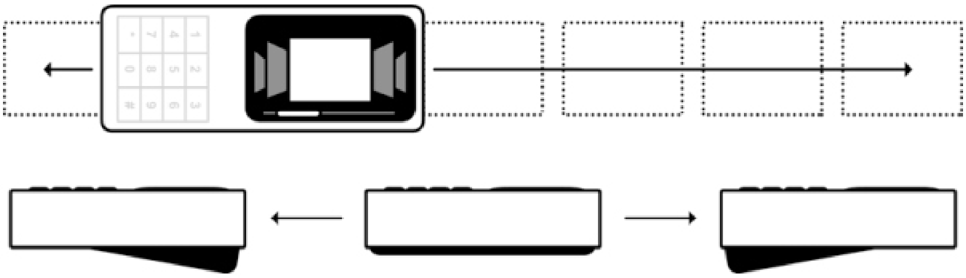


Figure 3.4: Interactive one-dimensional tactile feedback used to show the number of pictures right or left direction of the gallery [64]

EMERGE [156] is the first attempt to propose the dynamic bar chart, which enables the user to interact with data through dynamic physicalisation. The design of this project consists of three main modules on the hardware side; self-actuating rods, RGB LEDs and touch detection. This hardware is built from a 10 × 10 array of actuated plastic rods, each of which is linked to 100 motorised potentiometer sliders, shown in Figure 3.6(A). Moreover, the EMERGE software has three layers, including application, model, and firmware, Figure 3.6(B). Although his study provides physical dynamic bar charts which supports data analysis-based interaction techniques, the hardware is pre-built and limited to 10 rows. Moreover, this physical representation is the physical translation of visual bar charts. There are many efforts in the shape-changing field, which boost dynamic physicalisations. However, as it is explored in this thesis, the process of building them is tedious and complicated. In addition, they mostly use tactile and vision but not other sensations. There are some other studies which are not categorised as shape-changing interfaces but contribute to the dynamic physicalisation field. These studies focus on using haptic interaction and take advantage of this modality's strength in perceiving information [95].

The Heat-Nav [158] focuses on touch sense in order to transform data using thermal feedback. There are three thermal array displays in this device, as shown in Figure 3.7. The *proportional integral derivative* controllers are controlling these displays in order to generate the output temperature. Moreover, each display has a thermo-electronic cooling device that simulates warmth and coolness based on input data. There is a navigation application for this project. The user wears the device on their wrist and starts navigating through a 2D maze. There are two main thermal thresholds which

Figure 3.5: Surflex's deformation steps to get the new shape [31]

give feedback to the user whether they are on the right path or not. This experiment shows that continuous changes in the temperature can control the behaviour and assist the user to find the right direction more efficiently.

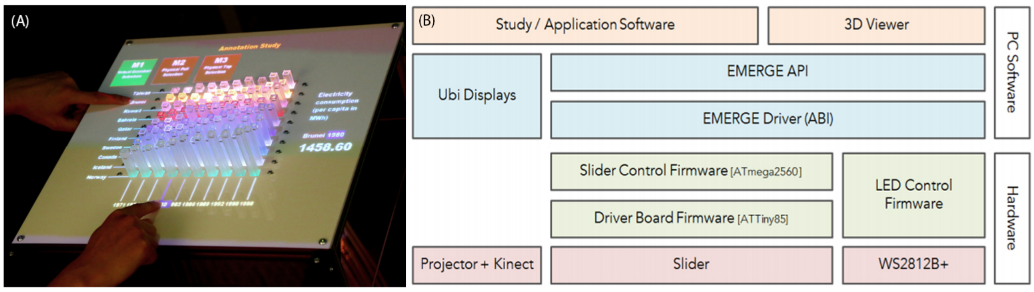


Figure 3.6: (A) EMERGE hardware built from self-actuating rods and RGB LEDs. (B) EMERGE three-layered software [156]

Iwasaki et al.[71] initiated the project named as AffectPhone, displayed in Figure 3.8, which is used to detect a user's emotional state using Galvanic Skin Response (GSR). AffectPhone conveys non-verbal information in an ambient manner and is expected to enhance existing telecommunication. After detecting the users' emotional state by AffectPhone, it translates this data into the temperature changes (warmth or coolness) in the back panel of the other handset using the Peltier module. Since the user does not need to wear any extra sensor, it does not have any impact on the user's daily use of the mobile phone.

Brown et al. [19] introduced the prototype, which is a mobile audio-tactile messaging system. They called it as Shake2Talk, which can send audio and tactile sensations together to the receiver. Shake2Talk comprises a phone and three sensors (accelerometers, gyroscopes and capacitive sensors) attached to

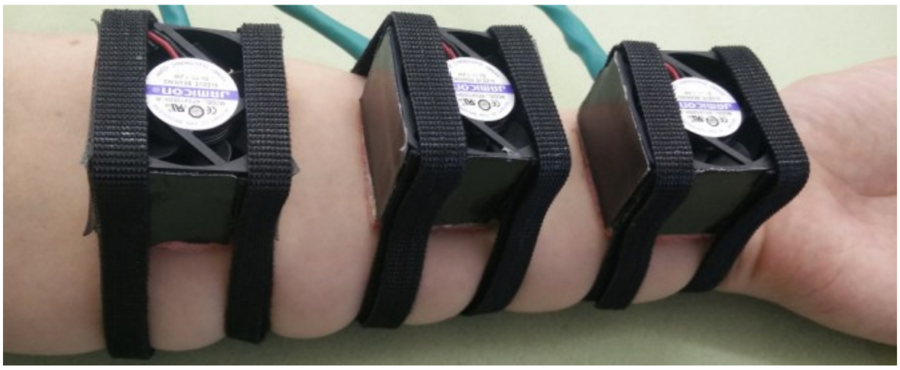


Figure 3.7: The Heat-Nav bracelet for transforming data in thermal form [158]

the phone. These sensors are used for the gesture recognition, and an eccentric motor provides tactile output [20]. To compose a message, the user should press the record button, and performs the gesture(s), explained in Table 3.1. There is an association between each gesture and the audio-tactile message. When the sender plays a gesture, the message is created only if a 3-way rocker button is pressed on the device in order to prevent accidental triggering. After sending the message, the incoming sound is synchronised with vibrotactile notification. It means that the receiver can feel the message by tactile even without opening, seeing and reading it.

Hiya-Atsu-Mouse [105] is the other project which transfers data using thermal feedback. As it is shown in Figure 3.9, Hiya-Atsu-Mouse is a mouse device with the thermal capabilities. This device is developed to convey information in an expressive manner using thermal feedback. It means the user can feel the object's temperature shown on the computer screen by their palm or fingertip because the mouse is equipped with the thermal capabilities for transferring data using temperature. Thermal hug [54], proposed by Gooch and Watts, is the other project using temperature to transfer data in order to make "social presence" real in the digital world. As social presence means "being there", this project focuses on turning the hugs into digital data and transferring it to the receiver via digital links. Figure 3.10 represents the vest that simulates the thermal hug, and the result of this paper shows that people who received the thermal hugs have a better feeling about social presence rather than those who did not receive it.

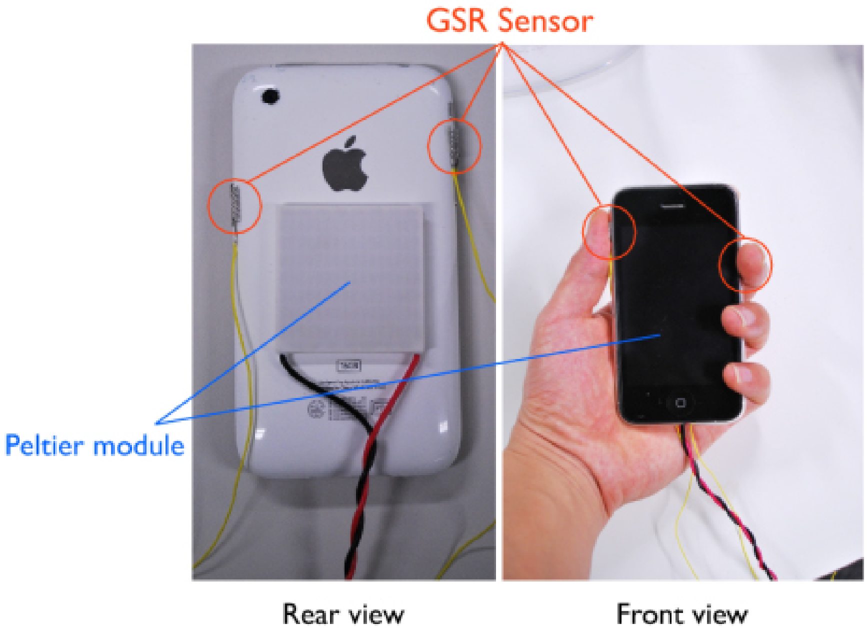


Figure 3.8: AffectPhone project to detect users' emotional state using GSR[71]

Gesture	Button Up	Button In	Button Down
Flick	Whip	Slap	Plate smash
Twist	Key in lock	Beer pour	Car start
Tap	Tap glass	Hit metal	Knock on wood
Stroke	Cat purr	Snore	Heartbeat

Table 3.1: Audio-tactile messages made by gesture and button position [19]

Besides all studies regarding thermal feedback, which contribute significantly to the dynamic physicalisation field, some other studies focus on conveying data using vibration. The Tesla-Touch [6] is a new technology for the tactile display based on electrovibration. This technology uses electro vibration system in order to provide richer user experiences. One of the applications of this technology is simulating the texture of the objects through the vibration feedback for visually-impaired people. Tesla-Touch consists of a touch screen made of a transparent and insulated electrode sheet. Moreover, It is equipped with motion sensors for fingers' position detection. Each graphic has a texture information tag. When the user touches

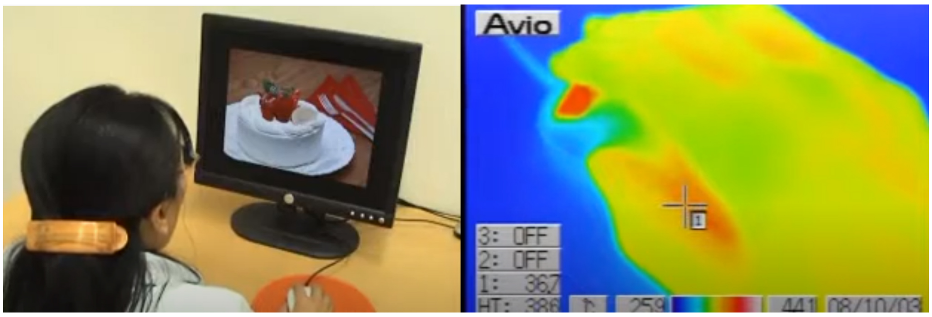


Figure 3.9: Hiya-Atsu-Mouse prototype which transfers the temperature of the object to the mouse [105]

the Tesla-Touch screen, the electro waves are produced to transfer texture information to the user through tactile modality. BubbleWrap [5] is the other study that provides haptic sensations in terms of vibration. BubbleWrap, is made up of a matrix of electromagnetic actuators enclosed in fabric, Figure 3.11. Each actuator is an expandable cell which provides active haptic feedback in terms of vibration and passive haptic feedback in terms of shape and firmness.

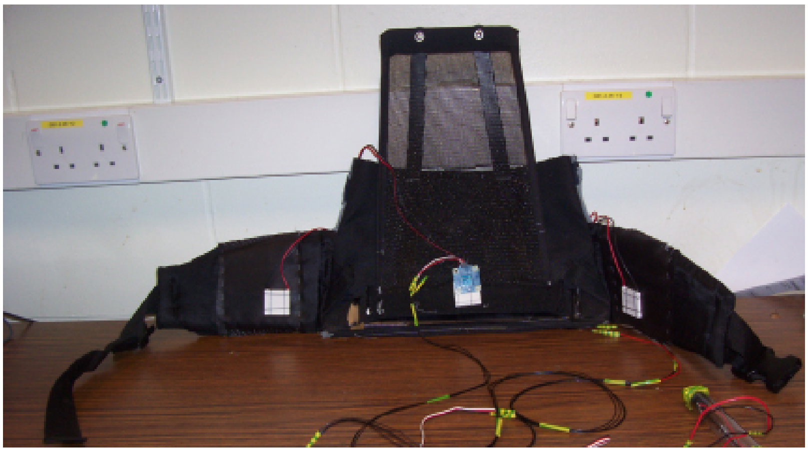


Figure 3.10: Thermal hug vest which simulates the real hug in order to support social presence [54]

A weight-changing device [108] is a prototype which can make changes in the weight and volume by transferring the liquid metal using a bi-directional pump. The motor is responsible for injecting and removing the liquid metal into and from a target object, and consequently, the weight and volume

Figure 3.11: BubbleWrap system which provides haptic feedback in terms of vibration and firmness [5]

of the object can alter dynamically. This prototype consists of two main parts; a weight-changing object and a mass supply. In addition, the mass supply has a pump, a liquid metal tank and a control circuit, Figure 3.12. Follmer et al. [45] proposed the application providing the novel forms of user interaction. Jamming User Interface controls the material stiffness based on a new hydraulic-based technique. It is a scalable technique for controlling the stiffness of the object programmatically in which the computer-controlled method for the jamming of the granular particles is used.

Figure 3.12: (A) Implementation of the weight/volume-changing system. (B) Changes in the weight result of injecting liquid metal, (C) Changes in the weight and volume result of injecting liquid metal [108]

3.2 Related Work Limitations

The literature reviewed in this section and Chapter 2 is just the small section of the main literature reviewed by the writer of this thesis. After reviewing several works in static and dynamic data physicalisation domains as well as the approaches they proposed for implementing the dynamic physicalisation, some limitations are addressed here. It is important to note that these limitations are related to the techniques that they used to build the representation and not to the quality or efficacy. As mentioned in Chapter 1, despite all the visualisation limitations, it is still a very powerful tool in revealing the pattern hidden in the data. Considering this strength, visualisation is mostly used to tell the data story. If the new alternative is being investigated to be replaced with visualisation or at least used as a complementary approach to tackle its limitations, it should be obviously more capable of representing data and support interactivity and dynamicity to cover the ad-hoc changes in the data stream. Physicalisation is proposed as an acceptable method due to its extensive usage of all human senses instead of the display and not favouring one sense over the others, as well as its capability of enhancing user's cognition. As all human's senses can be exploited to capture data from physicalisation simultaneously, the users' ability to capture and process more data is boosted.

As discussed before, static physicalisations are fabricated statically. It means once the physical model is built, it is incapable of depicting new data, or it will be very time-consuming to be adapted with it. It is sometimes forced to rebuild the complete new static physicalisation to show the small change in the data. Although all exciting works in the dynamic physicalisation domain have contributed significantly to this research area, there is still a gap that is so crucial to be filled. The lack of formalised method or grammar for encoding raw data to the physical variables to show them in physical forms. This grammar aids users to create the physicalisation precisely, efficiently and fast, while the final representation supports interaction and adaptability with spontaneous changes in data. This limitation is investigated in this thesis. As a result, the list of physical variables and their possible combination, which can be used as a unit in the physicalisation, are introduced. This list is used as the variables in the *Grammar of Physicalisation*. These physical properties are not dependant on material identity and can be changed without any impact on it. Finally, the first implementation of this grammar is proposed in the application named the *physicalisation framework*. The rest of this thesis discusses the proposed solution and implementation in detail.

4
Solution

Numerous studies within different contexts such as [175, 144, 24] concentrate on building the physical representation of data. They mainly endeavour to create static physicalisation based on a particular data set with a predefined purpose. If the data changes, they cannot be adjusted and not be formed based on the data stream for the same reason. In contrast, dynamically-changing physical representation of data can reconstruct itself by any modification in the data set. As previously stated, this thesis investigates the grammar, called the *Grammar of Physicalisation*[140] for encoding data from digital form to physical one. As the grammar specification, the list of physical properties of the material beside some of their behaviours, named as physical variables, are investigated. Moreover, the possible combination of these physical variables are studied in order to involve more audience senses, hence more aspects of the data can be represented in the final physicalisation.

The *Grammar of Graphics* [179], which describes the components of the graphics as well as the process of turning the raw data into the graphical shapes, is the primary inspiration for our *Grammar of Physicalisation*. As outlined in Chapter 1, graphic is a language that carries concepts to the human brain by using the visual channel in a more noticeable way [9]. Figure 4.1 depicts one part of the design process with which the grammar converts raw data to the graphics. This chart is the data flow diagram depicting how the

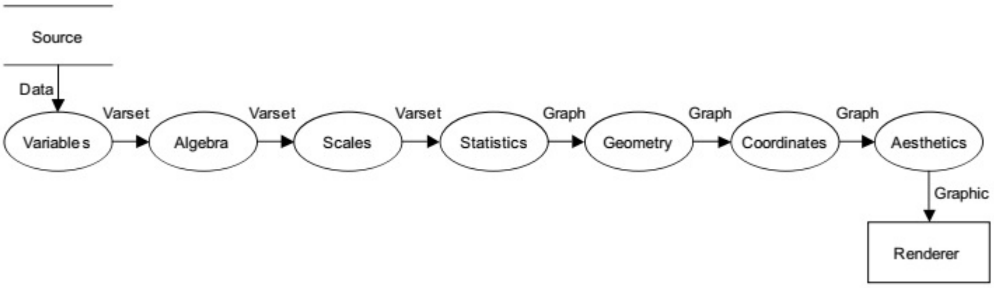


Figure 4.1: Process of converting data to graphics [179]

steps must be ordered and the inputs each steps requires. As it is shown, the data is retrieved from the source in the first step and the final outcome is the graphic generated by *Renderer* [179]. The *Grammar of Physicalisation* serves the same mission. It consists of the components whose duties are turning data into physical form and the fundamental rules organising the final physical representation. The grammar has corresponding parts that cooperate in arranging different physical artefacts and their attributes besides behaviours to expose data physically and accomplish the final physical visualisation. In order to have the clear determination of the *Grammar of Physicalisation* and its components, the general overview of the *Grammar of Graphics* and its components are explained briefly.

- The **DATA** component is responsible for operating data extracted from the source to generate the related variables from them, which are going to transform to the aesthetic attributes in the next steps.

- The **TRANS** component has *variable transformation* duty. For instance, if it is planned to decorate data in a bar chart, this component calculates the height of each bar from variables generated by the DATA component.

- The **SCALE** component adopts the variable calculations to the final presentation medium scale. For example, if the medium used to show the final visualisation is the 21-inch 2D screen, the SCALE component computes the height and width of each bar based on the size of the screen.

- The **COORD** component involves a coordination system. It calculates variables based on coordinate systems, including polar and Cartesian coordinates.

- The **ELEMENT** component is in charge of aesthetic attributes such as the colour of each bar in the bar chart.

- The **GUIDE** component produces the legend for each visual graphical representation in order to provide more complementary information about aesthetic rules for the audiences.

4.1 Grammar of Physicalisation Components

In this section, the components of the *Grammar of Physicalisation* and their duties are described. There are three components inspired from the *Grammar of Graphics*, named DATA, MAP and TRAN. Figure 4.2 illustrates how these components cooperate in turning raw data into physical shape.

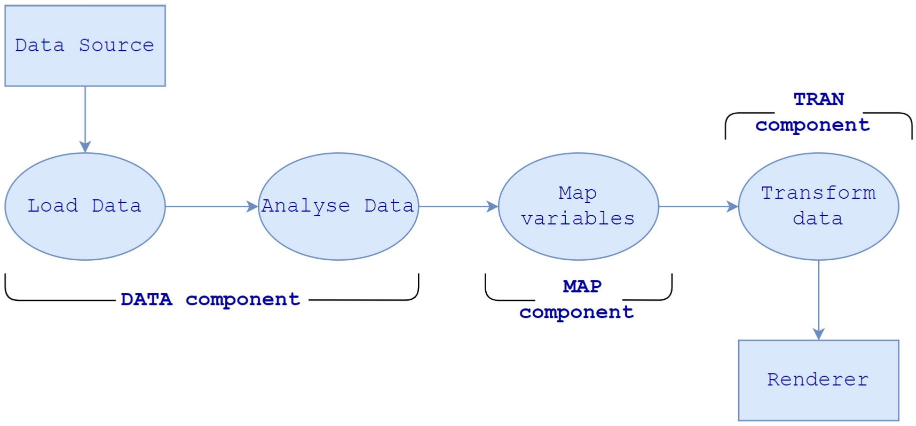


Figure 4.2: Process of converting data to physical representation

4.1.1 DATA Component

The DATA component has three primary tasks: data loading, defining data properties and summarising data using statistics. Data loading means reading data from the source and transforming it to a computer-understandable form, this duty is assigned to 'Load Data' task in the DATA component. The next task, as shown in Figure 4.2 is 'Analyse Data', which is composed of two sub-tasks, including the data properties definition and applying the required statistical functions in order to generate the normal data. Most popular data visualisation tools, such as Tableau, Looker or Qlik Sense[1] analyse data to define the data characteristics by themselves. They can distinguish between different data types and scales. Since this thesis is not about providing the data analysis tool, this step is left to the user to define the data properties manually. Nevertheless, as explained earlier in Section 1.1, due to the visualisation limitations, the physicalisation will be an alternative or complementary method to reveal the story hidden in data. However, this objective can be obtained by having a comprehensive framework supporting all data-related tasks, such as data loading, analysing or statistical computation. In order to have the physicalisation as extensive as visualisation, analysing data tasks should be considered as an unavoidable future work. Because data physicalisation addresses not only expert users, also novices and non-expert users and even expert users can decide not to get involved in data analysis task. In this thesis, the user accomplishes this task, it means after loading data, users are responsible for defining three characteristics for each column of data, including data scale (nominal, ordinal, interval or ratio), discrete or continuous and data types (date, number, string or binary). These data characteristics are used for proposing the physical variables in the following steps. These three data properties are chosen since they are common among all kinds of data and are clear to understand. However, any data properties can be utilised in order to translate data to physical form. Finally, if the statistical calculation is required to figure the final variables from data, the DATA component is responsible for applying statistical analysis to summarise data or generate the normal form of it. This function is not part of this study, and it is left for the user. Equation 4.1 demonstrates the sequence of tasks done in the DATA component. The *LoadData* function is responsible for loading the data source. The next step is defining the data properties using *Characterising* and eventually, *StatisticalComputation* will apply all required statistics in order to prepare data for the next component. As it is apparent, the DATA component in the *Grammar of Physicalisation* has the same responsibility as its counterpart in the *Grammar of Graphics* which is preparing the variables from the raw data. It is important not to confuse these variables with the final physical variables.

$$data = StatisticalComputation(Characterising(LoadData(dataSet))) \tag{4.1}$$

[1] `https://www.geeksforgeeks.org/10-best-data-visualization-tools-in-2020/` (Accessed on 05/07/2021)

4.1.2 MAP Component

The MAP component suggests a set of acceptable physical variables as candidates for decorating data physically. In comparison to the *Grammar of Graphics*, this component is new, and its responsibility is to seek the best physical medium by matching data characteristics extracted in the DATA component with the physical properties. The other measure used by the MAP component for selecting the best candidates among all physical variables is the data range. Moreover, each physical property (stimulus) has a different threshold which defines the "Just Noticeable Difference". If a physical property changes, it should produce the "noticeable variation" or the minimum amount of difference between two stimuli which human sensory channels are able to detect [89, 168]. Weber-Fechner law, proposed by Gustav Fechner and Ernst Heinrich Weber in 19^{th} , states the noticeable change in a stimulus is related to the initial stimulus value [89]. For instance, two observers are observing two light spots with 100 units of brightness, and one of the observers starts increasing the brightness of the one spot until the other observer can recognise the difference. If the observer distinguishes between the current and initial value for this stimulus at 110 units of intensity, the difference threshold for this observer would be 10 units, and the Weber fraction would be 0.1 calculated using 4.2 equation [89]. In this equation I shows the original value of the stimulus, and ΔI is the difference threshold. K represents that the proportion of the right side of the equation would be constant, no matter how much I varies.

$$K = \frac{\Delta I}{I} \tag{4.2}$$

MAP normalises data, using a 'Linear Scaling' technique[2]. Although the normalisation technique should be chosen based on the data distribution, in this thesis, it is assumed that data is uniformly distributed over a fixed range[3]. Data is normalised due to the convenient transformation from its standard range to the range of physical variables. Equation 4.3 is the standard equation for calculating the normalised data in the range of 0 to 1. Later the normalised data is transformed to the range of physical variables. This range is safe and perceivable for humans, and it differs for each physical variable. Moreover, this range is one of the criteria used to match the best physical candidate for each column of the data. If the user selects one or mul-

[2] `https://developers.google.com/machine-learning/data-prep/transform/normalization/(Accessedon09/08/2021)`

[3] `https://developers.google.com/machine-learning/crash-course/representation/cleaning-data` (Accessed on 09/08/2021)

tiple dimensions of the data set, the component calculates a set of physical candidates for each dimension. The end user can decide among candidates which physical variable is suitable to illustrate this specific data. It is not possible to map multiple data dimensions on one physical variable.

$$X_{new} = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{4.3}$$

It is not feasible to use physical variables that use the same sensory channel simultaneously to transfer data since the user cannot differentiate between them. Two different measures are used for preventing some physical variables simultaneously. The first one is the sense related to the physical variable. Suppose a specific sense captures the selected physical variable. In that case, this stimulus can occupy it so that the other physical variables related to this sensory channel can not be used for physically encoding data. However, vision is an exception since multiple stimuli can be seen and processed by sight at the same time. For example, the vision can recognise colour and shape simultaneously without confusion. The second measure is the effect of physical variables on the other. For instance, temperature and roughness cannot be used simultaneously due to the effect of the skin temperature on the perception of roughness [57]. Since each physical variable can filter some of the other candidates, the process of calculating the set of candidates for each selected data dimension is performed separately and sequentially. It means the first set of physical candidates is computed for the first selected data dimension. After finalising the physical variable for this data, the second set of candidates is computed for the next data dimension. This process is performed sequentially in order to implement and control the possible combinations of physical variables. Consequently, the order of selected data is important. The first set of physical variables candidates is computed first, and the rest of the candidate sets are dependent on the previous ones. In the next section, we explain the list of proposed physical variables that are potential candidates for representing data physically. Equation 4.4 demonstrates the input and output of the MAP component. In this equation, V is the set of proposed physical variables for all selected data dimensions, and it is the union of the small sets of v_n. $V = v_1 \cup v_2 \cup ... \cup v_n$ in which v_n is the set of proposed physical candidates for n^{th} dimension or d_n. Each v_n can have an intersection with the others. D, as a result of the DATA component, consists of n dimensions ($n \geq 1$) which a user has selected among the uploaded data set. Finally the user is responsible to map d_n onto one member of v_n and the selected physical variable would be m_n. For more clarification, if the uploaded data set has 10 dimensions including Year, Month, Date, Country, Province, City, Population, Total Affected, Total Recoveries and Total Death regarding Covid-19 and the user opts 3 dimensions as month, country and total affected among the all dimensions to physicalise, so $n = 3$ and $d_1 =$ Month, $d_2 =$ Country and d_3= TotalAffected, and $v_1 = \{colour, shape, texture, sound\}$, $v_2 = \{colour, spin, velocity, vibration, temperature\}$ and $v_3 = \{position\}$ would be the example of the proposed sets for these 3 data dimensions. If the user chooses to map d_1 onto colour it is not possible to map d_2 onto colour anymore. In this case $m_1 = colour$ and after this selection v_2 would be updated to $v_2 = spin, velocity, vibration, temperature$.

$$\begin{aligned} V &= Map(D) = v_1 \cup v_2 \cup ... \cup v_n \\ D &= d_1 \cup d_2 \cup ... \cup d_n \\ M &= m_1 + m_2 + ... + m_n \\ n &\geq 1 \end{aligned} \tag{4.4}$$

4.1.3 TRAN Component

The TRAN component is the last component in the *Grammar of Physicalisation* whose functionality changes based on the chosen physical variable. This component performs several tasks, such as calculating scales, coordination systems, axes or aesthetics. For instance, if the user selects the *location* variable from the set of physical candidates, the TRAN component calculates the coordinates of a place where the object should be located related to the exhibition space. This duty is done by the SCALE component in the *Grammar of Graphics*, as explained at the beginning of this chapter. The other example is transforming data to the *colour* by this component. Suppose the colour is suggested as one of the physical mediums, and the user determines this physical variable to decorate one part of the data. In that case, the TRAN component is responsible for mapping data onto appropriate colours. This mission is performed by the ELEMENT component in the *Grammar of Graphics*. Finally, if it is decided to utilise *temperature* as one unit of final physical representation, this component translates data to the appropriate temperatures. Since each physical variable is different from the other one, it is impossible to introduce the separate component which is responsible for scaling, coordinating or decorating variables aesthetically, so all these components are grouped in the TRAN component, and it has to compute the final data transformation to render the physical shape. As the rendering is not part of this thesis, the functionality of this component is left for future work.

4.2 Physical Variables

As the attributes of the materials and their different categories discussed previously in Chapter 2, some of these attributes are able to change dynamically and do not exert any influence on the material identity. Using these kinds of material properties as a medium for turning data from the digital format into the physical form is a bridge between static and dynamic physicalisation. They can participate as a block or unit in the physicalisation and support the systematic design and fabrication of dynamic interactive physicalisation since they can be controlled, parameterised, programmed or updated separately while the corresponding data is modified [150] due to the user interaction or any software [122]. As illustrated in Figure 4.2, the main job performed by the MAP component is suggesting a set of physical variables candidates for data based on multiple criteria mentioned in Section 4.1.2. Studying these variables and how to create dynamic interactive data physicalisation by mapping data onto them is the topic of the rest of this chapter. Table 4.1 consists of attributes of materials and artefacts as well as some of their behaviours which are appropriate to be used to physicalise data. All of these candidates are called physical variables in this thesis. This table has five columns which are explained in the following.

- **Variable Name** is the name of material property or behaviour which has the ability to be changed dynamically without any impact on the material identity. On the other hand, they are independent of the material identity such as location, temperature, size, speed, spin or texture. Each of these variables will form a unit in the final physical presentation since they can be programmed and parameterised individually.

- **Sense**: The human sensation system is responsible for capturing data from the external world [17]. In other words, capturing information from each physical variable relies on one or more senses. For instance, vision captures data from colour and length and sends it to the human brain for processing, while sensors in tactile modality are responsible for getting data from pressure and texture [125, 7].

- **Range**: Each physical variable has a range that is safe and perceivable for humans. Three various approaches are used to investigate ranges for each physical variable, including (1) some academic works, (2) a few informal experiments during this study and finally (3) several searches on the Internet.

- **Scale**: This column shows which kind of data scale can be mapped onto the physical variable.

- **Not-Combinable with**: This column represents the other physical variables that are not allowed to be combined by the variable for three different reasons; (1) These physical variables share the same sensory channel to transfer data to the user. (2) They could manipulate the information captured from the other physical variable since they can intensify or lessen the effect of data on the sensory channel. (3) They are prohibited based on the predefined assumptions for this thesis. For example, size cannot be utilised with shape simultaneously since in this thesis, it is assumed that the objects with the same shape can be compared in terms of size. If the difference is decent, it is possible to compare the cube and circle in terms of size. However, it is impossible to generalise the method to compare objects with different shapes in terms of size because it is out of this study scope.

Variable Name	**Sense**	**Range**	**Scale**	**Not-Combinable with**
Size **Length** **Area** **Volume**	Vision	> 0.1mm	Ordinal Interval	Shape
Shape	Vision	No limitation	Nominal	Size Length Area Volume
Colour	Vision	No limitation	Nominal Ordinal	Light Intensity
Luminance	Vision	Low Medium High	Ordinal Interval	Transparency Light Intensity Spin Velocity
Transparency	Vision	Opaque Semi Transparent	Ordinal	Luminance Light Intensity Spin Velocity
Light Intensity	Vision	0 lux - 250 lux	Ordinal	Color Luminance Transparency

Spin	Vision	0 - 7 cycles per second	Ordinal	Transparency Luminance Tactile stimuli Velocity
Velocity (Speed)	Vision	0 km/h - 120 km/h	Ordinal	Spin Transparency Luminance Tactile stimuli
Pressure	Tactile	0 atm - 100 atm	Ordinal	Vibration Temperature Weight Texture Spin Speed
Weight	Tactile	100 g - 5 000 g	Ordinal	Vibration Temperature Pressure Texture Spin Speed
Texture	Tactile	No limitation	Nominal	Weight Vibration Temperature Pressure Spin Velocity
Vibration	Tactile	Slow Medium Fast Various patterns	Ordinal Interval	Weight Temperature Pressure Texture Spin Velocity
Temperature	Tactile	15°C - 45°C	Nominal Ordinal	Weight Vibration Pressure Texture Spin Velocity

Position Location	Vision	[(0,0,0), (width,length, height)]	Ordinal Interval Ratio	-
Sound (musical sounds)	Hearing	No limitation	Nominal	Sound Loudness Sound Frequency Sound Direction
Sound Loudness	Hearing	0 dB - 60 dB	Ordinal	Sound (musical sound) Sound Frequency Sound Direction
Sound Frequency	Hearing	20 Hz - 20 000 Hz	Ordinal	Sound (musical sound) Sound Loudness Sound Direction
Sound Direction	Hearing	Left and Right	Ordinal	Sound (musical sound) Sound Loudness Sound Frequency
Taste	Taste	No limitation	Nominal Ordinal	-
Odour	Olfactory	No limitation	Nominal Ordinal	-
Wetness Dryness	Tactile	Wet Dry	Nominal	-
Stiffness	Tactile	Soft Hard	Nominal	Spin Velocity
Elasticity	Tactile	Rigid Elastic	Nominal	Spin Velocity

Table 4.1: Potential physical variables which can change dynamically and be used as a unit in the physicalisation

4.2.1 Size, Length, Area and Volume

The first proposed physical variable is size. According to to [78], size is an ambiguous physical variable since it can be referred to as length, diameter, surface or volume. In order to prevent any confusion, in this thesis, size is considered as a radius of the objects with the same shape, so size, length, area and volume are all considered as size. In other words, if the size is chosen as one physical variable, the shape cannot be used as the other one in the same data physicalisation. The smallest thing discovered in the universe in 'brutino' from which everything is made up and its radius is 4.05210^{-35}m [18], however the smallest object which the naked eye can see without any mechanical assistance has 0.1 mm diameter[4]. The upper bound of the size range is proposed as the radius of an object which can fit in the exhibition space. Surprisingly no recent information regarding Weber fraction is found for the size or length during this research.

4.2.2 Shape

There are uncountable shapes in the external world, such as the shape of a rock, an apartment, an automobile or a shirt and utilising any artefact with any shape is feasible in the data physicalisation if the shape is distinguishable from the other artefact's shape. As explained in the previous section, since it is confusing for the user to compare the size of two objects with dissimilar shapes, mixing these two variables is not allowed in this study in order to cope with uncertainty about the data captured from these physical variables.

4.2.3 Colour

Gott [55] believes the number of colours (hue) in the world is infinite. But all of them is not distinguishable by the human eye. It is said that the human eye can distinguish thousands of shades of light and hundred levels of red-green and yellow-blue. It means the eye can see almost ten million colours. However, all these colours are a mix of 3 primary colours; red, yellow and blue. In this thesis, no upper bound is considered for the colour and using any colours as long as they are distinguishable is possible. However, it is proposed not to mix colour by light intensity by the writer. So it is crucial to consider the colour distinguishability in the implementation. Moreover, colour saturation is proposed by [150] as one physical variable. Colour saturation means the intensity of colour. This value is changed by adding white or black to the colour [1] in order to increase or decrease the colour pureness. By increasing the amount of white or black in the colour, it becomes more "washed-out" or "soiled" respectively [9]. Using saturation in a way that the eye can distinguish the difference is possible, however, 0% turns colour to grey, and 100% is the purest state of the colour[5]. Colour can

[4] `https://www.youtube.com/watch?v=htPXMQ5s-yo&ab_channel=Vox` (Accessed on 20/11/2019)

[5] `https://www.techopedia.com/definition/1968/color-saturation`(Accessed on 20/11/2021)

be utilised to represent nominal data, while the different colour saturation can decorate ordinal data too.

4.2.4 Luminance

The luminance of the colour corresponds to the brightness of it [9]. It means if one colour is brighter than the other, its luminance is higher. According to [135], the Weber fraction is applicable for the luminance level greater than 10^2 cd/mth, but due to the lack of expertise in this field, the writer proposes the ternary range for the brightness as low, medium and high. The investigating the precise range is one of the future works.

4.2.5 Transparency

Transparency means how much light can pass through an object. Although the eye perceives it, the environment and the position of the user's head have a high impact on it. For example, if there is no light source, the physical object cannot reflect anything, and the light cannot pass through the object [150]. The writer suggests illustrating data using three different kinds of transparency, including opaque, semi and transparent. As [78] discussed any individual physical variable should be studied and tested as well as the usage of it with the other physical variables at the same time. Since the vision captures transparency and brightness and both are related to light and colour, it seems combining these two physical variables does not provide a clear view of showing data as well as using them with light intensity at the same time. However, studying this combination is left for future endeavours, in this study, it is proposed not to use transparency and luminance simultaneously.

4.2.6 Light Intensity

The light intensity is the other stimulus that can be programmed and changed dynamically as a physical variable. According to [145] the appropriate range of light intensity for the naked eye is 0 lux to 250 lux in the daytime when the user is in the office. The Weber fraction for light intensity is 0.08, which means the audience can recognise the new intensity after 8% change in the original value [157].

4.2.7 Spin

The rotating objects can be seen as stationary or seem to rotate in the opposite direction or even more slowly. This optical phenomenon is called the stroboscopic effect or Wagon-wheel effect [44]. The spinning wheel can be viewed stationary for the average observer if it turns 8–12 cycles per second [133]. So the safe range for preventing Wagon-wheel effect is proposed as 0 to 7 cycles per second by the writer. Moreover, it is suggested not to mix spin with any other physical variables felt by tactile as well as luminance and transparency due to their heavy dependency on the environment [150]. Also, the writer of this thesis anticipates that moving can manipulate the effect of any stimuli captured by tactile modality. The effect of all these physical variables is suggested to be studied precisely in the future. As Lakshminarayanan et al. [91] investigated the determination of "Noticeable Difference" for rotational speed in two standard speeds, 4 deg/s and 8 deg/s, they vary notably with each other in the different interstimulus intervals.

4.2.8 Velocity

An object as big as the ball should pass the user's face with a speed of 17.5 kilometre per second to become invisible for the human naked eye [38], however reaching this speed is not only complicated, also not safe for the audiences. Furthermore, the writer suggests the range of 0 Km/h, as the speed of the stationary object, to 120 Km/h as a safe range in which the physical artefacts can accelerate and move.

4.2.9 Pressure

Jansen et al. [77] discussed how to provide a sensation of the intensity of the hurricane to a user using pressure as one of usage of physicalisation. Inspiring of this scenario, pressure is proposed as the other physical variable to bring data from digital form to the stimulus, which can be sent through tactile to the human cognition system. According to [2] the pressure which humans can tolerate and is safe for them is 100 atm. However, no valid data has been found during this study about the average pressure people can stop with their hands. From the writer's standpoint, pressure cannot be combined with vibration, temperature, texture and weight because it could amplify these four physical variables effects. For example, if the surface is rough, the tactile sensors in the palm seem to feel the texture more intense by applying more pressure. The informal experiments have been performed to test the effect of this physical variable on the other mentioned ones but the writer provides no proven information to show the validity of this assumption. It is suggested to study the effect of pressure on the vibration, temperature, texture and weight to formalise this not-allowed combination.

4.2.10 Weight

Since holding a weight with one hand is heavily dependent on sex, age and physical strength, the range of 100 grams to 5 000 grams is proposed for this physical variable. Moreover, as some studies work on the systematic methods to change the weight dynamically, such as the remarkable study conveyed by Niiyama et al. [108], the changing weight, held by the hand, can simulate the same effect as changing pressure. As a result, it is proposed not to mix this variable with the same set of not-combinable physical variables with pressure. As Ross and Brodie [126] investigated the Weber fraction for the mass. They indicated that this fraction for the normal perceiver is 0.01 which means they can discriminate 10% change in the orginal value of the mass. For example if the original value is 1 Kg and it is increasing the perceiver can recognise the new value of the mass at 1.1 Kg.

4.2.11 Texture

There are plenty of textures in the physical world, and any tangible objects have a surface which is textured in different categories such as *"smooth or rough, soft or hard, coarse of fine, matt or glossy"* [184]. Any textures can be utilised to represent digital data physically without any limitations as long as various distinguishable textures are used.

4.2.12 Vibration

Dynamic vibration is used commonly, such as using different vibration patterns in cellphones. Since no useful information during this study has been found regarding "noticeable variation" for vibration that helps the writer propose the precise range for this physical variable, the range is proposed in two simple points of view; speed and pattern. Three different types of vibration in terms of speed are proposed; (1) slow, (2) medium and (3) fast. However, various patterns of vibration can be utilised to show additional data. Birznieks et al. [12] studied the vibration stimulus in low (6 Hz) and high (200 Hz) frequency in order to determine the detection thresholds for the human finger and the result is 30% and 7% for low and high frequency respectively.

4.2.13 Temperature

The coldest temperature that has been captured until now on the surface of the earth is $-89.2°C$ [160] and the highest is $56.7°C$ [40] While the measured hottest temperature in the universe is surprisingly $4X10^{12}°C$ [119] and the coldest one is **absolute zero** which equals to $-273.15°C$ [36]. Obviously, none of these temperatures is safe for a human to touch directly, even for one second. The safe temperature range which humans can sense without any pain and skin damage is from 15°C [61] to 45°C from 1 second to infinity [42]. According to [81] the thermal sensory in human body is exceptionally sensitive to the changes of the temperature. In means it detect small altering in the value of this stimulus. He indicated that the threshold for detecting the temperature rising in thumb is 0.20°C and this threshold is even smaller for lowering the temperature and it is 0.11°C.

4.2.14 Position or Location

As physicalisation is represented in the external physical world, the position means where it is located. In other words, it is the x, y and z of the physical artefacts which are decorating data [150]. So that if the space in which the data physicalisation happens is considered the physical world and the centre of this space is (0,0,0), the position of different parts of physicalisation is determined by (width, length, height) relative to the centre.

4.2.15 Sound and its Parameters

There are four sound parameters, including musical sound, loudness, frequency and direction. Musical sounds mean any kind of sound which is played by an instrument. Simulating natural sounds such as the sound of rustling or rain is considered a musical sound too. There is no limitation for this category. There is a "erroneous belief" that the safe threshold for humans is 85 decibel which seems caused most Americans suffers from hearing loss these days. However, the safe level of sound which does not hurt human hearing for a continuous time is 60 decibels or lower [43]. Obviously, the distance impacts this physical variable, so it is assumed that the sound source is not changed in terms of location. The range of sound frequency which is perceptible by the ear starts from 20 Hz (lowest pitch) to 20 kHz (highest pitch) [96], and the sound direction is limited to left and right in this thesis. The Weber fraction for sound intensity is 0.04, which means the audience can detect the new sound if the new value is 4% more than the original one [157].

4.2.16 Taste

Although it is accepted that there are four basic tastes, including sweet, sour, salty, and bitter (or five due to umami) [35], no limitation can be considered for taste. There are uncountable edible foods and items worldwide with different flavours that can be used to transfer data from the original format to the human taste receptor cells. The Weber fraction for saltiness is 0.08, leading to new taste detection by the user if the edible substance is 8% saltier than the previous one [157].

4.2.17 Odours

Humans can distinguish more than 1 trillion different odours by one estimation [21]. In other words, it is not possible to limit the range of this physical variable, and any sort of smell can be used for data mapping as long as they are discernible.

4.2.18 Wetness and Dryness

This proposed binary physical variable, with two discrete values as wet and dry, is considered a behaviour of the artefact. As the writer assumes, this physical variable can be mixed with all other physical variables since its range is binary.

4.2.19 Stiffness

Stiffness means the quality of being difficult to bend[6]. This physical variable is introduced by Stusak et al. [150]. However, through her investigation, the writer has not found any valid range for this physical variable, so she proposes the binary range as hard and soft. Moreover, in the writer's view, the moving object can not be tested in terms of stiffness precisely, so it is proposed not to utilise this physical variable with spin and velocity at the same time.

4.2.20 Elasticity

An elastic object is made of material that can transform to its original shape after being pressed or expanded[7]. Elasticity is the other physical variable

[6] `https://www.oxfordlearnersdictionaries.com/definition/english/stiffness?q=Stiffness`(Accessed on 20/11/2021)

[7] `https://www.dictionary.com/browse/elasticity`(Accessed on 06/01/2022)

that seems to be used as a physical medium to represent data in a tangible form. Since no valid range has been found for this variable, the binary range is proposed as rigid and elastic. Similar to Stiffness, since the artefact in motion is not an appropriate candidate to be investigated in terms of elasticity, it is proposed not to combine this physical variable with spin and velocity. Apart from that, as the range of this variable is binary, it does not seem to confuse the audience who tries to feel data from this physical variable besides the other ones.

5

Implementation

Essentially, the implementation of the *physicalisation framework* [140] is a free, open-source software tool in a modular format utilising a client-server architecture style for democratising dynamic interactive data physicalisation building process from the digital data. The implementation of the proposed solution has been fulfilled through three steps. As the first step, a prototype has been designed, using Figma[1], which is a web-based prototyping tool, in order to study the best options for implementing the proposed solution. Secondly, for the software development, the architectural, package and use-case diagrams are prepared and used to facilitate the process of implementation. Finally, the software is implemented to achieve the required functionalities which serve the defined objectives in the defined solution. In this chapter, the steps which lead to implementing the first version of the *physicalisation framework*, as a software tool supporting the data transformation to the physical shape using the developed physical variables are discussed in detail. Moreover, the grammar described in Chapter 4 is implemented as a core of the software whose responsibility is offering the appropriate set of candidates among the developed physical variables for each data intended to represent physically by the user.

[1] `https://www.figma.com/`(Accessed on 05/10/2020)

5.1 Prototyping

Before diving into the implementation step, in order to investigate the best practices and evaluate the designed solution, prototyping and interviewing the expert have been utilised to assure the validity of the design. The interactive prototype has been prepared using Figma, shown in Figure 5.1. Afterwards, the supervisor and advisor of this thesis were asked to review the prototype. Their opinions have been used to enhance the quality of the design and add more functionalities to the framework. This step is done to assess the design in terms of *feasibility, ease of use, effectiveness, efficiency, fidelity with real-world phenomenon, operationality, robustness or suitability* [143].

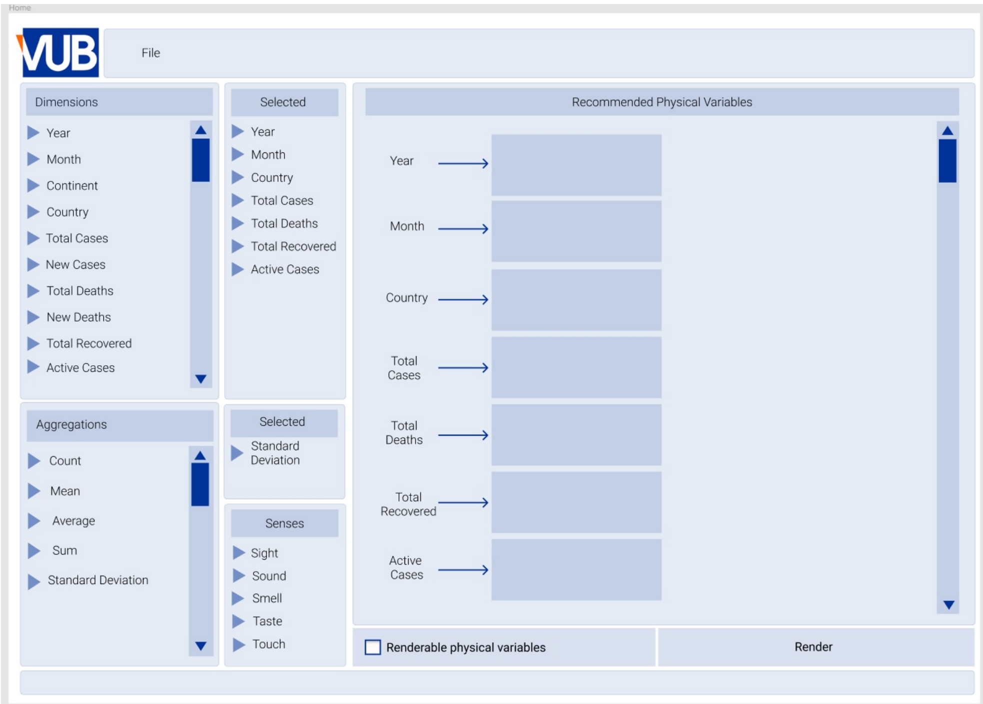


Figure 5.1: Prototype of the main functionality of the framework in Figma

After validating the design, the implementation started. What is shown in Figure 5.1, is a part of the solution which leads to offering the physical options for each aspect of data selected by the user. However, from the beginning of this research and due to the broad range of literature involved, the supervisor suggested considering the section in this tool for keeping the related publications and associating them with the rest of the solution. Although the provided prototype does not contain this part, it is explained in the following sections. The rest of this chapter is divided into two parts; the first part consists of the conceptual model and diagrams, including an architectural, package, and a use-case diagrams. They provide a comprehensive overview of the tool and clarify how the system's components communicate to serve the requirements and the sections for storing the related publications and making connections between them. The second part holds the information regarding the implementation details.

5.2 Conceptual Diagrams

In this section, a conceptual architectural diagram, besides package and use-case diagram, are provided to represent the general overview from the abstract point of view, the design and implementation of software follow these diagrams.

5.2.1 Architectural Diagram

The architecture of the software, as shown in Figure 5.2, is a client-server application. The client-side is an one-page application implemented using Angular version 11.2.4 and TypeScript and the server-side is implemented using Node.js version 12.13.0 consist of three main parts including Web APIs, Business layer and Database. For this version of the application, a straightforward architecture is used, since in the implementation time, the writer was not familiar with "clean architecture[2]", so it is strongly recommended to use the clean architecture for the next versions of the software. The user interface consists of different parts, including "papers" , "variables", "hardware", "statistical functions", "grammar rules" and the "dashboard" by which the user can fulfil multiple tasks. Most of the logic is implemented in the client-side and the business layer in the server-side consists of the main logic defined in the MAP component of the grammar in Section 4.1.2. The user is able to upload the data file, select the desired part of data, determine the data characteristics as explained in the DATA component in Section 4.1.1 and finally be offered the set of appropriate physical variables which have the ability to encode data physically. Moreover, the user can define the hardware which is able to render physical variables based on the related publications. It is important to point out that rendering the final physicalisation is out of this study scope, and the hardware section is for associating the existing hardware with the developed physical variables. This section can be advanced to

[2] `https://github.com/jasontaylordev/CleanArchitecture`(Accessed on 06/01/2022)

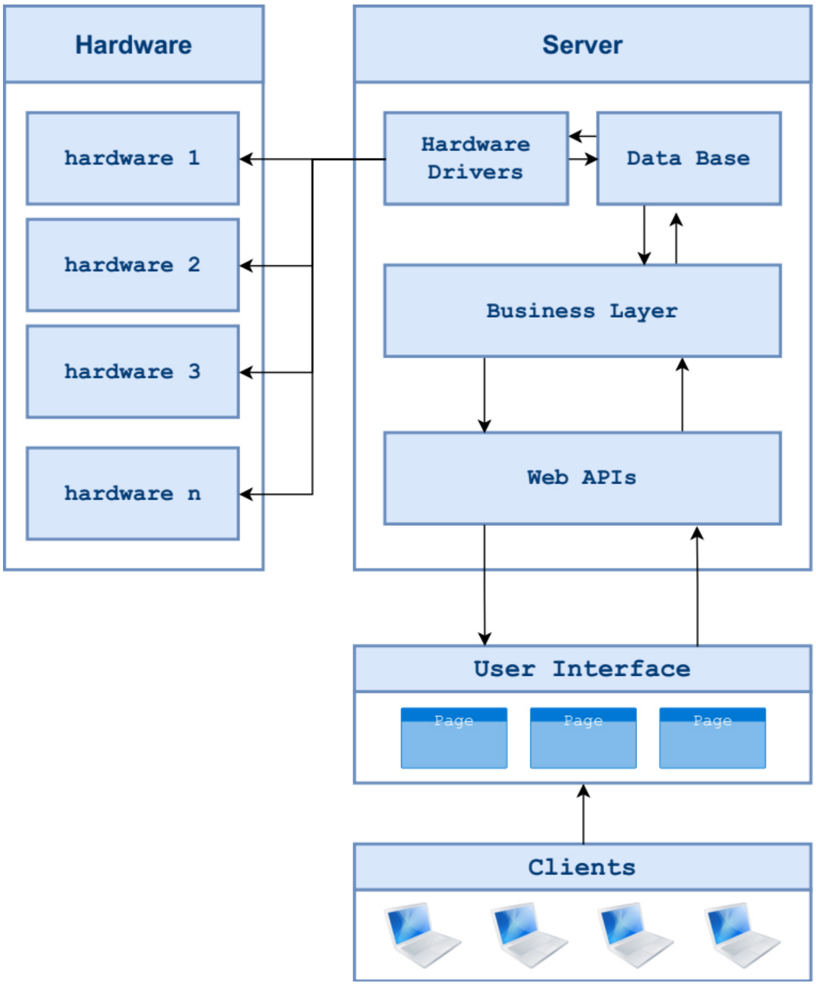


Figure 5.2: Architectural diagram

support rendering as a future work by implementing the coupled drivers to connect the software to the hardware, controlling each unit of the physicalisation in confronting with the user interaction or changes in the data.

5.2.2 Package Diagram

The package diagram is provided in order to illustrate the collaboration and dependencies between elements. Figure 5.3 (top) shows the package diagram for client-side application and 5.3 (bottom) depicts the same diagram for the server-side application. A client-side application is a one-page application implemented by Angular and TypeScript consists of 5 main packages. The router package is responsible for interpreting the URL in order to nav-

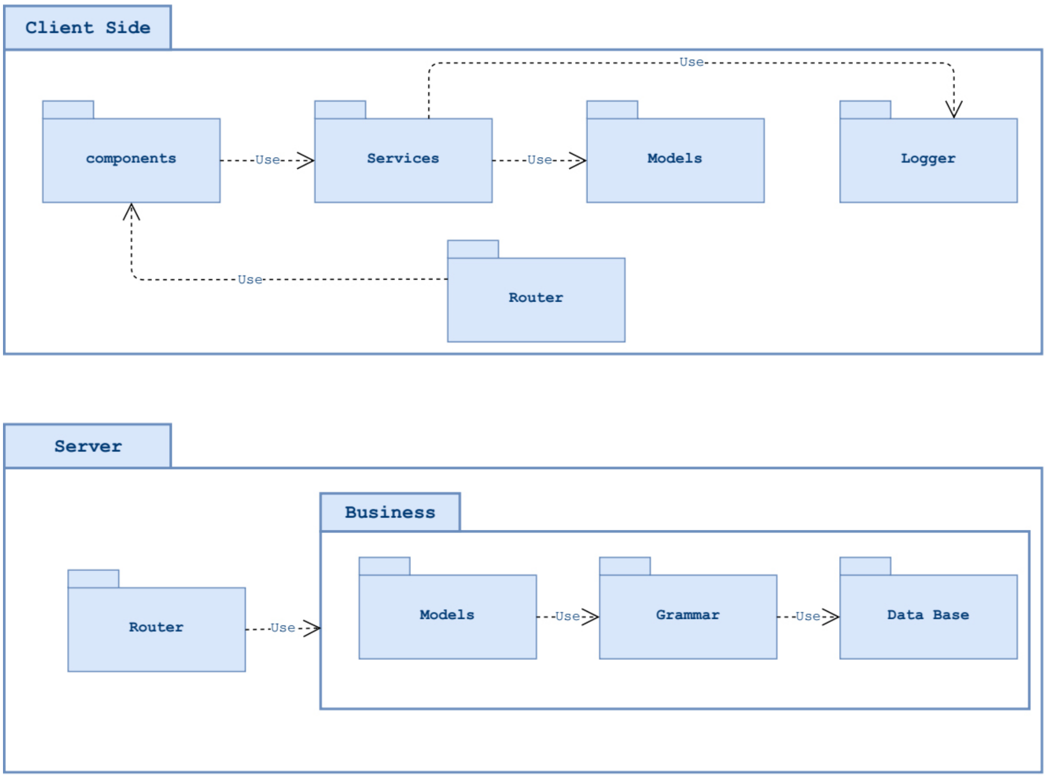


Figure 5.3: Package diagram

igate to the appropriate view. The component package consists of all main components used in the user interface, such as paper or physical variable components. The service package contains the main logic in the client-side including the data loading, determining the data characteristics, data validation, defining the papers, physical variables and hardware or linking them together. As mentioned in Section 5.2.1 all businesses are implemented on the client-side logic related to the MAP component, which is responsible for recommending the one or some physical variables which have the ability to encode data from its digital form to physical shape. The models package has data models for all entities in the application, such as paper, variable or hardware. Considering the first version of the implementation, this application is the skeleton of the extensive framework, which is supposed to have several functionalities; due to this purpose, the logger module is implemented in this application which serves two functions; managing the logs and notifications. In the server-side application implemented by Node.js and JavaScript, models, grammar and database packages collaborate to propose the best set of variables to the user.

5.2.3 Use-case Diagram

A use-case diagram performs an indispensable role in representing requirements for a software system. It plays a communication role between developers and users to help them comprehend the requirements as straightforward as possible and have a common perspective of them [138]. In this section, as shown in Figure 5.4, the use-case diagram of the system is provided, which represent the complete overview of tasks the user can perform in the application. Moreover, the system's tasks in the background to fulfil the primary purposes are depicted in the diagram. 'Process Dimensions/Functions', 'Process Hardware' and 'Suggest Physical Variables' are background processes whose responsibilities are described as follows. 'Process Dimensions/Functions' processes the data dimensions selected by the user and associates them to the data characteristics the user decides for each column of data. This process is coupled with the DATA component. 'Process Hardware' process the available hardware for the final physical variable the user selects among all suggested variables. 'Suggest Physical Variables' process plays an essential role in preparing the set of physical candidates for each selected column of data. On the other hand, this process is the implementation of the MAP component. The rest of use-cases are representative of the tasks performed by the user.

5.2.4 End-to-End Flow Diagram

Figure 5.5 illustrates the end-to-end flow, which leads to proposing the set of physical candidates for each selected raw data from the data set. This diagram is dedicated to representing the application's main purposes, and the other tasks are not included in it. As shown in the diagram, in the first step, the user uploads the file consisting of the data. Then they choose the intended data dimensions that they want to participate in the final physicalisation. This version of the application does not contain any module for data analysis to extract data properties since it is out of this work scope, and it is the users' responsibility to determine the data characteristics. After determining the data type, scale and required statistical function for each dimension in the next step, the user can filter senses if they want to use specific senses to capture data from the final physicalisation. As mentioned in Section 5.2.3 there is a process in the server-side, as the implementation of the MAP component, which uses data from these four steps to compute the appropriate physical variables for each dimension. As explained in Section 4.1.2, it is important to take into account the order of the selected dimensions since each set of physical variables are computed based on the

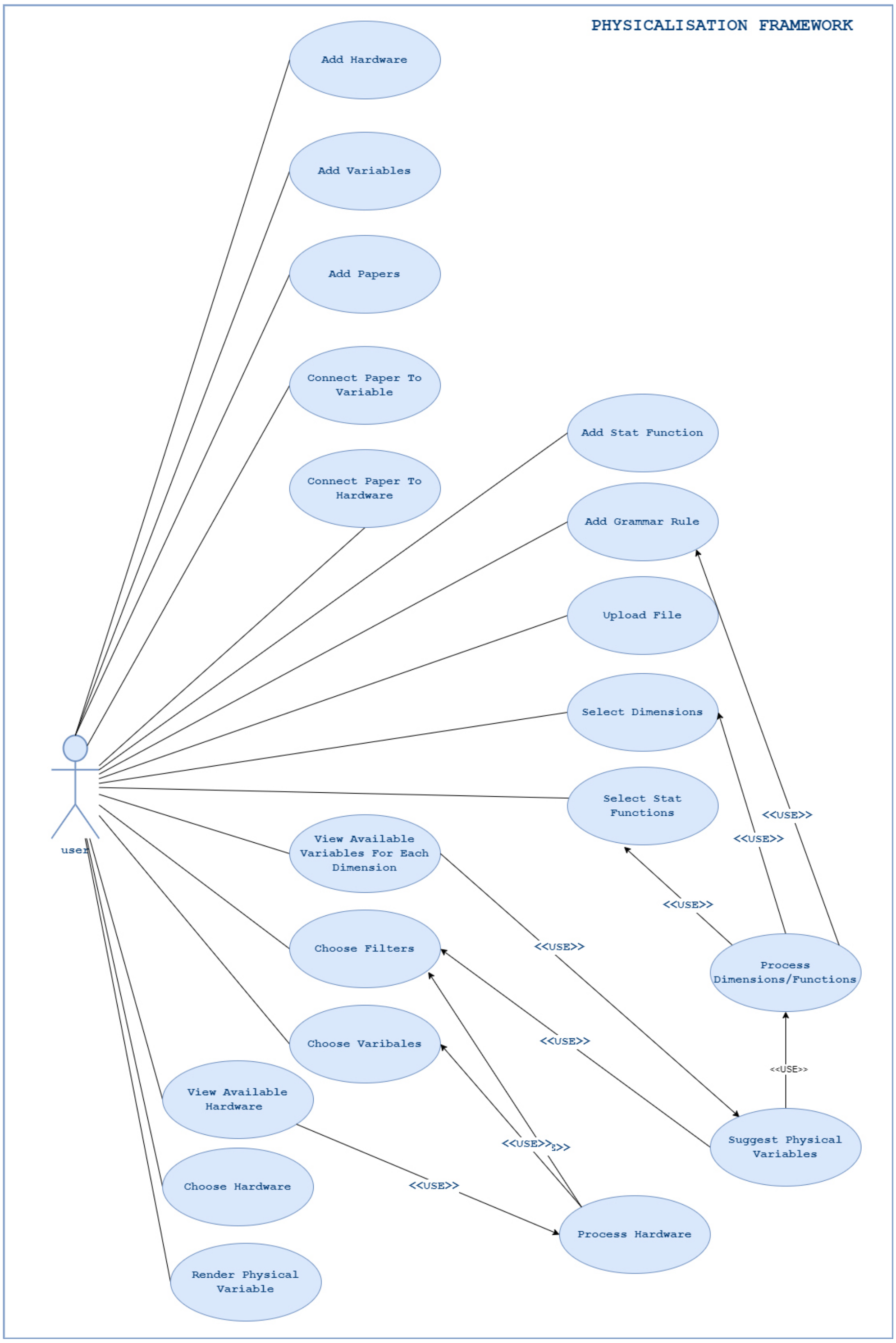


Figure 5.4: Use-case diagram

previous selected physical variable. For example if the suggested set of variables, v_1, for the first dimension, d_1, includes shape, colour and texture, $v_1 = \{shape, colour, texture\}$, after choosing the colour for mapping d_1 onto it by the user, $m_1 = colour$, the set of physical variables, v_2, for the next dimension, d_2, could not contain colour any more. This sequential computing is chosen in order to prevent mixing the 'not-combinable' variables with each other. Although this step is not shown completely in the diagram, the last step covers the whole of this computation. Finally, the filter for rendering variables is proposed in the application whose purpose is to propose physical variables that can be rendered using available pre-defined hardware. If the user connects the specific physical variable with the hardware, this variable is considered a renderable variable, although rendering will not happen in this application.

5.3 Software

The main goal of this chapter is discussing the the initial implementation of the *physicalisation framework* by providing technical information about the components as well as the design process of translating the requirements to the system modules. As estimated, having the completed framework to support the dynamically changing and interactive physicalisation requires years of studying, and this work could be considered very early steps in this prolonged path. Obviously it requires lots of future works to accomplish the ultimate goal that is implementing the final framework which transforms digital raw data to the final dynamic interactive physicalisation. since it is the first attempt to propose the real implementation, it is tried to think, design and implement each parts as a individual module to facilitate the scalability and expandibility for the next versions. The rest of this section is divided into two main parts as preparation phase and mapping phase. The first part is a brief explanation of the functions and tasks necessary to prepare the application for its primary purpose. These sections include defining the papers, variables, hardware and how to connect all of them with each other. The output of these modules is the input of the final module, which is the implementation of the MAP component and it is called map too. This module is explained in the second part of this section. It is tried to implement the application module-based in order to facilitate any future development.

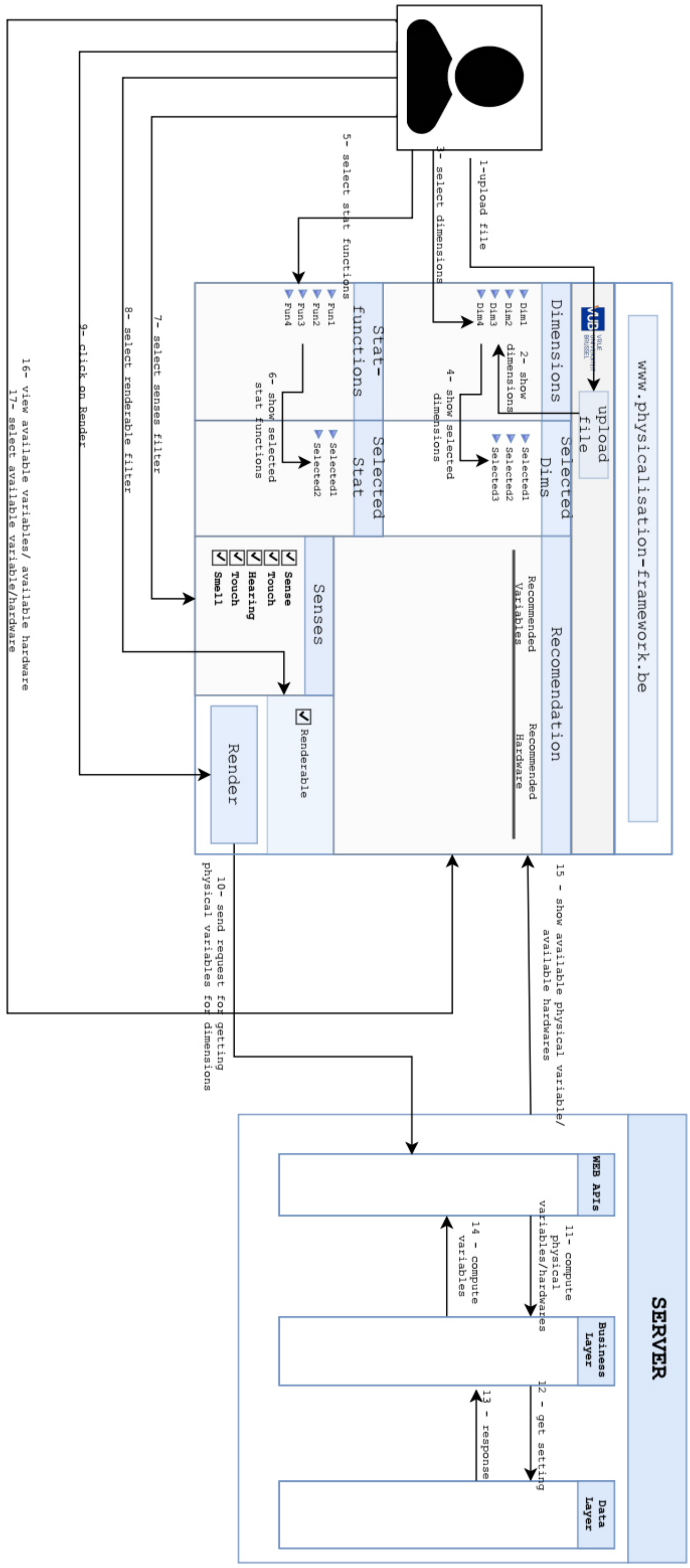


Figure 5.5: End-to-End Flow Diagram

5.3.1 Defining Papers

As mentioned in Section 5.1, due to ta large variety of reviewed literature in this study, the publication management section, Figure 5.6, is implemented in this tool for keeping the related publications and associating them with the physical variables and hardware. There are two possibilities for defining the papers in the application: using the Bibtex format and entering the paper properties manually. This section is provided to keep all the papers related to physicalisation in order to prepare the foundation of physicalisation library. In the next versions the user would be able to connect papers to each other and mention tags and keywords in paper definition in order to provide deep searching through them.

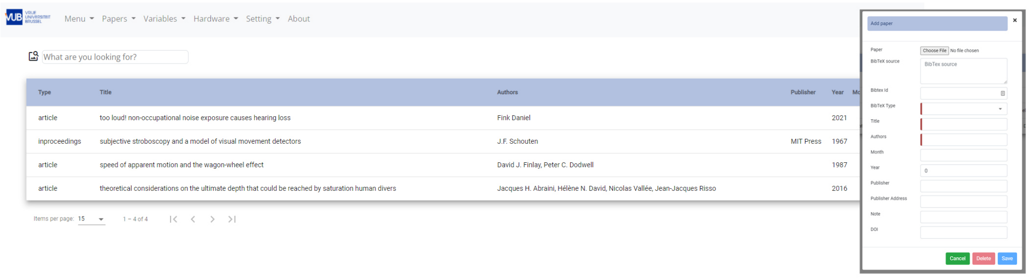


Figure 5.6: Papers entry

5.3.2 Defining Variables

For defining the physical variables in the application, the user should enter the required information, shown in Figure 5.7. The first entry is the variable's name that defines the material's physical property or behaviour. These variables are discussed in Section 4.2 in detail. The next entry is the SI unit, in this version of the application, this entry is not applicable, but the unit of each variable will be connected to the related hardware for final rendering. Related senses, safe range, data type and data scales are the other data characteristics that can associate with the physical variables. Moreover, it is possible to group some physical variables together. For example as explained in Section 4.2, size, length, area and volume are grouped, since the size is a vague physical variable [78] and for preventing any confusion, all of these variables are assumed the same. Besides, the other entry for defining the “Noticeable Difference” [89] would improve the expandability of the application dramatically.

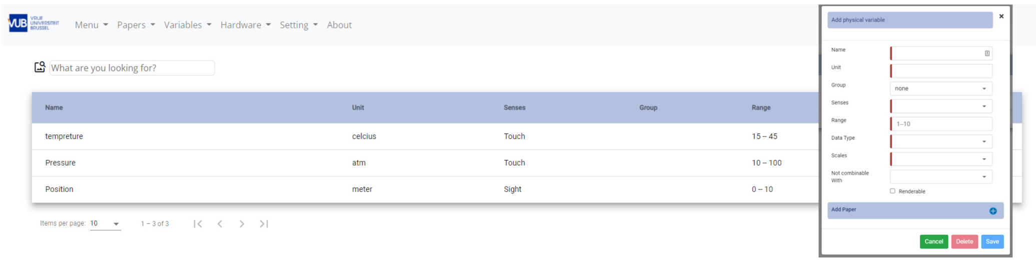


Figure 5.7: Variables entry

5.3.3 Defining Hardware

For defining the hardware which is used to render the physical variable, the other section is implemented in the application, shown in Figure 5.8. Using this section the user is able to define the name, related variable and range of the hardware. Moreover it is possible to connect the hardware to the related publication. For example, as it is shown in this figure, the viScent prototype, developed by Patnaik et al. [113] for transferring information through an interactive olfactory interface, is defined for smell sensory channel and associated to the related publication. As mentioned above, it is possible to define the SI unit for each physical variables so that it is proposed to add the same entry for hardware in the next version.

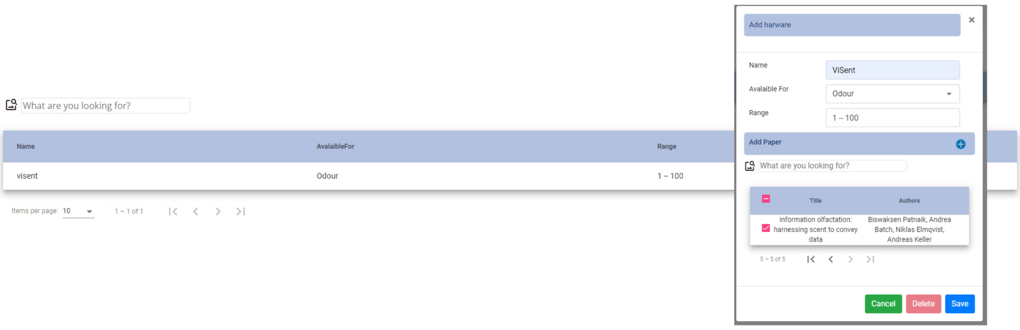


Figure 5.8: Hardware entry

5.3.4 Defining Statistical Functions

Recommending suitable statistical computation for a data set is an advanced feature that many visualisation applications propose to their users. In this work, although this part is not included, defining the statistical functions is possible using using arrow function syntax. If the user needs a specific statistical process on the data, they can define it in this section.

5.3.5 Defining Dashboards

As end-to-end flow described in Section 5.2.4, a user starts the main task by uploading the data set in order to have the physical data in the final representation. This flow can be performed using the main dashboard in the tool, Figure 5.5 illustrates how a user can start physicalisation by uploading data, selecting dimensions, adding complementary information such as data type, scale and continuous or discrete data type and desired statistical function to apply, and then filtering the senses. Afterwards, the framework suggested the set of physical variables for each dimension. This process is shown in Figure 5.9 in the tool. The steps are described in Figure 5.9 as (1) represents the empty dashboard while the user does not upload any data file. (2) After the user uploads the file with data, the column of the data is shown in the dimension sections, and the user can select among them using the drag and drop or the plus button. Then complementary information for each column of data must be added by the user. (3) By finalising the data characteristics and clicking on 'Map Dimensions on Variables' button, the drop-down menu is appeared in the recommended variables section. (4) Finally, the user can investigate their options and select one physical variable from the proposed ones.

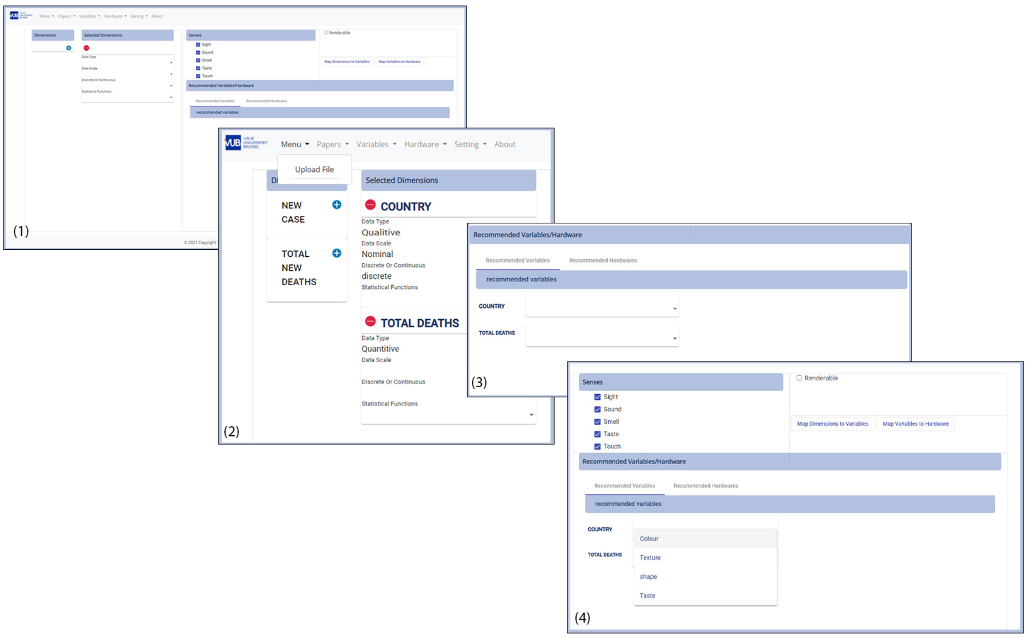


Figure 5.9: Mapping Process

5.3.6 Grammar Module

The process defined in the previous section, which leads to mapping data onto the physical variables, is implemented by conditional statements. However, for implementing the final version of the grammar, the rules and specifications of the grammars should be defined and implemented in order to generalise the process of adding new physical variables and the mapping process.

6 Evaluation

According to the latest standard in the HCI field, designing and building the interacting product is a critical task that consists of four primary phases, shown in Figure 6.1 [4]. As displayed in this figure, after establishing the requirement as a first phase, designing alternatives in the second phase, and prototyping in the third one, the final phase, which is evaluating, complements the design process. Although evaluation is an essential step of the design process, most works in DSR concentrate more on building activities and technological rigour rather than evaluating the built artefact [143]. For example, in the DSR process, proposed by Peffers et al. [114], the evaluation occurs after constructing the artefact, which can imply that the main concern is building the artefacts in this methodology. However, some frameworks, such as [30, 120], guide selecting the appropriate strategy to evaluate the artefact in which the evaluation plays the role as indispensable as building activities. The benefit of the evaluation phase is checking user requirements compliance and evaluating user experiences in terms of security, efficiency or attractiveness. Moreover, it aims to determine if the final artefact is a practical solution in order to solve the stated problem and achieve the identified objectives [3, 4].

Evaluation is an iterative step [4]. It means that each time the design is evaluated, the result shows the drawbacks that should be overcome in the next iteration, and then after refining the requirements and alternative solutions, the new design will be re-evaluated. This iteration will be stopped when the satisfying results are achieved. This chapter provides the first round of evaluating the implementation of the *physicalisation framework*. The evaluation result, discussed in Section 6.2.3, has established an original road-map in which the final result will be a *physicalisation framework* as a novel alternative for telling the story hidden in data.

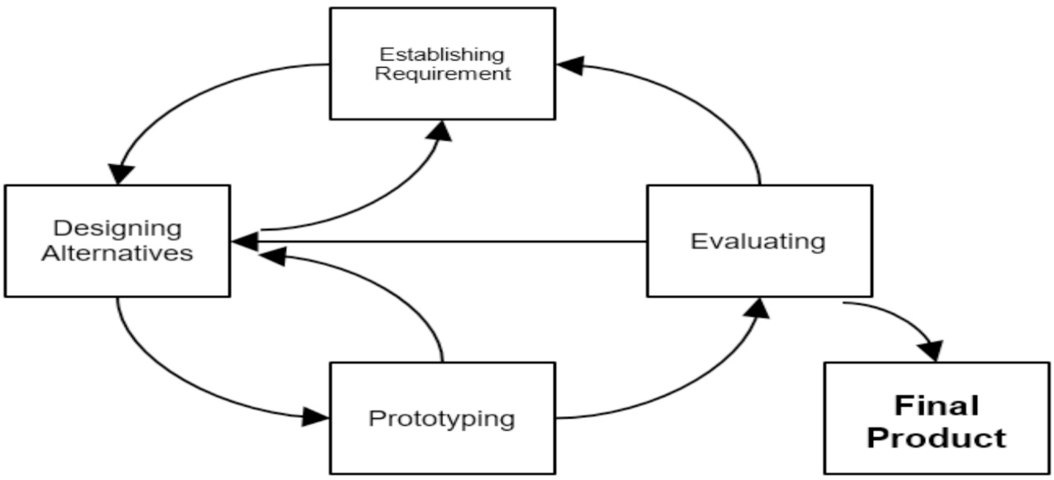


Figure 6.1: Life cycle Model of Interaction Design

6.1 Evaluation Activity

There are different sorts of evaluation activities [143]; since this thesis is following DSRM, the main evaluation activity serves to study how the artefact performs in practice [114]. Various methods can be applied to investigate the final artefact in different aspects. Sonnenberg and vom Brocke [143] proposed case study, field experiment, survey, expert interview, and focus group for this purpose. This thesis has employed the case study and survey to evaluate the artefact.

6.1.1 Experiment

For evaluating the designed artefact, which is the *physicalisation framework*, in terms of user experience. The experiment is designed in order to assess the tool in terms of six various scales based on the User Experience Questionnaire

(UEQ)[1]. It is used to study how people interact and think about the tool. Since the implemented prototype of the *physicalisation framework* aims to explore the data in the physical form, and the goal of this experiment is assessing this important point, 8 participants (4 females and 4 males) with a mean age of 27.8 were chosen to participate in this experiment.

Procedure

In the designed experiment, the participants had to go through one pre-test, three phases, and finish one task. None of the participants had neither knowledge of physicalisation nor the previous experience of working with professional visualisation tools to analyse data, but all of them had experience working with data using Microsoft Excel. In order to ensure that all participants have a clear insight about data visualisation, before starting the main experiment, they were asked to create the arbitrary visualisation using the same data set in Microsoft excel. Appendix A.1 shows some sample visualisations made by three participants. The first phase of the experiment was being introduced to the physicalisation and the goal of this thesis, this steps was performed individually using through a 10-minute online meeting. In phase two, the writer taught the participants how to work with the framework interface through a short online training session. Then the small data set including data about Covid-19 was given to them to start the task. This data set is composed of five columns including European countries, total confirmed cases, total confirmed new cases, total deaths, total new deaths in July 2020 extracted from World Health Organisation[2]. Afterwards, the participants were asked to perform one task with following steps: uploading the data set, selecting four columns of data by their choice, arranging the columns based on their preference, filtering the senses they want to use in the physicalisation (this step is optional), and as the last step, choose between the suggested physical variables. After finishing the experience, they were asked to fill in the user experience questionnaire to express their experience in terms of the designed user interface.

Questionnaire

The User Experience Questionnaire (UEQ) is a fast and reliable questionnaire to measure the comprehensive user experience in working with interactive artefacts. It consists of 26 questions that measure 6 different scales

[1] `https://www.ueq-online.org` (accessed 05/08/2021)

[2] `https://www.who.int/docs/default-source/coronaviruse/20200630-covid-19-sitrep-162.pdf?sfvrsn=e00a5466_2` (accessed 01/05/2021)

of Attractiveness, Perspicuity, Perspicuity, Dependability, Stimulation, and Novelty. Each question has seven ratings from one to seven, and they are arranged in a random order to prevent tendencies in the answers. In the following, each scale is described briefly:

- **Attractiveness**: Six questions form this scale to assess the overall user impression about the product. It means if the user enjoys their experience of working with the artefact or not.
- **Perspicuity**: Four questions are prepared in the questionnaire to evaluate the Perspicuity, which means whether the artefact is understandable or not.
- **Efficiency**: Four questions measure whether the user can perform the task using as few as steps, or they need to make extra efforts.
- **Dependability**: This scale has four questions and measures the user's feeling about how much they control the artefact as well as security and predictability.
- **Stimulation**: Four questions form this scale to evaluate how much the artefact is motivating for the user.
- **Novelty**: The rest of the questions (four questions) assess if the artefact is creative or it is a conventional design.

6.2 Evaluation Results and Feedback

This section discusses the result of the questionnaires and users' opinions about how to improve the *physicalisation framework* exchanged during online interviews right after performing the task.

6.2.1 Pre-Test Results

As mentioned before, the pre-test is conducted to assess the participants' knowledge about visualisation and physicalisation. In this test, participants were asked to answer seven questions, shown in A.1. As it is displayed in the Figure 6.2, all participants had worked with Microsoft Excel and tried to visualise data even if they had not known what the visualisation is. Interestingly half of the participants claimed that they had used physical artefacts before as a medium to show data. Two of the participants referred to their childhood when they used stones to show the numbers. One of them mentioned souvenirs as physical artefacts to keep memories alive, and the other explained how he uses wooden sticks to teach his 4-year-old son to count. However, none of the participants had any idea about physicalisation, and they claimed they had not used physicalisation before. It seems that 4 of the participants answered questions five and seven contradictory, it is because this questionnaire was filled before clarification about physicalisation, and after they got familiar with physicalisation, they noticed that they had used it before. After filling the questionnaires, the participants made some visualisations using the same data set to prove their skills in this field. The results are shown in Appendix A.1.

Figure 6.2: The results of pre-test

6.2.2 Observation Results and Participants' Ideas

All participants were able to finish the task they were asked to do. It means that the physicalisation framework is helpful to initiate the process of mapping data onto physical variables. Most participants were excited about the physicalisation, and after discussing it together and working with the framework, they had exciting ideas. for example, one of the participants suggested applying physicalisation in the Cockpit technologies. He suggested mapping critical meters such as engine status to the control wheel and a temperature. The other participant suggested mapping the speed exceeding of the car to the vibration of the seat. Moreover, the interesting suggestion given by one of the participants was using smells as a reminder of tasks. She explained that smells could quickly trigger memories, so using odour to remind people to do something will be interesting. However, all the participants expressed that they expected to see the physical result as an outcome of the framework, and they were not satisfied by the theoretical mapping process. Moreover, they found the relationship between framework and physicalisation complicated, which is more obvious in the next section.

6.2.3 Questionnaire Analysis

As mentioned before, after finishing the task, participants were requested to fill the prepared questionnaires. The original results are displayed in Appendix A.3. A data analysis tool provided by the UEQ has been used to analyse the results. Figure 6.3 represents the raw data of the gathered participants' feedback. Each column (called item in the table) represents one question in the questionnaire, and the associated row is the score given to the question by the participant.

Items																									
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
5	3	1	5	2	5	6	1	1	1	6	2	1	6	7	6	1	2	3	6	7	5	2	2	3	7
4	1	5	7	3	4	4	3	2	2	5	4	1	3	7	3	2	4	6	6	7	1	2	5	3	7
4	2	2	6	4	4	3	6	2	2	4	4	2	2	6	4	2	4	4	6	6	6	2	4	4	6
5	4	7	6	1	7	7	5	1	1	7	1	1	6	7	6	1	1	3	6	6	6	2	1	2	7
6	7	2	1	3	6	6	5	1	1	5	2	1	5	5	5	2	3	4	6	1	4	2	3	3	6
4	3	1	7	3	4	6	4	1	1	4	2	2	5	7	5	4	3	4	4	6	4	2	2	4	7
6	3	2	6	4	5	6	4	1	1	4	3	3	5	6	4	4	2	7	4	5	4	3	3	2	7
4	6	1	1	1	6	6	6	1	2	4	2	7	6	6	6	4	2	5	6	2	5	2	2	2	6

Figure 6.3: Raw data of filled questionnaires by participants

Figure 6.4 displays the distribution of answers per question. The distribution shows that participants had a positive opinions in many cases; however, they were not satisfied in terms of understandability. The further figures show this part more clearly. In order to calculate the mean value per question, the scale is defined from -3 to +3 in the data analysis tool. It means -3 and +3 are used to show the most negative and most positive answers, respectively, and 0 is the representative of the neutral answers. Figure 6.5 shows the mean value per question. As it is shown, most answers are positive, which shows the *physicalisation framework* is on a correct path; however, the questions regarding understandability got mostly negative answers which seems to stem from no rendering at the end of the process. Moreover, Figure 6.6 shows the mean value per person in each category. As it is shown, the design is not satisfactory in terms of Perspicuity and Dependability for most of the participants.

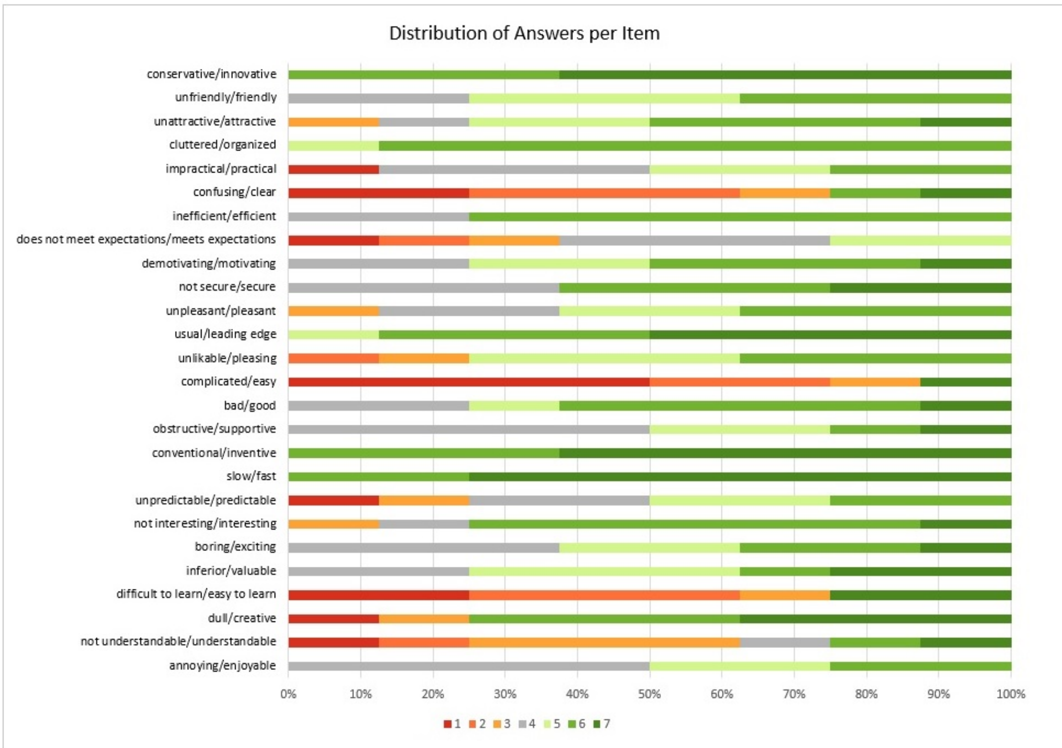


Figure 6.4: Distribution of answers per item

Benchmarking in the data analysis tool is based on data gathered from 21175 persons and 468 studies about different products such as business software, web pages, or social networks. This data makes comparing possible between the developed product and other ones. Figure 6.7 shows the benchmark result, which is compatible with the previous figures. As it is shown, the designed artefact is "bad" in terms of perspicuity and dependability, but it is excellent in terms of novelty. Efficiency and stimulation are acceptable for the first attempt of providing the *physicalisation framework*. Figure 6.8 shows the participants' overall impression about the *physicalisation framework*.

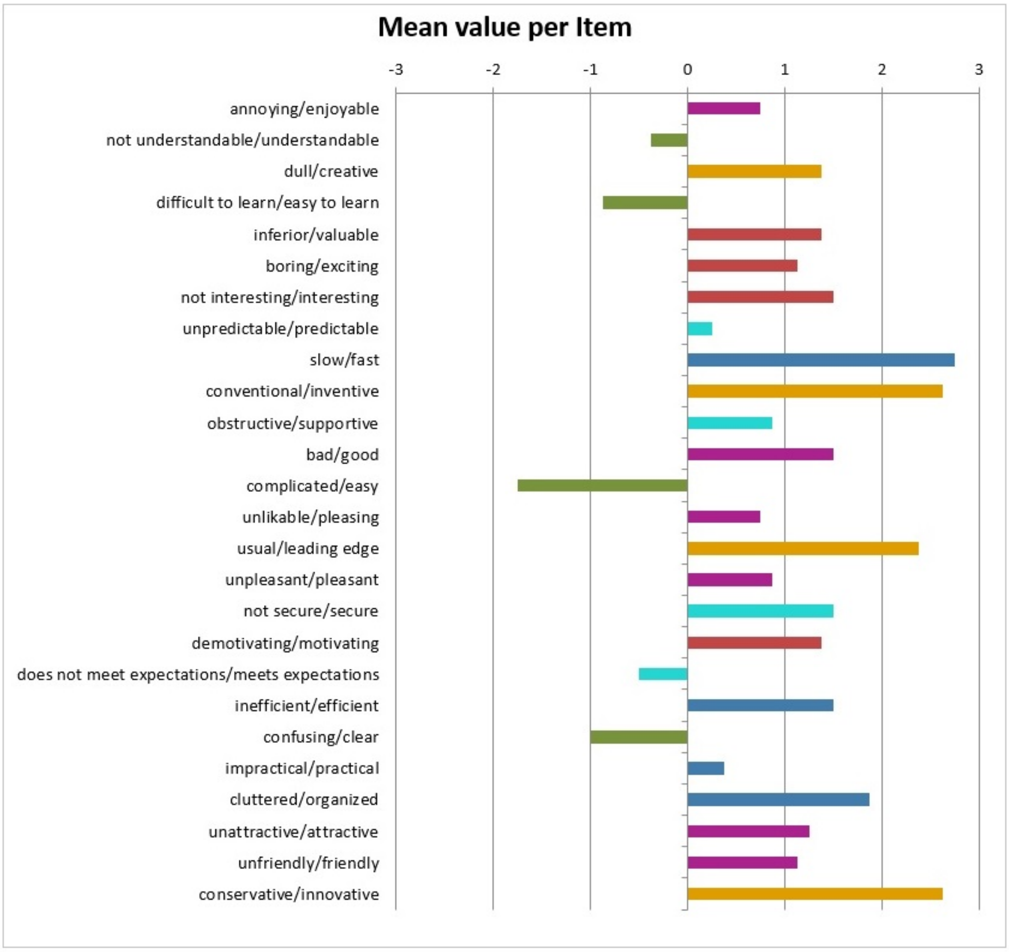
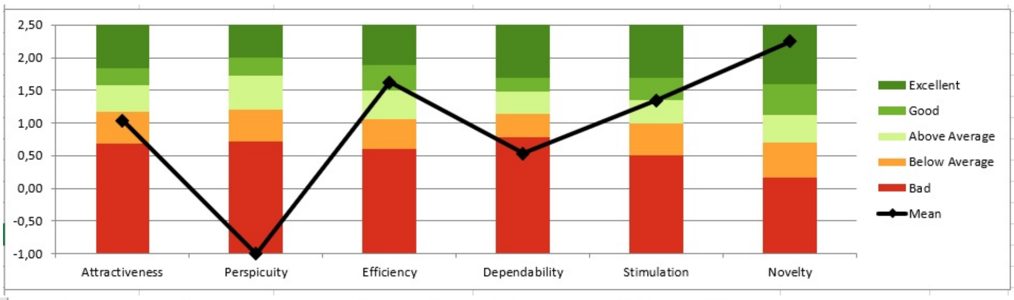


Figure 6.5: Mean value of answers per question



Scale	Mean	Comparisson to benchmark	Interpretation
Attractiveness	1,04	**Below average**	50% of results better, 25% of results worse
Perspicuity	-1,00	**Bad**	In the range of the 25% worst results
Efficiency	1,63	**Good**	10% of results better, 75% of results worse
Dependability	0,53	**Bad**	In the range of the 25% worst results
Stimulation	1,34	**Above Average**	25% of results better, 50% of results worse
Novelty	2,25	**Excellent**	In the range of the 10% best results

Figure 6.7: The Benchmark results

Scale means per person					
Attractiveness	Perspicuity	Efficiency	Dependability	Stimulation	Novelty
1,67	-2,00	2,00	0,75	1,75	3,00
-0,33	-3,00	0,75	0,00	0,25	1,75
-0,33	-2,00	2,00	1,00	-0,25	2,00
2,17	-1,75	2,25	2,00	3,00	1,50
1,33	1,50	1,75	1,00	1,50	2,00
1,00	-2,00	1,25	0,00	1,00	3,00
1,17	-1,25	1,00	-0,75	1,25	2,50
1,67	2,50	2,00	0,25	2,25	2,25

Figure 6.6: Mean value of answers per person

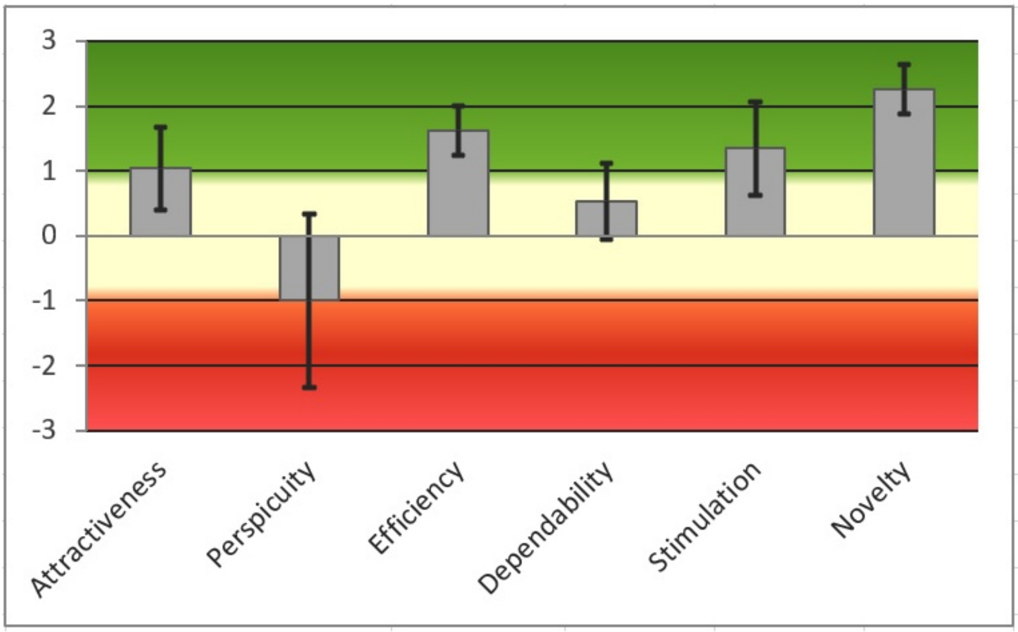


Figure 6.8: Means of participants' opinions

To conclude, the *physicalisation framework* left a good impression on participants in terms of novelty and stimulation. They found the tool, attractive and innovative. Since this concept is so novel and hard to comprehend, most participants found the framework unclear and complex, so it needs more investigation and effort to become more perspicuous for the end user. This result is an excellent road-map to follow which leads to achieving the framework that the expert and non-expert audiences can utilise to physicalise data.

7 Discussion and Future Work

7.1 Discussion

The presented work started with an introduction about physicalisation, the human perceptual system, the existing grammars for visualisation, and an elaboration of past endeavours about static and dynamic physicalisations using attributes of materials. As it stands, physicalisation is an emerging research area. While providing the extensible data physicalisation framework which supports prototyping, the physical visualisation is work in progress. The physicalisation framework enables researchers to experiment with data physicality and the new combinations of physical variables as well as the expert and non-expert users who want to explore the underlying physical form of data dynamically and interactively. The finding of this thesis is a limited contribution to the dynamic interactive physicalisation research area, through endeavours to improve the conceptual *physicalisation framework*, introduced in [140], and implement the first release of it. This purpose has been reached through several steps of study and work, starting from investigating the *Grammar of Graphics* to propose the formalised approach in the form of the *Grammar of Physicalisation* and ending with an experiment on the first release of the framework to evaluate how much the designed solution is applicable and practical in terms of dynamic interactive physicalisation. Various kinds of grammars, in classes of declarative general-purpose grammars of visualisation and domain-specific ones, have been studied in order to design the *Grammar of Physicalisation*. Besides, studying the different properties of the materials has led the writer to prepare the list of physical variables that can be used as a physical medium in physicalisation. These properties and behaviours of the materials are not dependent on the material identity and can change without any direct or indirect impact on it. Moreover, these physical variables do not require any peripheral devices to be sensed by people, and they are safe for the audiences in a way that the interaction with them does not cause any hurt for the users.

Since this thesis is mainly based on reviewing the literature, various works and applications regarding static and dynamic physicalisations have been explored to inspect the possibility of using different physical variables as a unit in physicalisation. However, the efficiency of using these variables have not been evaluated yet. Furthermore, the *Grammar of Physicalisation* has been designed, which tries to map data onto physical variables considering different criteria. This grammar is based on the *Grammar of Graphics*. In order to reflect this grammar as a suggested solution aiming to propose the formalised approach, encoding data to physical form and supporting interactivity, the implemented application is designed and implemented. So it is possible to evaluate how much the suggested solution is applicable and efficient in the dynamic physicalisation research area in terms of defined objectives. After conducting the designed experiment, since this idea is novel, the result shows the remarkable impression in terms of novelty and attractiveness. However, due to the lack of maturity in this research area, the proposed solution suffers from non-understandability and independability. These results will be used as a road-map for improving and developing the solution since the ultimate goal of physicalisation is providing the method to represent data physically for all people. Therefore, it is believed that this work's finding can be considered a contribution to this emerging research area due to the introduction of an initial step to build dynamic interactive physicalisation.

7.2 Future Work

The presented work raises several novel opportunities in the dynamic interactive physical representation of data, discussed in the following. Previous chapters of this thesis have elaborated the first version of the *physicalisation framework*, which has two different sections. The first one is the *Grammar of Physicalisation* which proposes the physical variables as a candidate for representing data physically. A second part is the publication library, which can gather all papers in this research area and makes a connection between them and any related topics. In the grammar section, the user is responsible for adding complementary metadata to the data set which is used as criteria to propose the physical variables. Due to the ultimate goal of this topic which is proposing the approach which makes the physicalisation a novel alternative or complementary method for data representation, adding the new functionalities to the tool which analyse the data is suggested. In this way, people who are not experts in data analysing can be the audience of the physicalisation framework.

Apart from that, the focus of this thesis is on the specification steps of the *Grammar of Physicalisation* and displaying and rendering of the final physical visualisation is not part of this work. The framework suggests potential physical variables for the data set, the user can create the one-to-one relation between selected data dimensions and suggested physical variables and after establishing this relation, no final physical representation is created for that suggested variables. The next future development can provide drivers that enable the framework to connect with available hardware in the physicalisation research area. By developing this section, the final rendering using existed hardware would be possible. By proposing the new hardware in this concept, the user should be able to add this hardware to the framework and enhance the rendering ability. For now, the user can add hardware dynamically and define some attributes such as name, related physical variable, and the possible range of variable which hardware can simulate. In the final version the user plugs the hardware to the system, and the framework recognises automatically. The main advantage of the physicalisation framework is that it can propose different candidates for each data dimension. Moreover, the user can add new physical variables to the software to expand the candidates for the final representation. But the properties of the physical variables is predefined in the current version, This part can be re-designed and re-implemented to have the ability of new property definitions for the variables. In this case, if the new property of the material is recognised as a new variable, it could be added to the framework without any concerns about mapping criteria.

Besides the proposed future works, any new property of the material can be investigated to expand the Table 4.1. Initially, the primary assumption for using the property as a physical variable was no extra tool requirement for sensing the data from them, and the user uses their palms to capture data through tactile modality or naked eye and ear for sensing related stimuli.

By ignoring the first assumption, new physical variables can be considered a physical medium. For example, the current flowing through the circuit requires an ammeter to be measured, so without initial limitation, many new physical variables can be introduced. Moreover, as discussed in [148], investigating the more complicated mechanical construction methods is considered as the future work, in order to use liquids as a medium to build non-rigid physicalisation. Without the assumption of using the palm for involving the touch sensors, if the user wants to use the entire body for this modality, all the ranges should be re-considered as the complementary work.

7.3 Conclusion

The *physicalisation framework* presented in this thesis proposes the democratised approach to building the dynamic interactive physicalisation more efficiently as a breaking of new ground in this research area. It can be considered as a starting point for those who wish to continue this work for establishing the method for building the non-static physicalisation, which can involve live data. The design and development of the *physicalisation framework* have been initiated out of a lack of formalised method, which clears the way of encoding data to the physical form and ultimately aims to construct the physical representation more efficiently. An initial investigation into the "Tangible Bits", by Ishii et al. [70], and its profound impact on dynamic interactive tangible interfaces, prompted the researchers for further investigations to establish the systematic method to take data out from the digital world into the physical one. However, based on what is explored in this thesis, there have been no methods aiding to build the non-static physicalisation so far. Since physical artefacts provide rich interaction mechanisms due to the human proficiency in communicating with the physical affordances, that boost people's reasoning about data [77]. The proposed method must support interactivity while it is using this proficiency besides facilitating the process of constructing physical visualisation of data. To achieve this purpose, the implementation of *physicalisation framework* is proposed in this thesis, which is an initial attempt to speed up the tedious process of mapping data onto proper physical variables. The proposed grammar is called the *Grammar of Physicalisation*, inspired by the *Grammar of Graphics* [179]. This framework proposes one to many relations between one data dimension and a set of material physical properties, such that the user can select among proposed physical candidates and create the one to one relation between data dimension and physical variable. In this way, the prototyping can be begun using the physical candidates. Accordingly, the *physicalisation framework* has been implemented through the application, which has the interface with which the user can see the relation between loaded data and physical candidates. Finally, this application has been evaluated using an established experiment in which eight non-expert users with no knowledge in physicalisation were asked to finish one task and fill in the User Experience Questionnaire (UEQ). Therefore, the results support establishing the physicalisation framework as a developing approach for crafting the dynamic interactive data physicalisation.

A

Appendix

A.1 Pre-Test Results

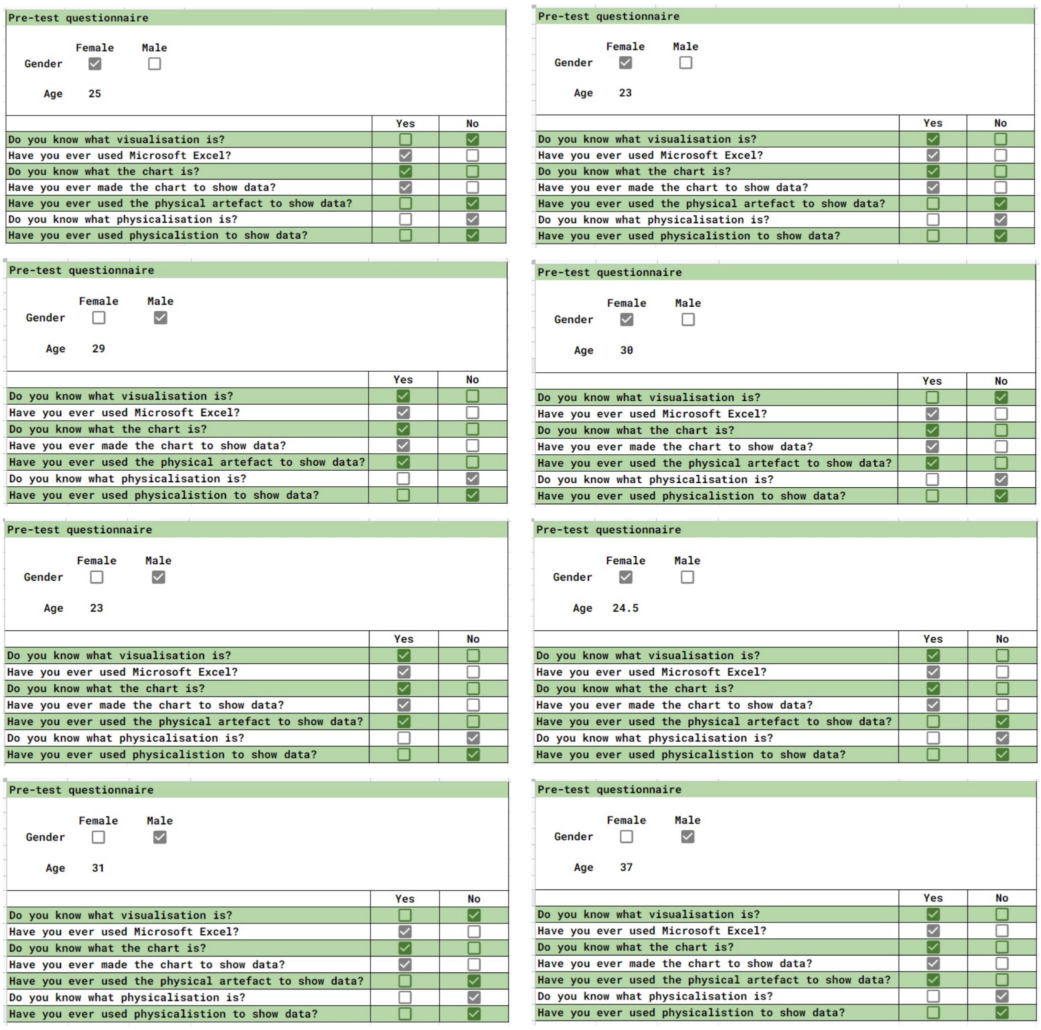
The pre-test is performed to assure the participants are familiar with visualisation. In the following (Figure A.2, A.3 and A.4) three samples of the visualisations made by the participants are displayed.

A.2 User Experience Questionnaire

The User Experience Questionnaire shown in Figure A.5 is used in order to evaluate the user experience.

A.3 Evaluation Results

The filled questionnaires by 8 participants are shown in Figure A.6.



Pre-test questionnaire

Gender: Female ☑ Male ☐

Age 25

	Yes	No
Do you know what visualisation is?	☐	☑
Have you ever used Microsoft Excel?	☑	☐
Do you know what the chart is?	☑	☐
Have you ever made the chart to show data?	☑	☐
Have you ever used the physical artefact to show data?	☐	☑
Do you know what physicalisation is?	☐	☑
Have you ever used physicalistion to show data?	☐	☑

Pre-test questionnaire

Gender: Female ☑ Male ☐

Age 23

	Yes	No
Do you know what visualisation is?	☑	☐
Have you ever used Microsoft Excel?	☑	☐
Do you know what the chart is?	☑	☐
Have you ever made the chart to show data?	☑	☐
Have you ever used the physical artefact to show data?	☐	☑
Do you know what physicalisation is?	☐	☑
Have you ever used physicalistion to show data?	☐	☑

Pre-test questionnaire

Gender: Female ☐ Male ☑

Age 29

	Yes	No
Do you know what visualisation is?	☑	☐
Have you ever used Microsoft Excel?	☑	☐
Do you know what the chart is?	☑	☐
Have you ever made the chart to show data?	☑	☐
Have you ever used the physical artefact to show data?	☑	☐
Do you know what physicalisation is?	☐	☑
Have you ever used physicalistion to show data?	☐	☑

Pre-test questionnaire

Gender: Female ☑ Male ☐

Age 30

	Yes	No
Do you know what visualisation is?	☐	☑
Have you ever used Microsoft Excel?	☑	☐
Do you know what the chart is?	☑	☐
Have you ever made the chart to show data?	☑	☐
Have you ever used the physical artefact to show data?	☑	☐
Do you know what physicalisation is?	☐	☑
Have you ever used physicalistion to show data?	☐	☑

Pre-test questionnaire

Gender: Female ☐ Male ☑

Age 23

	Yes	No
Do you know what visualisation is?	☑	☐
Have you ever used Microsoft Excel?	☑	☐
Do you know what the chart is?	☑	☐
Have you ever made the chart to show data?	☑	☐
Have you ever used the physical artefact to show data?	☑	☐
Do you know what physicalisation is?	☐	☑
Have you ever used physicalistion to show data?	☐	☑

Pre-test questionnaire

Gender: Female ☑ Male ☐

Age 24.5

	Yes	No
Do you know what visualisation is?	☑	☐
Have you ever used Microsoft Excel?	☑	☐
Do you know what the chart is?	☑	☐
Have you ever made the chart to show data?	☑	☐
Have you ever used the physical artefact to show data?	☐	☑
Do you know what physicalisation is?	☐	☑
Have you ever used physicalistion to show data?	☐	☑

Pre-test questionnaire

Gender: Female ☐ Male ☑

Age 31

	Yes	No
Do you know what visualisation is?	☐	☑
Have you ever used Microsoft Excel?	☑	☐
Do you know what the chart is?	☑	☐
Have you ever made the chart to show data?	☑	☐
Have you ever used the physical artefact to show data?	☐	☑
Do you know what physicalisation is?	☐	☑
Have you ever used physicalistion to show data?	☐	☑

Pre-test questionnaire

Gender: Female ☐ Male ☑

Age 37

	Yes	No
Do you know what visualisation is?	☑	☐
Have you ever used Microsoft Excel?	☑	☐
Do you know what the chart is?	☑	☐
Have you ever made the chart to show data?	☑	☐
Have you ever used the physical artefact to show data?	☑	☐
Do you know what physicalisation is?	☐	☑
Have you ever used physicalistion to show data?	☐	☑

Figure A.1: The pre-test results

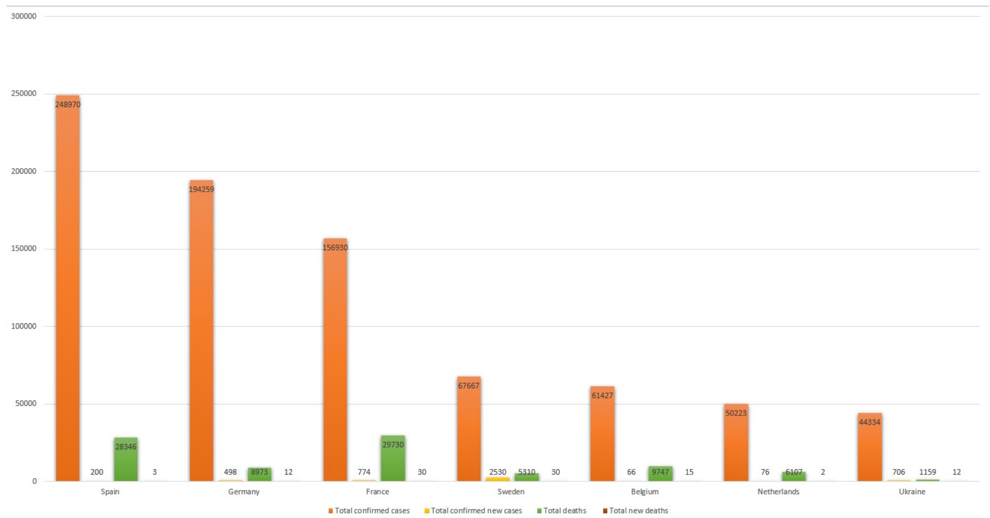


Figure A.2: Bar chart made by one of the participants to show total confirms case, total confirmed new cases, total deaths and total new deaths in seven European countries

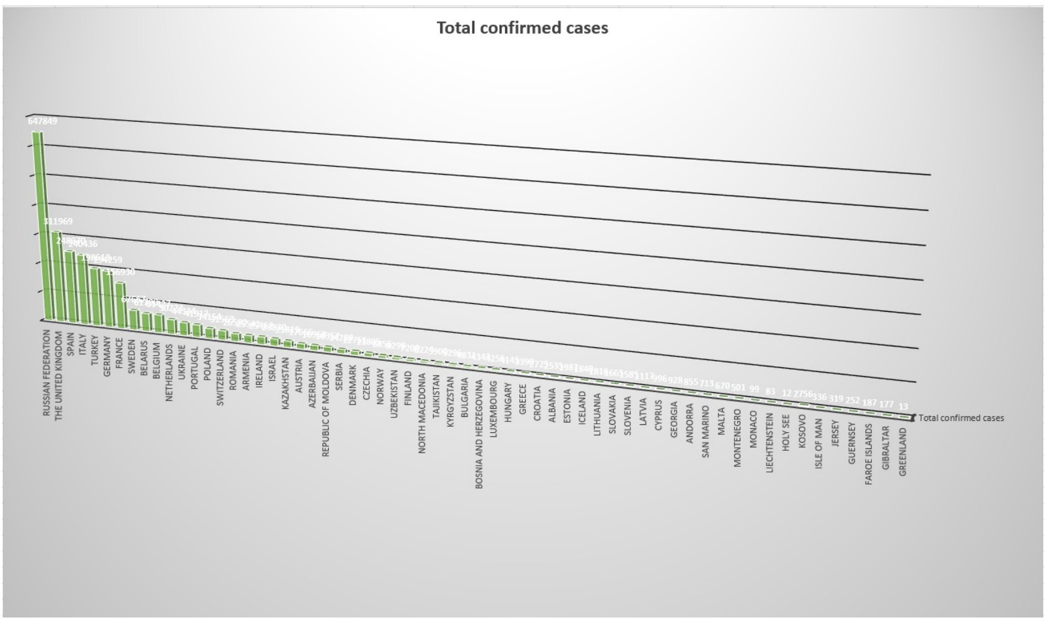


Figure A.3: Bar chart made by one of the participants to show the total confirmed cases in all European countries

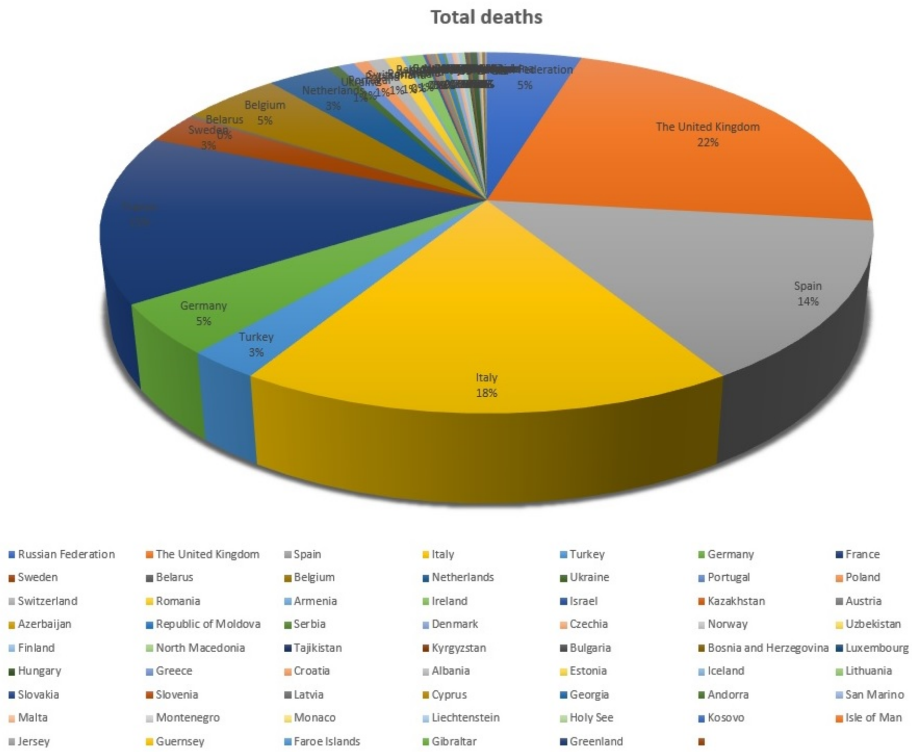
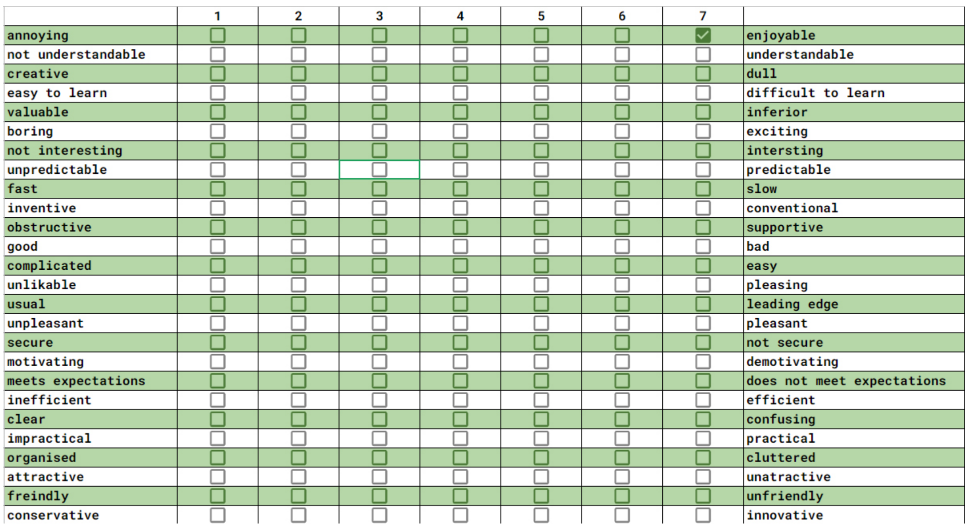


Figure A.4: Pie chart made by one of the participants to show the total deaths in all European countries



	1	2	3	4	5	6	7	
annoying	☐	☐	☐	☐	☐	☐	☑	enjoyable
not understandable	☐	☐	☐	☐	☐	☐	☐	understandable
creative	☐	☐	☐	☐	☐	☐	☐	dull
easy to learn	☐	☐	☐	☐	☐	☐	☐	difficult to learn
valuable	☐	☐	☐	☐	☐	☐	☐	inferior
boring	☐	☐	☐	☐	☐	☐	☐	exciting
not interesting	☐	☐	☐	☐	☐	☐	☐	intersting
unpredictable	☐	☐	☐	☐	☐	☐	☐	predictable
fast	☐	☐	☐	☐	☐	☐	☐	slow
inventive	☐	☐	☐	☐	☐	☐	☐	conventional
obstructive	☐	☐	☐	☐	☐	☐	☐	supportive
good	☐	☐	☐	☐	☐	☐	☐	bad
complicated	☐	☐	☐	☐	☐	☐	☐	easy
unlikable	☐	☐	☐	☐	☐	☐	☐	pleasing
usual	☐	☐	☐	☐	☐	☐	☐	leading edge
unpleasant	☐	☐	☐	☐	☐	☐	☐	pleasant
secure	☐	☐	☐	☐	☐	☐	☐	not secure
motivating	☐	☐	☐	☐	☐	☐	☐	demotivating
meets expectations	☐	☐	☐	☐	☐	☐	☐	does not meet expectations
inefficient	☐	☐	☐	☐	☐	☐	☐	efficient
clear	☐	☐	☐	☐	☐	☐	☐	confusing
impractical	☐	☐	☐	☐	☐	☐	☐	practical
organised	☐	☐	☐	☐	☐	☐	☐	cluttered
attractive	☐	☐	☐	☐	☐	☐	☐	unatractive
freindly	☐	☐	☐	☐	☐	☐	☐	unfriendly
conservative	☐	☐	☐	☐	☐	☐	☐	innovative

Figure A.5: The User Experience Questionnaire

This questionnaire is used to evaluate the user experience through Physicalisation Framework

	Female	Male		
Gender	✓		Age	25

	1	2	3	4	5	6	7	
annoying					✓			enjoyable
not understandable			✓					understandable
creative	✓							dull
easy to learn					✓			difficult to learn
valuable		✓						inferior
boring					✓			exciting
not interesting						✓		intersting
unpredictable	✓							predictable
fast	✓							slow
inventive	✓							conventional
obstructive						✓		supportive
good		✓						bad
complicated	✓							easy
unlikable						✓		pleasing
usual							✓	leading edge
unpleasant						✓		pleasant
secure	✓							not secure
motivating		✓						demotivating
meets expectations			✓					does not meet expectations
inefficient						✓		efficient
clear							✓	confusing
impractical					✓			practical
organised		✓						cluttered
attractive		✓						unatractive
freindly			✓					unfriendly
conservative							✓	innovative

This questionnaire is used to evaluate the user experience through Physicalisation Framework

	Female	Male		
Gender	✓		Age	23

	1	2	3	4	5	6	7	
annoying				✓				enjoyable
not understandable	✓							understandable
creative					✓			dull
easy to learn							✓	difficult to learn
valuable			✓					inferior
boring				✓				exciting
not interesting				✓				intersting
unpredictable			✓					predictable
fast		✓						slow
inventive		✓						conventional
obstructive					✓			supportive
good				✓				bad
complicated	✓							easy
unlikable			✓					pleasing
usual							✓	leading edge
unpleasant			✓					pleasant
secure		✓						not secure
motivating				✓				demotivating
meets expectations						✓		does not meet expectations
inefficient						✓		efficient
clear							✓	confusing
impractical	✓							practical
organised		✓						cluttered
attractive					✓			unatractive
freindly			✓					unfriendly
conservative							✓	innovative

This questionnaire is used to evaluate the user experience through Physicalisation Framework

	Female	Male		
Gender		✓	Age	29

	1	2	3	4	5	6	7	
annoying				✓				enjoyable
not understandable		✓						understandable
creative		✓						dull
easy to learn						✓		difficult to learn
valuable				✓				inferior
boring				✓				exciting
not interesting			✓					intersting
unpredictable						✓		predictable
fast		✓						slow
inventive		✓						conventional
obstructive				✓				supportive
good				✓				bad
complicated		✓						easy
unlikable		✓						pleasing
usual						✓		leading edge
unpleasant				✓				pleasant
secure		✓						not secure
motivating				✓				demotivating
meets expectations				✓				does not meet expectations
inefficient						✓		efficient
clear						✓		confusing
impractical						✓		practical
organised		✓						cluttered
attractive				✓				unatractive
freindly				✓				unfriendly
conservative						✓		innovative

This questionnaire is used to evaluate the user experience through Physicalisation Framework

	Female	Male		
Gender	✓		Age	30

	1	2	3	4	5	6	7	
annoying					✓			enjoyable
not understandable				✓				understandable
creative							✓	dull
easy to learn						✓		difficult to learn
valuable	✓							inferior
boring							✓	exciting
not interesting							✓	intersting
unpredictable					✓			predictable
fast	✓							slow
inventive	✓							conventional
obstructive							✓	supportive
good	✓							bad
complicated	✓							easy
unlikable						✓		pleasing
usual							✓	leading edge
unpleasant						✓		pleasant
secure	✓							not secure
motivating	✓							demotivating
meets expectations			✓					does not meet expectations
inefficient						✓		efficient
clear						✓		confusing
impractical						✓		practical
organised		✓						cluttered
attractive	✓							unatractive
freindly		✓						unfriendly
conservative							✓	innovative

This questionnaire is used to evaluate the user experience through Physicalisation Framework

	Female	Male		
Gender		✓	Age	23

	1	2	3	4	5	6	7	
annoying						✓		enjoyable
not understandable							✓	understandable
creative		✓						dull
easy to learn	✓							difficult to learn
valuable			✓					inferior
boring						✓		exciting
not interesting						✓		intersting
unpredictable					✓			predictable
fast	✓							slow
inventive	✓							conventional
obstructive					✓			supportive
good		✓						bad
complicated	✓							easy
unlikable					✓			pleasing
usual					✓			leading edge
unpleasant					✓			pleasant
secure		✓						not secure
motivating			✓					demotivating
meets expectations				✓				does not meet expectations
inefficient						✓		efficient
clear	✓							confusing
impractical				✓				practical
organised		✓						cluttered
attractive			✓					unatractive
freindly			✓					unfriendly
conservative						✓		innovative

This questionnaire is used to evaluate the user experience through Physicalisation Framework

	Female	Male		
Gender	✓		Age	24.5

	1	2	3	4	5	6	7	
annoying				✓				enjoyable
not understandable			✓					understandable
creative	✓							dull
easy to learn							✓	difficult to learn
valuable			✓					inferior
boring				✓				exciting
not interesting						✓		intersting
unpredictable				✓				predictable
fast	✓							slow
inventive	✓							conventional
obstructive				✓				supportive
good		✓						bad
complicated		✓						easy
unlikable					✓			pleasing
usual							✓	leading edge
unpleasant					✓			pleasant
secure				✓				not secure
motivating			✓					demotivating
meets expectations				✓				does not meet expectations
inefficient				✓				efficient
clear						✓		confusing
impractical				✓				practical
organised		✓						cluttered
attractive		✓						unatractive
freindly				✓				unfriendly
conservative							✓	innovative

This questionnaire is used to evaluate the user experience through Physicalisation Framework

	Female	Male		
Gender		✓	Age	31

	1	2	3	4	5	6	7	
annoying						✓		enjoyable
not understandable			✓					understandable
creative		✓						dull
easy to learn						✓		difficult to learn
valuable				✓				inferior
boring					✓			exciting
not interesting						✓		intersting
unpredictable				✓				predictable
fast	✓							slow
inventive	✓							conventional
obstructive				✓				supportive
good			✓					bad
complicated			✓					easy
unlikable					✓			pleasing
usual						✓		leading edge
unpleasant				✓				pleasant
secure				✓				not secure
motivating		✓						demotivating
meets expectations							✓	does not meet expectations
inefficient				✓				efficient
clear					✓			confusing
impractical				✓				practical
organised			✓					cluttered
attractive			✓					unatractive
freindly		✓						unfriendly
conservative							✓	innovative

This questionnaire is used to evaluate the user experience through Physicalisation Framework

	Female	Male		
Gender		✓	Age	37

	1	2	3	4	5	6	7	
annoying				✓				enjoyable
not understandable			✓			✓		understandable
creative	✓							dull
easy to learn	✓							difficult to learn
valuable	✓							inferior
boring						✓		exciting
not interesting						✓		intersting
unpredictable						✓		predictable
fast	✓							slow
inventive		✓						conventional
obstructive				✓				supportive
good		✓						bad
complicated							✓	easy
unlikable						✓		pleasing
usual						✓		leading edge
unpleasant						✓		pleasant
secure				✓				not secure
motivating		✓						demotivating
meets expectations					✓			does not meet expectations
inefficient						✓		efficient
clear		✓						confusing
impractical					✓	✓		practical
organised		✓						cluttered
attractive		✓						unatractive
freindly		✓						unfriendly
conservative						✓		innovative

Figure A.6: The evaluation results

Bibliography

[1] Quantitative visual psychophysics during the period of European enlightenment. The studies of the astronomer and mathematician Tobias Maye (1723-1762) on visual acuity and colour perception.

[2] Jacques H. Abraini, Hélène N. David, Nicolas Vallée, and Jean-Jacques Risso. Theoretical considerations on the ultimate depth that could be reached by saturation human divers. *Med Gas Res*, 2(6):119–121, July 2016.

[3] Stephan Aier and Christian Fischer. Criteria of Progress for Information Systems Design Theories. *Information Systems and e-Business Management*, 9:133–172, March 2011.

[4] A Andre and H Dinata. Interaction Design to Enhance UX of University Timetable Plotting System on Mobile Version. *IOP Conference Series: Materials Science and Engineering*, 407, September 2018.

[5] Olivier Bau, Uros Petrevski, and Wendy Mackay. BubbleWrap: A Textile-Based Electromagnetic Haptic Display. In *CHI 2009 Extended Abstracts on Human Factors in Computing Systems*, pages 3607–3612, New York, USA, 2009. Association for Computing Machinery.

[6] Olivier Bau, Ivan Poupyrev, Ali Israr, and Chris Harrison. Teslatouch: Electrovibration for Touch Surfaces. pages 283–292, October 2010.

[7] Mark F Bear, Barry W Connors, and Michael A Paradiso. *Neuroscience : exploring the brain*. Philadelphia : Wolters Kluwer, 4 edition, 2016.

[8] Frederick C. Beiser. Stanford Encyclopedia of Philosophy. `https://plato.stanford.edu/entries/fechner/`, January 2020. Accessed on 16/07/2021.

[9] Jacques Bertin. *Semiology of graphics*. University of Wisconsin Press, January 1983.

[10] A. Bezerianos and P. Isenberg. Perception of Visual Variables on Tiled Wall-Sized Displays for Information Visualization Applications. *IEEE transactions on visualization and computer graphics*, 18(12):2516–2525, December 2012.

[11] Arlene Birt and Marianne Rosolen. Death by Chocolate. `http://data-cuisine.net/data-dishes/death-by-chocolate`, May 2016. Accessed on 17/07/2021.

[12] Ingvars Birznieks, Sarah McIntyre, Hanna Nilsson, Saad Nagi, David Mahns, and Richard Vickery. Tactile sensory channels over-ruled by frequency decoding system that utilizes spike pattern regardless of receptor type. 8, August 2019.

[13] Way Kiat Bong, Florian Maußer, Margot van Eck, Diogo De Araujo, Jorg Tibosch, Tobias Glaum, and Weiqin Chen. Designing Nostalgic Tangible User Interface Application for Elderly People. In Klaus Miesenberger, Roberto Manduchi, Mario Covarrubias Rodriguez, and Petr Peňáz, editors, *Computers Helping People with Special Needs*, pages 471–479, Cham, 2020. Springer International Publishing.

[14] Katy Börner, Andreas Bueckle, and Michael Ginda. Data visualization literacy: Definitions, conceptual frameworks, exercises, and assessments. *Proceedings of the National Academy of Sciences*, 116(6):1857–1864, 2019.

[15] Michael Bostock and Jeffrey Heer. Protovis: A Graphical Toolkit for Visualization. *IEEE Trans. Visualization and Comp. Graphics (Proc. InfoVis)*, 2009.

[16] Michael Bostock, Vadim Ogievetsky, and Jeffrey Heer. D3 Data-Driven Documents. *IEEE Transactions on Visualization and Computer Graphics*, 17(12):2301–2309, 2011.

[17] Nick Braisby and Angus Gellatly. *Cognitive psychology.* Oxford University Press, 2 edition, 2012.

[18] Joseph M. Brown. *The Mechanical Theory of Everything.* Basic Research Press, 1 edition, June 2015.

[19] Lorna Brown, Abigail Sellen, Renan Krishna, and Richard Harper. Exploring the potential of audio-tactile messaging for remote interpersonal communication. pages 1527–1530, April 2009.

[20] Lorna M. Brown and John Williamson. Shake2Talk: Multimodal Messaging for Interpersonal Communication. In Ian Oakley and Stephen Brewster, editors, *Haptic and Audio Interaction Design*, pages 44–55, Berlin, Heidelberg, 2007. Springer Berlin Heidelberg.

[21] C. Bushdid, M.O. Magnasco, L.B. Vosshall, and Andreas Keller. Humans Can Discriminate More than 1 Trillion Olfactory Stimuli. Technical report, March 2014.

[22] Jonathan C. Roberts and Rick Walker. Using All Our Senses: the need for a Unified Theoretical Approach to Multi-sensory Information Visualization. *VisWeek Workshop*, 2010.

[23] Gemma Calvert, Charles Spence, and Barry Stein. *The Handbook of Multisensory Processes.* A Bradford Book, May 2004.

[24] León M. Carreño, Bringas J.A. Sandoval, Robles T. Alvarez, Castro R. Cosio, Cota I. Estrada, and Carrillo A. Leyva. Designing a Tangible User Interface for Braille Teaching. volume 12426 of *Stephanidis C., Antona M., Gao Q., Zhou J. (eds) HCI International 2020 – Late Breaking Papers: Universal Access and Inclusive Design.* Springer, Cham, September 2020.

[25] Hasok Chang. The Myth of the Boiling Point. *Science Progress*, 91(3):219–240, 2008. PMID: 18853575.

[26] Mindy Chang, Ge Wang, and Jonathan Berger. Sonification and Visualization of Neural Data. January 2010.

[27] W. Chang and Hadley Wickham. ggvis: Interactive grammar of graphics. `http://CRAN.R-project.org/package=ggvis`, 2020. R Package Version 0.4.7, Accessed on 04/08/2021.

[28] Chun-houh Chen, Wolfgang Karl Härdle, and Antony Unwin. *Handbook of Data Visualization.* Springer, 2008.

[29] T Clarkson. Diagram of the slave ship Brooks. `http://www.garstangfairtrade.org.uk/johns_images/slave_ship.jpg`, 1808. Accessed on 05/06/2021.

[30] Anne Cleven, Philipp Gubler, and Kai Hüner. Design alternatives for the evaluation of design science research artifacts. May 2009.

[31] Marcelo Coelho, Hiroshi Ishii, and Pattie Maes. Surflex: A Programmable Surface for the Design of Tangible Interfaces. In *CHI 2008 Extended Abstracts on Human Factors in Computing Systems*, CHI EA 2008, pages 3429–3434, New York, USA, 2008. Association for Computing Machinery.

[32] Rob Comber, Eva Ganglbauer, Jaz Choi, Jettie Hoonhout, Yvonne Rogers, Kenton O'Hara, and Julie Maitland. Food and interaction design: Designing for food in everyday life. *Conference on Human Factors in Computing Systems - Proceedings*, May 2012.

[33] D. R. Cox. Some Remarks on the Role in Statistics of Graphical Methods. *Royal Statistical Society*, 27(1):4–9, 1978.

[34] Helder da Rocha. *Learn Chart.js.* Packt Publishing, February 2019.

[35] J. Delwiche. Are there 'basic' tastes? *Trends in Food Science Technology*, 7(12):411–415, 1996.

[36] Christian Deppner, Waldemar Herr, Merle Cornelius, Peter Stromberger, Tammo Sternke, Christoph Grzeschik, Alexander Grote, Jan Rudolph, Sven Herrmann, Markus Krutzik, André Wenzlawski, Robin Corgier, Eric Charron, David Guéry-Odelin, Naceur Gaaloul, Claus Lämmerzahl, Achim Peters, Patrick Windpassinger, and Ernst M. Rasel. Collective-Mode Enhanced Matter-Wave Optics. *Phys. Rev. Lett.*, 127, August 2021.

[37] Daniel Dietrich and Henri Myrttinen. Data visualisation. Technical report, Topic report, 2012.

[38] Vision Direct. How fast would an object have to go to be invisible to the human eye? `https://www.visiondirect.co.uk/blog/how-fast-can-we-see`, January 2016. Accessed on 20/11/2021.

[39] Dragicevic, Pierre and Jansen, Yvonne and Vande Moere, Andrew and Vanderdonckt, Jean. Data Physicalization. *Springer Handbook of Human Computer Interaction*, September 2019.

[40] Khalid I. El Fadli, Randall S. Cerveny, Christopher C. Burt, Philip Eden, David Parker, Manola Brunet, Thomas C. Peterson, Gianpaolo Mordacchini, Vinicio Pelino, Pierre Bessemoulin, José Luis Stella, Fatima Driouech, M. M Abdel Wahab, and Matthew B. Pace. World Meteorological Organization Assessment of the Purported World Record

58°C Temperature Extreme at El Azizia. *Bulletin of the American Meteorological Society*, 94(2):199–204, 2013.

[41] Fouzia El Mountassir, Christine Belloir, Loïc Briand, Thierry Thomas-Danguin, and Anne-Marie Le Bon. Encoding odorant mixtures by human olfactory receptors. *Flavour and Fragrance Journal*, 31(5):400–407, 2016.

[42] Ungar Eugene and Stroud Kenneth. A New Approach to Defining Human Touch Temperature Standards . *Man/System Technology and Life Support*, January 2010.

[43] Daniel Fink and Jan Mayes. Too loud! Non-occupational noise exposure causes hearing loss. *Proceedings of Meetings on Acoustics*, 43(1), 2021.

[44] David J. Finlay and Peter C. Dodwell. Speed of apparent motion and the wagon-wheel effect. *Perception & Psychophysics*, 41:29–34, January 1987.

[45] Sean Follmer, Daniel Leithinger, Alex Olwal, Nadia Cheng, and Hiroshi Ishii. Jamming user interfaces: Programmable particle stiffness and sensing for malleable and shape-changing devices. pages 519–528, October 2012.

[46] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. inFORM: Dynamic Physical Affordances and Constraints through Shape and Object Actuation. pages 417–426, October 2013.

[47] Michael Friendly. A Brief History of the Mosaic Display. *Journal of Computational and Graphical Statistics*, 11(1):89–107, 2002.

[48] J.J. Gibson. *The senses considered as perceptual systems.* Houghton Mifflin, 1966.

[49] Kyle Gilpin, Kent Koyanagi, and Daniela Rus. Making self-disassembling objects with multiple components in the Robot Pebbles system. In *2011 IEEE International Conference on Robotics and Automation*, pages 3614–3621, 2011.

[50] David H. Gire, Diego Restrepo, Terrence J. Sejnowski, Charles Greer, Juan A. De Carlos, and Laura Lopez-Mascaraque. Temporal Processing in the Olfactory System: Can We See a Smell? *Neuron*, 78(3):416–432, May 2013.

[51] Seth Copen Goldstein, Jason Campbell, and Todd C. Mowry. Programmable matter. *Computer*, 38(6):99–101, May 2005.

[52] S.R. Gomez, R. Jianu, C. Ziemkiewicz, Hua Guo, and D.H. Laidlaw. Different Strokes for Different Folks: Visual Presentation Design between Disciplines. *IEEE transactions on visualization and computer graphics*, 18(12):2411–2420, December 2012.

[53] V. Gonzalez and A. Kobsa. Benefits of information visualization systems for administrative data analysts. In *Proceedings on Seventh International Conference on Information Visualization, 2003. IV 2003.*, pages 331–336, 2003.

[54] Daniel Gooch and Leon Watts. Communicating Social Presence Through Thermal Hugs. September 2010.

[55] Davey Gott. How many Colors Are There In the World? `https://www.ncifm.com/how-many-colors-are-there-in-the-world/`, May 2019. Accessed on 02/08/2021.

[56] Robert Grant. Pretty Persuasion: The Advantages of Data Visualisation. *Impact*, 2019(2):19–23, 2019.

[57] BG Green, SJ Lederman, and JC Stevens. The effect of skin temperature on the perception of roughness. *Sens Processes*, 3(4):327–333, December 1979.

[58] Ian Gwilt, A. Yoxall, and K. Sano. Enhancing the understanding of statistical data through the creation of physical objects. 1:117–124, January 2012.

[59] Steffen Haesler, Jorn Hurtienne, Franz Ertle, and Patricia Theile. A Classification Schema for Data Physicalizations and a Carbon Footprint Physicalization. In *Workshop co-located with IEEE VIS 2018 on Toward a Design Language for Data Physicalization organized by Trevor Hogan, Uta Hinrichs, Jason Alexander, Samuel Huron, Sheelagh Carpendale, Eva Hornecker*, October 2018.

[60] Friedrich Hart. COVID-19 Deaths as Nails. `http://dataphys.org/list/covid-deaths-as-nails/`, December 2020. Accessed on 16/07/2021.

[61] G. Havenith, R. Heus, and HA Daanen. The hand in the cold, performance and risk. *Arctic Med Res*, 54:37–47, January 1995.

[62] Jeffrey Heer and Michael Bostock. Declarative Language Design for Interactive Visualization. *IEEE Trans. Visualization and Comp. Graphics (Proc. InfoVis)*, 2010.

[63] Jeffrey Heer, Stuart Card, and James Landay. Prefuse: A toolkit for interactive information visualization. pages 421–430, April 2005.

[64] Fabian Hemmert, Susann Hamann, Matthias Löwe, Anne Wohlauf, and Gesche Joost. Shape-changing mobiles: tapering in one-dimensional deformational displays in mobile phones. In *TEI 2010*, 2010.

[65] Alan R. Hevner, March Salvatore T., Park Jinsoo, and Ram Sudha. Design Science in Information Systems Research. *MIS Quarterly*, 28(1):75–105, 2004.

[66] Trevor Hogan and Eva Hornecker. Towards a Design Space for Multisensory Data Representation. *Interacting with Computers*, 29(2):147–167, March 2017.

[67] Trevor Hogan, Eva Hornecker, Simon Stusak, Yvonne Jansen, Jason Alexander, Andrew Vande Moere, Uta Hinrichs, and Kieran Nolan. Tangible Data, explorations in data physicalization. In *TEI 2016: Proceedings of the TEI 2016: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 753–756, February 2016.

[68] Eva Hornecker. The Role of Physicality in Tangible and Embodied Interactions. *Interactions*, 18(2):19–23, March 2011.

[69] IBM. Graphics and Visualization. `https://researcher.watson.ibm.com/researcher/view_group.php?id=143`. Accessed on 03/08/2021.

[70] Hiroshi Ishii and Brygg Ullmer. Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms. pages 234–241, March 1997.

[71] Ken Iwasaki, Takashi Miyaki, and Jun Rekimoto. AffectPhone: A Handset Device to Present User's Emotional State with Warmth/-Coolness. *B-Interface Workshop at BIOSTEC2010(International Joint Conference on Biomedial Engineering Systems and Technologies)*, 2010.

[72] Yvonne Jansen. *Physical and tangible information visualization*. PhD thesis, Universite Paris Sud-Paris XI, 2014.

[73] Yvonne Jansen and Pierre Dragicevic. List of physical visualizations. `http://dataphys.org/list/`, 2012. Accessed on 19/06/2021.

[74] Yvonne Jansen and Pierre Dragicevic. The Very First Sculptures. `http://dataphys.org/list/the-very-first-sculptures/`, 2012. Accessed on 19/06/2021.

[75] Yvonne Jansen and Pierre Dragicevic. An Interaction Model for Visualizations Beyond The Desktop. *IEEE Transactions on Visualization and Computer Graphics*, 19(12):2396–2405, December 2013.

[76] Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. Evaluating the Efficiency of Physical Visualizations. pages 2593–2602, April 2013.

[77] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. Opportunities and Challenges for Data Physicalization. *CHI 2015: Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pages 3227–3236, April 2015.

[78] Yvonne Jansen and Kasper Hornbæk. A Psychophysical Investigation of Size as a Physical Variable. *IEEE Transactions on Visualization and Computer Graphics*, 22(1):479–488, 2016.

[79] Ou Jifei. Material transformation designing shape changing interfaces enabled by programmable material anisotropy. Master's thesis, Massachusetts Institute of Technology. Department of Architecture. Program in Media Arts and Sciences.; Program in Media Arts and Sciences (Massachusetts Institute of Technology), June 2014.

[80] Roberts Jonathan C. and Rick Walker. Using All Our Senses : the need for a Unified Theoretical Approach to Multi-sensory Information Visualization. 2010.

[81] Lynette Jones. Thermal touch. `http://www.scholarpedia.org/article/Thermal_touch`, 2009. Accessed on 20/12/2019.

[82] Philip J. Kellman and Christine M. Massey. Chapter Four: Perceptual Learning, Cognition, and Expertise. volume 58 of *Psychology of Learning and Motivation*, pages 117–165. Academic Press, 2013.

[83] George N. Kenyon and Kabir C. Sen. The Perception Process. In *The Perception of Quality*. Springer, London, UK, 2015.

[84] Andy Kirk. *Data Visualisation, a handbook for data driven design.* SAGE, London, UK, 2 edition, 2019.

[85] Gregory Kramer, Bruce Walker, Terri Bonebright, Perry Cook, John Flowers, Nadine Miner, John Neuhoff, Robin Bargar, Stephen Barrass, Jonathan Berger, Grigori Evreinov, W. Fitch, M. Grohn, S. Handel, Hans Kaper, H. Levkowitz, S. Lodha, Barbara Shinn-Cunningham, Mary Simoni, and Sever Tipei. The sonification report: Status of the field and research agenda. Report prepared for the National Science Foundation by members of the International Community for Auditory Display. January 1999.

[86] Gregory Kramer, Bruce Walker, Terri Bonebright, Perry Cook, and John H. Flowers. Sonification Report: Status of the Field and Research Agenda. March 2010.

[87] Ronald D. Kriz. Thermodynamic Case Study: Gibbs' Thermodynamic Graphical Method. `http://esm.rkriz.net/classes/ESM4714/methods/Gibbs.html`, 2012. Accessed on 08/02/2021.

[88] Prem Kumar and Nanduri R. Prabhakar. Peripheral chemoreceptors: function and plasticity of the carotid body. *Comprehensive Physiology*, 2(1):141–219, 2012.

[89] USD Internet Sensation & Perception Laboratory. Weber's Law of Just Noticeable Differences. `http://apps.usd.edu/coglab/WebersLaw.html`. Accessed on (05/01/2022).

[90] George Lakoff and Mark Johnson. *Metaphors we live by.* University of Chicago Press, 1980.

[91] Vasudevan Lakshminarayanan, Aparna Raghuram, and Ritu Khanna. Psychophysical estimation of speed discrimination. I. Methodology. *Journal of the Optical Society of America. A, Optics, image science, and vision*, 22:2262–2268, November 2005.

[92] Mathieu Le Goc, Charles Perin, Sean Follmer, Fekete Jean-Daniel, and Pierre Dragicevic. Dynamic Composite Data Physicalization Using Wheeled Micro-Robots. *IEEE Transactions on Visualization and Computer Graphics, Institute of Electrical and Electronics Engineers*, 25(1):737–747, October 2019.

[93] Thomas Levine and Elona Shatri. Transparency Sandwiches. `http://data-cuisine.net/data-dishes/transparency-sandwiches`, March 2017. Accessed on 17/07/2021.

[94] Shixia Liu, Weiwei Cui, Yingcai We, and Mengchen Liu. survey on information visualization: recent advances and challenges. *Vis Comput*, 30:1373–1393, December 2014.

[95] J. M. Loomis and S. J. Lederman. Tactual perception. In *In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), Handbook of perception and human performance*, volume 2, pages 1–41. John Wiley & Sons, 1986.

[96] Jiao Yang Lu, Xin Xing Zhang, Qiu Yan Zhu, Fu Rui Zhang, Wei Tao Huang, Xue Zhi Ding, Li Qiu Xia, Hong Qun Luo, and Nian Bing Li. Highly Tunable and Scalable Fabrication of 3D Flexible Graphene Micropatterns for Directing Cell Alignment. *ACS Applied Materials & Interfaces*, 10(21), May 2018.

[97] S. MacNeil and N. Elmqvist. Visualization Mosaics for Multivariate Visual Exploration. *Comput. Graph. Forum*, 32(6):38–50, September 2013.

[98] Marketa Hulpachova Majid Albunni, Christine Liehr. Halal Internet. `http://data-cuisine.net/data-dishes/halal-internet`, January 2015. Accessed on 17/07/2021.

[99] Eric Martz and Eric Francoeur. History of Visualization of Biological Macromolecules. `http://www.umass.edu/microbio/rasmol/history.htm`, August 1997. Accessed on 08/02/2021.

[100] Michael Mateas, John Stasko, and Zachary Pousman. Casual Information Visualization: Depictions of Data in Everyday Life. *IEEE Transactions on Visualization and Computer Graphics*, 13(6), November 2007.

[101] Dan Maynes-aminzade. Edible Bits: Seamless Interfaces between People, Data and Food. In *Proceedings of the 2005 ACM Conference on Human Factors in Computing Systems (CHI 2005*, 2005.

[102] Denise Schmandt-Besserat. *How Writing Came About*. Austin : University of Texas Press, 1997.

[103] Michael Andy McEvoy and Nikolaus Correll. Shape-Changing Materials Using Variable Stiffness and Distributed Control. *Soft Robotics*, 5(6):737–747, December 2018.

[104] Tamara Munzner. *Visualization Analysis and Design*. Boca Raton: CRC Press, Taylor and Francis Group, CRC, 2015.

[105] Mutsuhiro Nakashige, Minoru Kobayashi, Yuriko Suzuki, Hidekazu Tamaki, and Suguru Higashino. “Hiya-Atsu” media: augmenting digital media with temperature. pages 3181–3186, April 2009.

[106] Kiyomitsu Nara, Luis R Saraiva, Xiaolan Ye, and Linda B Buck. A large-scale analysis of odor coding in the olfactory epithelium. *Neurosci*, 31(25):9179–9191, June 2011.

[107] Michael Nees and Bruce Walker. *Principles of Sonification: An Introduction to Auditory Display.* Logos Publishing House, January 2012.

[108] Ryuma Niiyama, Lining Yao, and Hiroshi Ishii. Weight and Volume Changing Device with Liquid Metal Transfer. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction*, pages 49–52, New York, USA, 2014. Association for Computing Machinery.

[109] J. Norman, J. Todd, V. Perotti, and J. Tittle. The visual perception of three-dimensional length. *Journal of experimental psychology. Human perception and performance*, 22(1):173–86, 1996.

[110] Oxford. Oxford Learner’s Dictionaries. `https://www.oxfordlearnersdictionaries.com/definition/english/embody?q=embody`. Accessed on 09/10/2021.

[111] Sabrina Paneels and Jonathan C. Roberts. Review of Designs for Haptic Data Visualization. *IEEE TRANSACTIONS ON HAPTICS*, 3(2):120–137, April 2010.

[112] Deokgun Park, Steven M. Drucker, Roland Fernandez, and Niklas Elmqvist. Atom: A Grammar for Unit Visualizations. *IEEE Transactions on Visualization and Computer Graphics*, 24(12):3032–3043, 2018.

[113] Biswaksen Patnaik, Andrea Batch, Niklas Elmqvist, and Andreas Keller. Information Olfactation: Harnessing Scent to Convey Data. *IEEE InfoVis*, March 2018.

[114] Ken Peffers and Tuure Tuunanen. A Design Science Research Methodology for Information Systems Research. *Management Information Systems*, 24(3):45–77, December 2007.

[115] Merle C. Potter and Craig W. Somerton. *Schaum’s Outline of Thermodynamics for Engineers.* McGraw-Hill Education, 3 edition, 2014.

[116] Ivan Poupyrev, Tatsushi Nashida, Shigeaki Maruyama, Jun Rekimoto, and Yasufumi Yamaji. Lumen: Interactive Visual and Shape Display for Calm Computing. In *ACM SIGGRAPH 2004 Emerging Technologies*, SIGGRAPH 2004, New York, USA, 2004. Association for Computing Machinery.

[117] Ivan Poupyrev, Tatsushi Nashida, and Makoto Okabe. Actuation and Tangible User Interfaces: The Vaucanson Duck, Robots, and Shape Displays. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction*, TEI 2007, pages 205–212, New York, USA, 2007. Association for Computing Machinery.

[118] Zachary Pousman and John Stasko. A Taxonomy of Ambient Information Systems: Four Patterns of Design. In *Proceedings of the Working Conference on Advanced Visual Interfaces*, pages 67–74, New York, USA, 2006. Association for Computing Machinery.

[119] Devin Powell. Hottest Temperature In The Universe Measured. `https://www.insidescience.org/news/hottest-temperature-universe-measured`, February 2010. Accessed on 15/10/2021.

[120] J. Pries-Heje, R. Baskerville, and J. Venable. Strategies for Design Science Research Evaluation. In *Proceedings of 16th European Conference on Information Systems (ECIS 2008)*, Galway, Ireland, 2008.

[121] Sarah Pruitt. The WWI Origins of the Poppy as a Remembrance Symbol. `https://www.history.com/news/world-war-i-poppy-remembrance-symbol-veterans-day`, May 2020. Accessed on 04/08/2021.

[122] Majken K. Rasmussen, Esben W. Pedersen, Marianne G. Petersen, and Kasper Hornbæk. Shape-Changing Interfaces: A Review of the Design Space and Open Research Questions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI 2012, pages 735–744, New York, NY, USA, 2012. Association for Computing Machinery.

[123] Casey Reas and Ben Fry. *Processing: A Programming Handbook for Visual Designers and Artists.* The MIT Press, 2014.

[124] Jonathan Roberts, Panagiotis Ritsos, Sriram Badam, Dominique Brodbeck, Jessie Kennedy, and Niklas Elmqvist. Visualization beyond the

Desktop–the Next Big Thing. *IEEE Computer Graphics and Applications*, November 2014.

[125] R. Romo, A. Hernández, and M. Alvarez. Role of Primary Somatosensory Cortex in Perceptual Touch Detection and Discrimination. In Richard H. Masland, Thomas D. Albright, and Gardner Esther P., editors, *The Senses: A Comprehensive Reference*, pages 215–232. Elsevier, 2008.

[126] H E Ross and E E Brodie. Weber fractions for weight and mass as a function of stimulus intensity. *Q. J. Exp. Psychol. A*, 39(1):77–88, February 1987.

[127] Anne Roudaut, Abhijit Karnik, Markus Löchtefeld, and Sriram Subramanian. Morphees: Toward High “Shape Resolution” in Self-Actuated Flexible Mobile Devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI 2013, pages 593–602, New York, NY, USA, 2013. Association for Computing Machinery.

[128] Christopher S. Henshilwood, Francesco d’Errico, Zenobia Jacobs, and Chantal Tribolo. Emergence of Modern Human Behavior: Middle Stone Age Engravings from South Africa. *Sciences*, 295(5558):1278–1280, March 2002.

[129] Arvind Satyanarayan, Dominik Moritz, Kanit Wongsuphasawat, and Jeffrey Heer. Vega-Lite: A Grammar of Interactive Graphics. *IEEE Transactions on Visualization and Computer Graphics*, 23(1):341–350, 2017.

[130] Arvind Satyanarayan, Ryan Russell, Jane Hoffswell, and Jeffrey Heer. Reactive Vega: A Streaming Dataflow Architecture for Declarative Interactive Visualization. *IEEE transactions on visualization and computer graphics*, 22, September 2015.

[131] Arvind Satyanarayan, Kanit Wongsuphasawat, and Jeffrey Heer. Declarative Interaction Design for Data Visualization. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology*, UIST 2014, pages 669–678, New York, NY, USA, 2014. Association for Computing Machinery.

[132] Nik Sawe, Chris Chafe, and Jeffrey Treviño. Using Data Sonification to Overcome Science Literacy, Numeracy, and Visualization Barriers in Science Communication. *Frontiers in Communication*, 5, July 2020.

[133] J.F. Schouten. Subjective stroboscopy and a model of visual movement detectors. In *Models for the Perception of Speech and Visual Form*, pages 44–55. MIT Press, November 1967.

[134] Patricia Search. Interactive Multisensory Data Representation. volume 9187, pages 363–373. Springer, 2015.

[135] M. Ibrahim Sezan, Kwok-leung Yip, and Scott J. Daly. Uniform Perceptual Quantization: Applications to Digital Radiography. *IEEE Transactions on Systems, Man, and Cybernetics*, 17(4):622–634, 1987.

[136] Orit Shaer and Eva Hornecker. Tangible User Interfaces: Past, Present, and Future Directions. *Foundations and Trends in Human-Computer Interaction*, 3:1–137, January 2009.

[137] Orit Shaer and Eva Hornecker. *Tangible User Interfaces: Past, Present and Future Directions*. Now Foundations and Trends, 2010.

[138] Wuwei Shen and Liu2 Shaoying. Formalization, Testing and Execution of a Use Case Diagram. *Formal Methods and Software Engineering. ICFEM 2003*, 2885, 2007.

[139] Ben Shneiderman and Martin Wattenberg. Ordered Treemap Layouts. In *Proceedings of the IEEE Symposium on Information Visualization 2001 (INFOVIS 2001)*, INFOVIS 2001, USA, 2001. IEEE Computer Society.

[140] Beat Signer, Payam Ebrahimi, T.J. Curtin, and A.K.A Abdullah. Towards a Framework for Dynamic Data Physicalisation. October 2018.

[141] Stusak Simon, Tabard Aurélien, Sauka F, Khot RA, and Butz Andreas. Activity Sculptures: Exploring the Impact of Physical Visualizations on Running Activity. *IEEE Trans Vis Comput Graph*, 20(12):2201–2210, December 2014.

[142] Jack Slater. Is Remembrance Day for WW1 or WW2 and why are poppies used to commemorate war? `https://metro.co.uk/2019/11/10/remembrance-day-ww1-ww2-poppies-used-commemorate-war-11073634/`, November 2019. Accessed on 04/08/2021.

[143] J. Sonnenberg, C.and vom Brocke. Evaluation Patterns for Design Science Research Artefacts. In *Helfert M., Donnellan B. (eds) Practical Aspects of Design Science*, volume 286, pages 71–83. Springer-Verlag, Berlin Heidelberg, 2011.

[144] Moritz Stefaner and Susanne Jaschko. Data Cuisine. `http://data-cuisine.net/`, 2021. Accessed on 17/07/2021.

[145] Oliver Stefani and Christian Cajochen. Should We Re-think Regulations and Standards for Lighting at Workplaces? A Practice Review on Existing Lighting Recommendations. *Frontiers in psychiatry*, 12, May 2021.

[146] Chris Stolte, Diane Tang, and Pat Hanrahan. Polaris: A System for Query, Analysis, and Visualization of Multidimensional Relational Databases. *IEEE Transactions on Visualization and Computer Graphics*, 8(1):52–65, 2002.

[147] Domestic Data Streamers. First Date Noodles. `http://data-cuisine.net/data-dishes/first-date-noodles`, June 2014. Accessed on 17/07/2021.

[148] Simon Stusak. Exploring the Potential of Physical Visualizations Share on. pages 437–440, January 2015.

[149] Simon Stusak and Ayfer Aslan. Beyond Physical Bar Charts An Exploration of Designing Physical Visualizations. April 2014.

[150] Simon Stusak, Andreas Butz, and Tabard Aurelien. Variables for Data Physicalization Units. 2018.

[151] Simon Stusak, Andreas Butz, and Aurélien Tabard. Can Physical Visualizations Support Analytical Tasks? December 2013.

[152] Saiganesh Swaminathan, Conglei Shi, Yvonne Jansen, Pierre Dragicevic, Lora Oehlberg, and Jean-Daniel Fekete. Creating Physical Visualizations with Makervis. *CHI 2014 Extended Abstracts on Human Factors in Computing Systems*, pages 543–546, April 2014.

[153] Saiganesh Swaminathan, Conglei Shi, Yvonne Jansen, Pierre Dragicevic, Lora A. Oehlberg, and Jean-Daniel Fekete. Supporting the design and fabrication of physical visualizations. pages 3845–3854, April 2014.

[154] Engen T. Psychophysics. In *States of Brain and Mind. Readings from the Encyclopedia of Neuroscience*. Birkhäuser, Boston, USA, 1988.

[155] Faisal Taher, Yvonne Jansen, Jonathan Woodruff, John Hardy, Kasper Hornbæk, and Jason Alexander. Investigating the Use of a Dynamic Physical Bar Chart for Data Exploration and Presentation. *IEEE*

Transactions on Visualization and Computer Graphics, 23(1):451–460, 2017.

[156] Taher, Faisal and Hardy, John and Karnik, Abhijit and Weichel, Christian and Jansen, Yvonne and Hornbæk, Kasper and Alexander, Jason. Exploring Interactions with Physically Dynamic Bar Charts. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI 2015, pages 3237–3246, New York, USA, 2015. Association for Computing Machinery.

[157] Robert Teghtsoonian. On the exponents in Stevens' law and the constant in Ekman's law. *Psychological Review*, 78(1):71–80, 1971.

[158] Jordan Tewell, Jon Bird, and George Buchanan. Heat-Nav: Using Temperature Changes as Navigation Cues. pages 1131–1135, May 2017.

[159] Henry S. Tropp. Mathematics of the Incas: code of the quipu. *The Mathematical Gazette*, 82(494):329–330, 1998.

[160] John Turner, Phil Anderson, Tom Lachlan-Cope, Steve Colwell, Tony Phillips, Amélie Kirchgaessner, Gareth J. Marshall, John C. King, Tom Bracegirdle, David G. Vaughan, Victor Lagun, and Andrew Orr. Record low surface air temperature at Vostok station, Antarctica. *Journal of Geophysical Research: Atmospheres*, 114(D24), 2009.

[161] John C. Tuthill and Eiman Azim. Proprioception. *Current Biology*, 28(5):R194–R203, 2018.

[162] Brygg Ullmer and Hiroshi Ishii. Emerging frameworks for tangible user interfaces. *IBM Systems Journal*, 39:915–931, February 2000.

[163] IOWA State University. Materials and Processes. `https://www.nde-ed.org/Physics/Materials/index.xhtml`. Accessed on 24/07/2021.

[164] MADHAV University. Types of Properties of Engineering Materials. `https://madhavuniversity.edu.in/types-of-properties-of-engg-materials.html`. Accessed on 24/07/2021.

[165] A. Vande Moere and Stephanie Patel. The Physical Visualization of Information: Designing Data Sculptures in an Educational Context. In *Huang M., Nguyen Q., Zhang K. (eds) Visual Information Communication*, Boston, MA, 2009. Springer.

[166] Andrew Vande Moere. Beyond the Tyranny of the Pixel: Exploring the Physicality of Information Visualization. *International Conference on Information Visualisation (IV)*, July 2008.

[167] vanderbilt. Primary Sources: Art, Artifacts, and Photographs. `https://researchguides.library.vanderbilt.edu/c.php?g=68881&p=446169`, February 2021. Accessed on 05/08/2021.

[168] Forrest W. and Nutter Jr. Weber-Fechner Law. In Neil J. Salkind, editor, *Encyclopedia of Research Design*. SAGE Publications, Inc., 2010.

[169] Song Wang and Ning Xi. Sensing and Data Analysis for Assessing Human Balance Ability. In *2018 IEEE 8th Annual International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (CYBER)*, pages 807–812, 2018.

[170] Yun Wang, Xiaojuan Ma, Qiong Luo, and Huamin Qu. Data Edibilization: Representing Data with Food. pages 409–422, May 2016.

[171] colin Ware. *Information Visualization: Perception for Design*. Elsevier, 3 edition, 2013.

[172] Pierre Wellner, Wendy Mackay, and Rich Gold. Back to the Real World. *Communications of the ACM*, July 1993.

[173] Martin S. Westwell, Mark S. Searle, David J. Wales, and Dudley H. Williams. Empirical Correlations between Thermodynamic Properties and Intermolecular Forces. *Journal of the American Chemical Society*, 117(18):5013–5015, 1995.

[174] Eric White. Teaching the SLAVE SHIP. `https://blogs.princeton.edu/notabilia/2020/05/28/teaching-the-slave-ship/`, 2020. Accessed on 05/06/2021.

[175] Mitchell Whitelaw. Measuring Cup. `https://mtchl.net/measuring-cup/`, August 1997. Accessed on 19/02/2021.

[176] H. Wickham and H. Hofmann. Product Plots. *IEEE Transactions on Visualization and Computer Graphics*, 17:2223–2230, 2011.

[177] Hadley Wickham. A Layered Grammar of Graphics. *Journal of Computational and Graphical Statistics*, 19(1):3–28, 2010.

[178] Hadley Wickham. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag, New York, USA, 2 edition, 2016.

[179] Leland Wilkinson. *The Grammar of Graphics (Statistics and Computing).* Springer-Verlag, Berlin, Heidelberg, July 2005.

[180] Chris Wilson. *RaphaelJS.* O'Reilly Media, Inc., December 2013.

[181] Zhen Xie, Alissa Antle, and Nima Motamedi. Are tangibles more fun?: Comparing children's enjoyment and engagement using physical, graphical and tangible user interfaces. pages 191–198, February 2008.

[182] James Yarker. Of All The People In All The World. `http://www.stanscafe.co.uk/project-of-all-the-people.html`, June 2006. Accessed on 10/10/2021.

[183] Jack Zhao and Andrew Vande Moere. Embodiment in Data Sculpture: A Model of the Physical Visualization of Information. *DIMEA 2008: Third International Conference on Digital Interactive Media in Entertainment and Arts*, pages 343–350, September 2008.

[184] Dongxiao Zhou. Texture analysis and synthesis using a generic Markov-Gibbs image model. January 2006.