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SPHERE BURST: A NOVEL APPROACH FOR DATA PHYSICALISATION ON A SPHERE

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Abstract

We live in an era where the amount of data to be processed grows rapidly and has grown exponentially over the last few years [9]. This data is being generated by multiple sources such as online platforms, research labs, observation of the world around us and so on. This data however belongs to different categories depending on their origin. For example, we have datasets on geographical locations, datasets on medical records, weather conditions and so on. Most times, these datasets have similar features and properties and there are visualisations idioms that best display the information represented by each of these datasets [21]. In the context of information visualisation, it is good to use a visualisation idiom which is best suited to represent a certain type of data as this makes data analysis and comprehension easier. As a result of this, research in the information visualisation community has made some observations over time to make suggestions on the types of visualisation idiom to use for specific datasets [21].

Furthermore, the need to make visualisations more accessible to a wider audience and also increase the performance of the already existing visualisations idioms gave rise to research areas such as data physicalisation [25]. Though physicalising data has existed for centuries, it only becomes a formal area of research in the past couple of years. The existing visualisation idioms make use of the visual senses to analyse data but data physicalisation comes as a multi-modal way for analysing datasets. It was found that the multi-modal exploration of data was more performant as the users can use more than just their visual senses to explore data [25]. It should however be noted that the cost of physicalising data is often expensive and constitutes a major reason why extensive research has not yet been made on this topic [28].

With regard to data physicalisation, it is important to have physicalisations that could be used to represent multiple datasets, considering that it will be really expensive to build a single physicalisation for every dataset we want to physicalise. Therefore, while trying to physicalise data, care should be taken to make the physicalisation dynamic and which can be easily modified to be used to represent another dataset.

In this regard, we present in this thesis *SphereBurst* which is an early proto-

type that can be used to physicalise data on a sphere. People can make use of their multi-modal senses to explore and make data analysis of the dataset under observation using our prototype. *SphereBurst* focuses on the fusion of tangible interactions and augmented reality to enable the multi-modal understanding of datasets on a sphere. The data physicalisation is facilitated by the use of some electronic hardware which will provide tangible feedback to users. The Augmented reality enabled by the use of an Android application adds a dynamic overlay that supplements the tangible representation with visual information.

In a nutshell, *SphereBurst* is an early prototype that is used to explore how to physicalise data on a sphere. This novel approach was evaluated by conducting a user study where participants engaged with our prototype. Feedback was collected on the way they interacted with our prototype and they were asked to perform some basic data analysis tasks to help us evaluate the performance of our prototype.

We noticed more excitement and engagement from the audience who tested our prototype. One participant said the setup was captivating and made them more focused while performing the data analysis task. We also noticed that all the participants who took part in our user study rotated the sphere to navigate through it and none walked around the sphere. Based on this, we can say that the most preferred way of exploring a sphere is by rotating it in all directions and this should be taken into account while designing future spherical visualisations.

Acknowledgement

I wish to take this opportunity to thank Professor. Beat Signer whose support was incredible in the context of this master thesis. I want to thank him for his dedicated time and patience in giving me feedback and providing insights to complete this master's thesis.

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Contents

Chapter 1

Introduction

What is data physicalisation all about? Are there any significant advantages in physicalising existing digital visualisations such as spherical ones? While data physicalisation as a whole has been slowly getting attention in the research community and especially in the context of data visualisation, visualising data on a sphere is a more specific area of research within the general research area of information visualisation.

Very little known research has been made in the context of physicalising data on a sphere which is our area of concern in this thesis. Some artwork involving the use of spheres exists whereby artists use spheres to represent data. An example is the sphere within-sphere[1] bronze sculpture present in multiple locations around the globe such as the Italian parliament, Dublin and in Tel Aviv which represents the project or the vision of creating a new world from the old world.

While data physicalisation has only recently gotten more attention in the information visualisation research community, the concept of representing data physically has been around for a very long time and dates back thousands of years. From clay stones used in Mesopotamia to the Ishango Bone used in the Congo Basin [43], humans have for a very long time (around 20,000 BC) made use of physical artefacts to convey information or as a means of communication [54]. However, some researchers in the information visualisation community have been wondering if going through the complex experience of trying to physicalise data is really worth it [22] and many observations have been made in this regard and it was found that data physicalisation provides a multi-modal way of interacting and analysing data which increases the performance of idioms which make not only use of their visual senses. This comes with a cost and therefore, such physicalisations have to be dynamic and not static to accommodate not just a single dataset [28].

A more formal and often used definition of data physicalisation proposed by

[1] https://www.un.org/ungifts/sphere-within-sphere

Jansen et al. [28] is: *"Data Physicalisation is a physical artefact whose geometry or material properties encode data"*. Another used definition of data physicalisation is that it is an area of research that investigates the benefits or advantages of using computer-supported physicalisations in areas such as education, accessibility and problem-solving in general [28].

One of the motivations behind data physicalisation which is related to other research areas such as tangible interfaces and human-computer Interaction, with the most prominent one being data visualisation is to determine how users comprehend, manipulate, perceive and interact with data beyond the 2D screens which have been widely used to display data for human comprehension to date.

Since we are interested in applying the concept of data physicalisation to spherical visualisations, this thesis is an attempt to provide a high-level data physicalisation prototype that can be used in the context of spherical visualisation. We later proceed to investigate how we can make our proposed implementation dynamic for future use. By dynamic, we aim to have a solution whereby changes in our underlying data are directly reflected and perceived in our physicalisation, unlike static data physicalisations where the shape of the physicalisation cannot be changed. That is the size or shape cannot be changed to represent a different dataset or a change in data. More about static and dynamic data physicalisation will be discussed later in this thesis.

Spherical visualisations or sphere-based visualisations which are at the centre of our research in this thesis are simply the visualisation of data on a sphere. Visualising data on a sphere is mostly suitable but not limited to geographical data. Visualising data on a sphere comes with some advantages such as distortion reduction when analysing relative positions on a globe and some disadvantages such as the fact that data such as images will be distorted at the edges of the sphere due to its curvature, unlike a flat surface which can has no curves and such data images will not be distorted [5]. Furthermore, we will investigate the outcome of the physicalisation of these spherical visualisations and observe if it enhances user experiences or provides some insights into new research areas.

In our quest to have a dynamic prototype and referring to the dynamic data physicalisation we mentioned above, we propose a physical sphere that is built of individual modules whereby each module contains some physical variables that will be used to represent the data values we want to physicalise.

Augmented reality has been used considerably in several data physicalisations as a means to achieve dynamic data physicalisations. Devices such as the Hololens[2] have been released recently to get the immersive effect performed using augmented reality. Augmented reality applications can also be deployed on devices such as Android and IOS devices. With augmented reality, graphics can be superim-

[2] https://nl.wikipedia.org/wiki/Microsoft_HoloLens

posed/overlaid to physical objects leading to an idiom that combines tangible objects and virtual information.

We conducted a user study to evaluate our prototype and highlight its drawbacks and limitations for future studies. The research done in this thesis is an attempt to explore the opportunities and challenges involved in physicalising spherical visualisations and the data displayed on them and possibly create new research questions for the data visualisation research community.

1.1 Problem Statement

Visualising information on spheres allows better analysis and understanding of data belonging to a specific category. Geographical data have been widely used in the context of spherical visualisation. However, spheres have also been used to represent other types of data such as datasets that have elements which are interconnected such as networks where it is important to see the different connections between the nodes in a network [20]. Representing data on a sphere can also be used to achieve a fish-eye view when trying to explore data in scenarios where we want to focus on data in a dataset while having awareness of the entire dataset. An example of a dataset that can be used in this context is a dataset about the organisation of files in a file directory [10].

Benefiting from the work and research of cartographers, it is important to represent information in shapes that are a reflection of our actual world. This improves affordance and eases the understanding of the subject being investigated. In this regard, spheres constitute an appropriate medium through which global data is represented [67]. Displaying information on spheres gives characteristics that are unique and are known to enhance user engagement.

One of these unique characteristics offered by spherical visualisation is: a 360-degree unobstructed visual field achieved by either moving around the sphere or just rotating the sphere around its axis [2]. This not only provides a different user experience which was found to be more engaging but also makes the user apprehend the data being displayed on the sphere from different viewing angles.

In the context of visualising data on spheres, the geometry of a sphere makes a user better understand the relative position of objects found or displayed on a sphere unlike on a flat surface. If we take the example of the world map, having a world map drawn on a flat surface like a computer screen makes it more difficult for a user to rapidly apprehend the inherent distance between countries located on the map, unlike on a sphere. Displaying information on spheres also facilitates multi-user interaction [2].

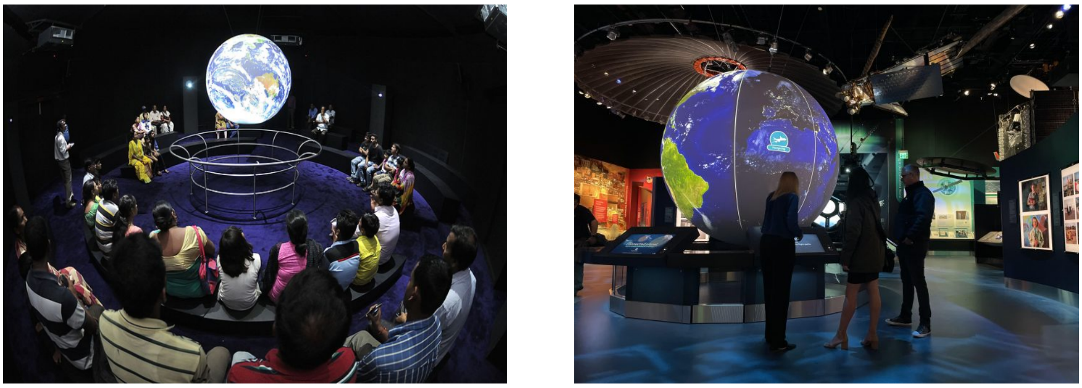
The most readily available spherical visualisation we could find is the representation of the world map which can be seen below:

Figure 1.1: Display of a globe. Credit: Shavul

As shown in Figure 1.1, this type of representation of the globe makes it easier for a user to make observations and ease understanding of the data being displayed. Such observations could be the relative distance between different locations on the globe. This representation has been widely used in schools for learning purposes [6].

Another fascinating example of spherical visualisation is the work by Alexander McDonald who brought the concept of Science on a Sphere[3] which is basically a system where data on our planet is projected on spheres of a diameter of six feet to make the comprehension of the science of the earth easy to people of all ages. An illustration of a Science on a Sphere project is shown in Figure 1.2a.

[3]https://sos.noaa.gov



(a) (b)

Figure 1.2: Examples of existing spherical visualisations: (a) Science Museum in Kolkata by Digital Studio India; (b) Science Museum in London by Evikka.

As shown in Figures 1.1, 1.2a and 1.2b, some of the existing visualisations on spheres are visualisations which have static data (e.g. Figure 1.1) or dynamic (e.g. Figure 1.2b). However, the data being displayed on the surface of these spheres is in digital form and provides no means of tangible exploration of the data being displayed. As a result of this observation, the work presented in this thesis addresses this problem and the research questions investigated are as follows:

- How do we physicalise data being displayed on a tangible sphere and are there any significant advantages of doing this?
- What physical variables can we use to physicalise the data on a sphere?
- Does physicalising data displayed on a sphere make it more engaging and does it have a noticeable effect on performance as compared to its digital form?

1.2 Contribution

The work concluded in this thesis is an attempt to contribute to the research on data physicalisation and more precisely, the physicalisation of spherical visualisations. In this regard, the contributions (some at the conceptual level) being made in this thesis are:

- Identify the unique characteristics of data visualisation on spheres.
- An attempt to provide a design space on how to display physicalised data on a tangible sphere.
- Establish guidelines on how to physicalise data on a sphere.
- Propose a prototype accessible to a wide audience including people with disabilities.
- A user study to evaluate our proposed solution and evaluate the user experience.

1.3 Research Methodology

In order to investigate the topic at hand in this thesis, we opted for the Design Science Research Methodology by Peffers et al. [41]. This methodology serves as a guideline for conducting our research in a way that is scientifically appealing to the audience. This methodology makes it easier for reviewers to evaluate the work done in this thesis.

The methodology is summarised in six points which are: *identification of the problem and motivation, objectives of the proposed solution, design and development, demonstration, evaluation and communication.*

Following these guidelines and applying them in the context of our research on data physicalisation of spherical visualisations, we start by identifying the existing problems or limitations of representing data in digital format on spheres. We also highlight the limitations of some existing spherical displays as we did in our introduction above, one of which was that the data presented on these tangible spheres was final and could not be altered [40]. In the case of interactive spherical displays, the users have little to no haptic feedback and also little to no means of physically interacting with the data being displayed [70].

A study related to our topic under investigation is the work by Satriadi et al. [51] where they investigated how tangible globes can be used for data visualisation in augmented reality. Gaining insight from their research, led us to our proposed solution where we provide a design space on how to design our tangible sphere made of hexagonal building blocks which we call modules. Each of these modules has a couple of physical variables that can be used to represent different features of a given dataset. The objective of this proposed solution is to evaluate the performance of dynamic data physicalisation on a sphere.

In the design and development phase, we start with a conceptual model which is a sphere made up of individual hexagonal components or units. Each of these units will represent some region on the sphere and will be enhanced by augmented reality. In this phase, We also identify the physical variables that we shall use to physicalise our data.

After the design and development, we test our prototype in the demonstration phase by taking a use case in order to identify the strengths and weaknesses of our proposed solution. Since one of the goals of data physicalisation is also to have prototypes that can be used for data analysis, we also demonstrate how our prototype which is an early model of our ideal prototype can be used to perform some basic data analysis tasks and therefore be useful to a wide audience.

During the evaluation phase, we perform a user study where we invite selected participants to interact with our prototype and keep track of how they interact with our system while collecting feedback for analysis and evaluation. This feedback is collected by using questionnaires[4] and the data collected is analysed and observations made based on this.

We observe if our proposed solution effectively solved some of the problems we highlighted in our introduction. We leave the door open for feedback on how to make our proposed solution more effective and reapplying feedback collected by the users who interacted with our proposed solution in a later iterative process.

Finally, as stated earlier, the existing spherical visualisations have data displayed on them either in digital form or static printed form and this thesis is a high-level proposal on how to physicalise this data dynamically in such a way that makes it more engaging and performant.

We intend to benefit from the unique characteristics of spherical displays coupled with augmented reality to have a system that could give us a different perspective on data visualisation. All of this is done in the last phase of this design science research method where we present all of this in this thesis for the appreciation of our readers and the jury.

1.4 Thesis Structure

An overview of the structure of this thesis is shown below:

- **Chapter 1:** Is the introduction, where we present an overview of the research questions and give motivation as to why we perform this research and more specifically data physicalisation of spherical visualisations.

- **Chapter 2:** In this chapter, we present some background history and related work on data physicalisation. We highlight the different types of physicalisations and bring out the advantages and limitations of these different types. At the time of writing this thesis, we could not find any related work on an attempt to display data on spheres in a dynamic and physical way. There however exists research on how to represent information on spheres in digital form and so we will be presenting in this chapter some related work on digital spherical visualisation and some other studies on dynamic data physicalisation with some using augmented reality technology to lay a foundation for our proposed solution which comes as an answer to some of the limitations observed in these related works. This chapter also covers some background knowledge on digital spherical visualisations and their limitations.

  A brief overview of how augmented reality has been used for good in this research field in order to validate our choice to use it in our prototype solution is also highlighted in this section. This topic will help the audience in general

[4]https://www.ueq-online.org/

and not just experts or people in the data visualisation community to have some background knowledge to have a minimal understanding of the topic discussed in this thesis.

- **Chapter 3:** This chapter deals with the proposed solution to the research problem introduced in Chapter 1. It brings out a conceptual model and design of a solution which shall be implemented in the next chapter. We present here the software and hardware requirements to implement our proposed solution.

- **Chapter 4:** Here, more details about the actual implementation of our proposed solution are given. The prototype solution is brought to life and ready to be evaluated.

- **Chapter 5:** This chapter gives more details about the evaluation of our proposed solution. Here, a user study is done with some participants interacting with our proposed solution and their feedback was collected.

- **Chapter 6:** In conclusion, observations are made based on the results obtained from our evaluation process and more insights into what could be done in future to improve our solution are documented in this chapter.

Chapter 2

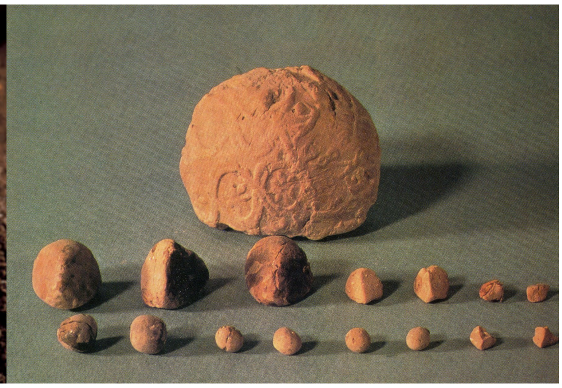
Related Work

2.1 History of The Physical Representation of Data

Representing data in physical form is a practice that has existed for a very long time. Dating back to over 20000 BC [30] even though the concept of *data physicalisation* is just a recent research area in the research community involved in information visualisation and to an extent human-computer interaction (HCI). One of the goals of data physicalisation is to provide a better understanding, exploration and communication of data using data represented in physical forms and sometimes with the help of computer systems [28]. Research in the field of data physicalisation has shown that exploring data in their physical form as opposed to their digital counterpart on 2D screens enhances the way people perceive data and also increases information memorability [28]. One of the reasons for this observation is that these physical representations assume the practical advantages of the objects we handle in our day-to-day activities such as touching and being possessed [27].

Examples of such physicalisations that have been around for a very long time are the blombos ocher shown in Figure 2.1a which is one if not the oldest known physical object used to represent data/information [11]. Research to date has not yet been able to say with certainty if the marks on this object encode some sort of data or if they are just used as ornaments [26]. Another example of ancient data physicalisation is the Mesopotamian clay stones shown in Figure 2.1b. These stones were used 8000 BC and each of these stones represented a particular amount of an entity such as goods or the entity as a whole. This gave birth to a counting system known as *concrete counting system* which is basically a system whereby things are being counted with the use of different objects. This system was used to do trade by barter. Another example of such an old artefact that could be put

(a)



(b)

Figure 2.1: Examples of ancient data physicalisations: (a) Blombos ocher. Picture credit: Caroline Seawright. (b) Mesopotamia clay stones. Picture credit: Denise Schmandt-Besserat.

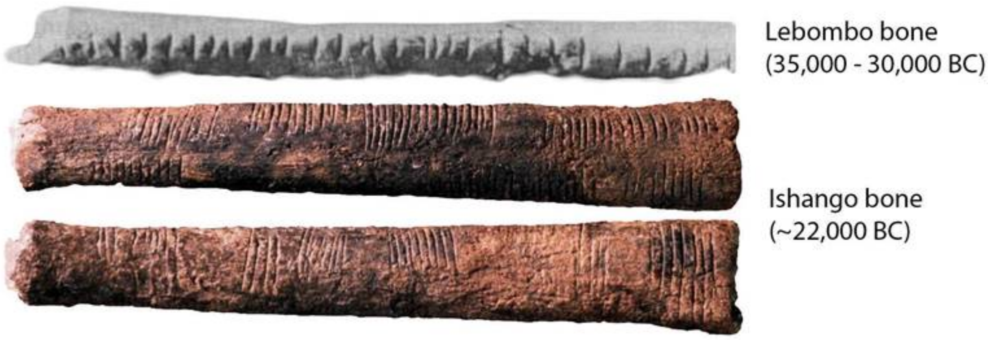


Figure 2.2: Lebombo bone at the top and Ishango bone at the bottom. Credit: J.D Loreto and Smithsonian

under the umbrella of data physicalisation is the Lebombo bone and the Ishango bone shown in Figure 2.2. Research has shown that the Lebombo bone which contains 29 marks as shown was most likely used to represent a lunar calendar. The Ishango bone on the other hand, due to its marks on its front and back after investigations from the research community was most likely used for counting purposes. These examples listed above go a long way to show that the idea of representing data physically has been around for a very long time.

2.2 More Recent Uses of Data Physicalisation

In order to highlight some recent examples of data physicalisations, it is important to note that two different types of physicalisations have been identified which are:

- **Static data physicalisation**
- **Dynamic data physicalisation**

In the context of static data physicalisation, we have some recent examples such as the "Of All The People In All The World"[1]. In this project, these artists embark on a mission to know what the actual total number of people on Earth looks like [63]. While this number is known, having an actual physical representation of this number turns out to provide the audience with more information than what they actually thought. It helped the audience actually have a visualisation of what they are compared to the entire global population and this validates some of the points we made in our introduction where we stated that having data in physical form enhances user experience by making the user have a better understanding of the data being explored.

In this project, these artists made use of grains of rice as shown in Figure 2.3. With one grain representing one person, the comparison has to be made with the remaining grains of rice which represent the remaining population.

Figure 2.3: All of the people of the world project done by artists in Stan's cafe

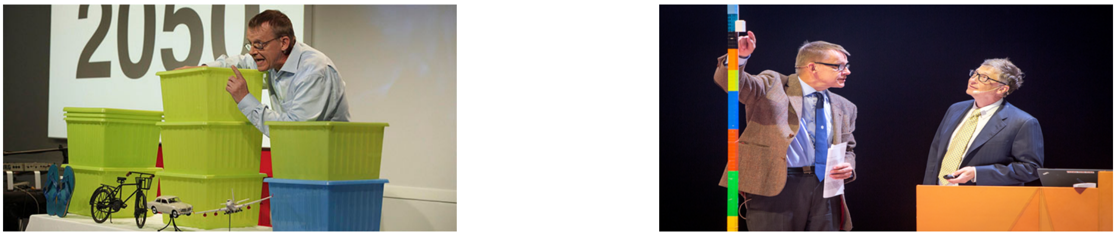
Statistics about our everyday lives such as the number of people living in a city, the number of people who identify as male or female, the number of deaths per day, and the number of engineers in a certain domain were collected and these numbers were represented as piles of rice and each person who fits in a category could see how they compare to the remaining quantity [63]. The overall experience was wonderful based on the audience feedback and some of the feedback made by one of the participants named Tom Ottoway was *"This is a superb example of art*

[1]https://stans.cafe/project/project-of-all-the-people/

for and about the average person on the street which takes the abstract and makes it powerfully representational" [63].

Another example in this category focuses on the work of notable physician Hans Rosling who is known for using data visualisation to examine issues related to development and inequalities around the world. In one of his talks on wealth inequality which he gave at the TEDx Summit in Doha in 2012, he used 7 stones to represent the world population which is known to be approximately 7 billion to make notable observations [45].

Hans Rosling also made a demonstration of population growth since 1960 using boxes from IKEA [49]. During this talk, he used these IKEA boxes shown in Figure 2.4a to demonstrate how population growth will be evolving based on a number of factors and how we can effectively regulate this. The images below show Rosling making use of data physicalisations for his presentations in recent years.



(a) (b)

Figure 2.4: Hans Rosling makes use of different physical objects to demonstrate some statistics on the global population

One of the concerns in the research community involved in data physicalisation is how to make these physicalisations dynamic so that these physicalisations can reflect any change in the underlying data. In this regard, Hogan et al. [23] emphasised the need to build dynamic physicalisations that could make use of the multiple sensory organs humans have. Dynamic data physicalisations are physicalisations that have the ability to adapt to changes made to the data they represent. This change in data could be either given using input from software or during live interaction by the user [55]. Examples of dynamic data physicalisations are the work by Gao et al. [19] who introduced DataLev which uses acoustophoresis which is the process of using sound waves to manipulate materials. In a nutshell, sound waves are used to reconfigure the material properties of objects. DataLev introduced in this research supports multi-modal interaction and different data physicalisation patterns could be obtained using these sound waves as when the sound waves are applied to the material, its particles are suspended which can then be manipulated to give geometries of different shapes and sizes in air. Fabric, liquid droplets, threads, food items and particles are the different categories of materials that can be used in this research. A use case of DataLev was the visualisation of different segments of a 3D-printed object. This object was a skull which was used to visualise the different sections of a human head. More details can be seen in the image below:

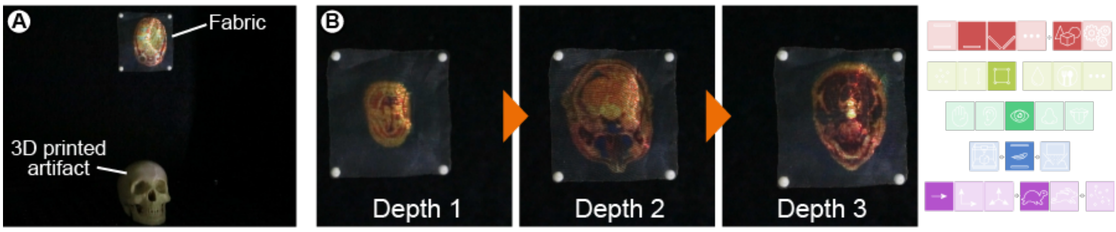


Figure 2.5: Dynamic physicalisation is achieved by obtaining different cross-sections of the human head. (a) Initial state (b) Different images are obtained when the fabric has different depths representing different cross-sectional images. The skull is used to know which part of the head is displayed on the fabric.

Another example of dynamic data physicalisation is the EMERGE project which was introduced by Taher et al. [60] in which dynamic data physicalisation is obtained by the use of dynamic physical bar charts. Bar charts are mostly used on 2D screens to represent data but this project physicalised these bars and made them dynamic as their length varies based on the value of the data it represents. Figure 2.6 shows the layout of the bar charts used in this project.

In order to explore the data, users have to touch each bar and the projection displays additional information on the data point being investigated.

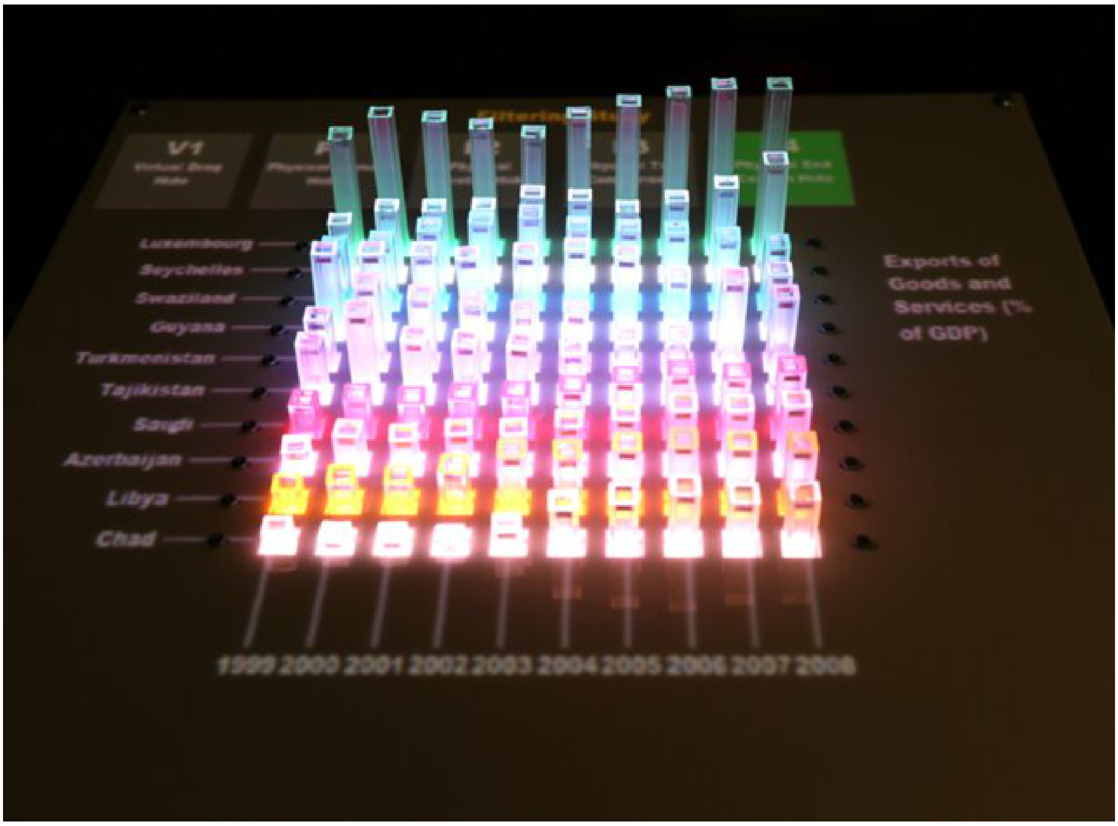


Figure 2.6: Dynamic physical bar charts.

Another way to achieve dynamic data physicalisations is to use wheeled micro-robots as in the research conducted by Le Goc et al. [33]. These micro-robots are called zooids and are used for decision-making. One use case of these zooids was in the scenario where an admission committee had to decide on the students to be admitted to a given program based on their grades. The dataset is fed into these zooids and each zooid moves to a specific position based on the data value they represent [33]. So, these zooids could be used to represent different datasets and are not only specific to one dataset.

As we mentioned earlier, the goal of dynamic data physicalisations is to have physicalisations that can adapt to changes made to the data they represent. In our case, these changes in data will not be given by live interaction with our physicalisation but the change in data values will be given using the code written for this purpose which will read a CSV file of data values and pass these different values to our physical variables.

Dynamic physicalisations have a major advantage in that, they make the overall experience more realistic for the audience and notable research has been made to provide a framework through which dynamic data physicalisation systems could be built [55].

This way, a particular system could not only be used to represent multiple datasets but could also be used to see the results of changes being made in a dataset. Seeing this type of interaction live in action has more persuasive power and better communication techniques for users to have a better understanding and comprehension of the information being communicated by the data under observation.

2.3 Advantages and Disadvantages of Data Physicalisation

The background information provided above serves as a basis for our readers to have a general overview and get acquainted with basic knowledge to understand the rest of the work done in this thesis. Added to this and based on the information provided in this section we identify some advantages that data physicalisation brings to the general research area of Information visualisation. We also intend to highlight some notable challenges encountered during the overall process of data physicalisation. It should be noted that a trade-off needs to be made between the advantages of data physicalisation and the effort required to obtain these physicalisations and we relate to research areas close to data physicalisation to identify what we can consider as these advantages [28, 32, 36, 71].

Some of the advantages of data physicalisation are:

- Data physicalisation allows data to be brought to our real physical world which makes it possible to exploit the benefits of physical objects as opposed to virtual objects [24].

- With regard to accessibility, data physicalisations make it possible for data to be communicated to a broader audience. Visually impaired people have the ability to use their other senses to perceive, explore and understand data when they are in physical form.

- Increase human engagement with the data. Since users can use not just their visual senses to explore data, with data physicalisation, users can make use of multiple senses and this makes the overall experience more engaging [28].

Regarding the disadvantages, some of these are:

- Not every data visualisation can be physicalised due to their very dynamic nature and there is currently a lack of methods to encode these dynamic properties.

- Producing a physical artefact is time-consuming, unlike their digital counterparts.

- There is a huge challenge in the evaluation of physicalisations as one of the challenges is to have people interact with the physicalisation without giving instructions. It therefore means that physicalisations will have to be in a form that users can easily recognise which is always not the case.

In order to achieve dynamic data physicalisation for an optimal experience, care needs to be done in the choice of the physical variables we use to represent the properties of the data. All this while taking into account that vision and touch (haptic feedback) were found to be the most acute senses through which users interact with data physicalisations [44, 12]. Examples of such physical variables used in the context of our research and more on this are provided in the next section.

2.4 Physical Variables

As mentioned in the previous section, to convert data into physical form, we need to relate its properties to variables that best represent their inherent nature. These variables are called *physical variables*. Stusak et al. [57] in their research identified 14 such variables which we can consider as potential physical variables to convert data from digital to physical form for data physicalisation purposes. In their studies, they came up with 4 different categories of physical variables, which can be used to encode the properties of a given dataset. These categories are:

- Colour

- Geometry

- Tactile

- Kinesthesia[2]

[2] https://en.wikipedia.org/wiki/Kinaesthetics

Colour:

Under this category, 4 physical variables were identified which are: *saturation, hue, luminance and optics*. So any digital information or data set with these properties could clearly be brought to the physical form.

Geometry:

The different variables under this category are: *orientation, position and shape*. Since physical artefacts have to occupy space in our physical environment, these variables are clearly eligible variables to use in the context of data physicalisation.

Tactile: Here we have *temperature, lay, roughness and vibration*. As they indicate by their names, these variables can be used to physicalise data that have these respective properties.

Kinesthesia

The different kinesthetic variables identified here are weight and slipperiness and more on this is covered in the previous work by Stusak et al. [57].

It should be noted that the variables identified above are a non-exhaustive list of the different physical variables which can be used to achieve data physicalisation and our goal here is to give an overview to our audience of examples of the various physical variables used in this research area.

Some of these physical variables have been used to physicalise data such as in the work by Tewall et al. [62] where the physical variable temperature was used to physicalise the data under observation. In this study, a prototype called Heat-Nav was used to represent the different values used for navigation purposes into thermal values that could be felt by users. The temperature being felt by the user ranged from warm to cool based on the data values and there was a navigation application coupled to this to help the user identify their path through a 2D maze. The user had to wear this Hear-Nav on their wrist and higher temperature values being felt by the user indicated regions to avoid on the maze.

In the context of this master thesis, we will be using tactile in our proposed solution and more precisely haptic feedback through vibration and speed to conduct our experiment. More details on this are given in the proposed solution section.

More details on other different types of physical variables and how to combine these different physical variables to prevent the effect desired by one from being biased due to the properties of another are covered in the previous work by Reinaneh [29].

2.5 Spherical Visualisations

Spherical visualisations can be defined as the display of information on spherical surfaces [48]. This can either be a digital sphere or a physical sphere as is the case in this thesis. Digital spheres however will be examined through a 2D flat screen such as our computer screens and they have some disadvantages as compared to physical tangible spheres like the fact that a digital sphere can only be examined by one person at a time, unlike a tangible physical sphere which can be explored by multiple people at the same time. More on this is covered later in this thesis.

As we mentioned in our introduction, spherical visualisations are mostly suited but not limited to when we want to represent geographical data. Martin Behaim is known to be the first person to have created what we call today a globe(sphere). Several years later, panels made of LEDs and digital projectors have made it possible to create displays with a spherical shape and digital globes which have facilitated the presentation of a variety of information such as animations and dynamic information which can be updated as well as static information [17].

Using spherical visualisations, we can obtain an experience similar to the fish-eye view [68, 18]. With this view, a user can focus on a particular data in the data set with the other part of the data being pushed away to prevent any form of distraction so as to avoid some bias when making observations based on the appreciation of the data under investigation.

Projects involving spherical visualisations have been undertaken by some scientists such as Munzer [37, 38] who built a tree visualisation using spheres and she made the observation that the inherent nature of spheres plays a predominant role in balancing its limitations such as clutter and the advantages which can be obtained from its density. Another more familiar example of spherical visualisations is the well-known project by Google named Google Earth[3]. More details on this will be given in the next chapter.

While 2D screens have been used to present 3D data, this has brought up some shortcomings in the way users interact with this data and it makes the exploratory process quite unnatural. Human beings in general tend to easily navigate through structures they frequently use and it makes life easier to handle an object in a form which we expect it to be. Spherical displays come as a solution to this and they have been widely accepted and used on multiple occasions especially when trying to represent geographical data.

[3] https://earth.google.com/web/

The early 2000s saw more advanced implementations of spherical displays with the very first spherical display in colour [35] which have only gotten better due to the rapid evolution of technology even though they still do offer limited physical interaction. The research community especially those involved in information visualisation and tangible user interfaces have made research on how to make such displays more interactive [8, 31].

2.6 Augmented Reality

Augmented Reality was first introduced by Ivan Sutherland [59] in the 1970s. Since then, many improvements have been made to this technology and it has been used across multiple fields to enhance user experience and interactivity by adding virtual information to our existing physical environment.

Augmented Reality makes it possible to add additional layers of virtual information on already existing physical displays. We can think of notable use cases like providing additional information on artefacts in a museum like age, history and so on.

Some commercially available products that make use of augmented reality technology include head-mounted displays such as Microsoft HoloLens[4], Lenovo thinkReality A3[5]. Some known AR applications are also available such as IKEA's Place[6] which helps users use augmented reality technology to see how well furniture fits in their home space before purchasing the product.

Research has been made [66, 42] which clearly showed how data physicalisations can be beneficial to the information visualisation community. In the next section, we shall be talking about related work close to our topic under research which is data physicalisations on spheres and we shall bring out more on these advantages and limitations.

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[4] https://nl.wikipedia.org/wiki/Microsoft_HoloLens

[5] https://unboundxr.be/lenovo-thinkreality-a3-pc-edition

[6] https://www.ikea.com/nl/nl/customer-service/mobile-apps/

2.7 Spherical Displays

As discussed earlier, spherical displays are very suitable and have been extensively used to represent geographic information such as information about global pandemics, global population, events with a global perspective and so on [47]. However, they are not only limited to geographical data as spheres have also been used to represent other forms of data as mentioned in our previous chapter.

Our topic investigated in this thesis spans multiple research fields such as tangible interactions, spherical displays, augmented reality and data physicalisation. At the time of writing this thesis, we could not identify any academic research on dynamic data physicalisation on spheres and how the audience interacts with such a system. Therefore, we highlight some related work close to our research question where we have spheres or globes with digital information being displayed on them. We bring out related work on how people interact with virtual spherical displays on 2D screens as it has been widely used in multiple sectors such as entertainment and also media. For example in scenarios where news anchors want to present some geographic data like covid-19 data to better narrate relevant stories like the spread of covid around the globe, the effect of covid on airline travel[7] or even in scenarios where we want to present the growth in the global population.

After giving an overview of such virtual spherical displays and how data is being represented on them, we shall move to examples of tangible spheres where the data presented on them are in digital format. We shall explore how people interact with these different displays.

2.7.1 Virtual Spherical Displays or Globes

Virtual globes are often used in the context of geographical information systems and also in systems where we need to show the relationship between entities in a network or in a system [65]. Communication of global data is made possible over the Internet by using these virtual representations or globes.

These virtual spherical displays like Google Earth are present on many personal computers around the globe or can be accessed using the internet and thus make it possible to reach an even larger audience. These virtual globes on computer screens make it possible for people to interact dynamically with global data as they are just a virtual representation of our globes whose inherent form is widely understood by the general public [58, 34]. In this regard, the global information system can be defined as *"the branch of science concerned with places on or close to the earth's surface"*.

The vision behind virtual spherical displays or globes was promoted by Al Gore

[7]https://www.theage.com.au/interactive/2020/coronavirus/silent-skies/

in the early nineties with the Digital Earth[8] project. This project was all about having a digital representation of our planet whereby data could be mapped to different areas on our globe based on their actual geographical location. Since then, this concept has given rise to novel technologies such as Google Earth which was mentioned in the previous chapter.

However, the first known company to come up with such a product is ART+COM with the Terravisison[9] project which was released in 1994.

Google later released Google Earth after acquiring Keyhole[10] who developed the Earth viewer in the early 2000s.

Between the first release of this earth viewer and its acquisition by Google. NASA also came up with a virtual globe project which was called World Wind[11]. The figure below shows the evolution of virtual spherical displays on 2D screens over time [4].

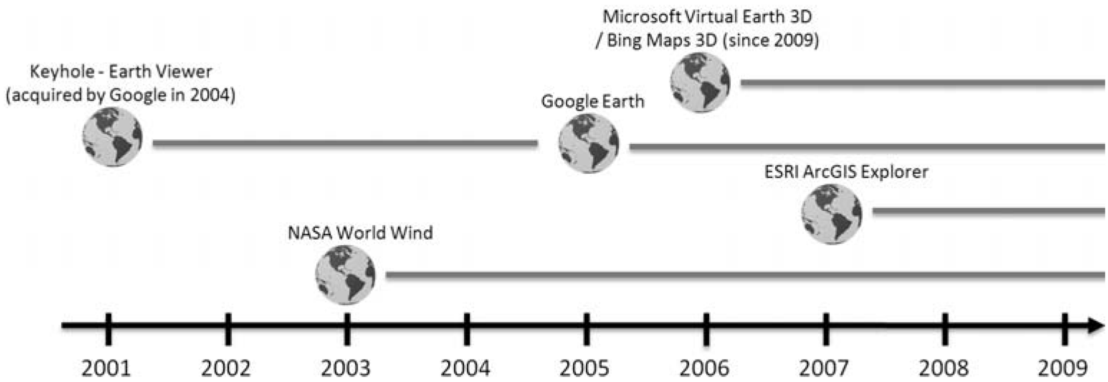


Figure 2.7: Occurrence of virtual globes on 2D screens

In order to display information or data on these virtual globes, it suffices to encode layers of data on different regions of the globe which represent the real positions which are specific to this data. As such we can superimpose information such as the names of places, road numbers, names of cities and so on and users can obtain a high resolution of these layers of data by zooming in on a precise location [64].

Over the last couple of years, these globes have been enhanced and there has been a need to explore not just virtual globes, but a combination of both virtual and tangible globes enhanced by either augmented reality or virtual reality. There are a couple of such projects where tangible globes are being used in combination with either augmented or mixed reality [52, 53].

[8]https://joint-research-centre.ec.europa.eu/scientific-activities-z/digital-earth_en
[9]https://en.wikipedia.org/wiki/Terravision_(computer$_{program}$)
[10]https://en.wikipedia.org/?title=Keyhole,_Incredirect=no
[11]https://worldwind.arc.nasa.gov/

2.7.2 Tangible Spherical Displays

Tangible spherical displays have had many use cases such as globes used for education purposes in schools or regular 3D spheres used for artwork and so on. Due to the rapid growth of technology, these tangible spheres can also now have data displayed on them in a digital format with some of them having a touch interface [61].

Augmented reality enabled by the use of head-mounted displays such as Microsoft HoloLens and other devices such as mobile devices has also made it possible to enhance these globes by reducing the number of hardware used in the design of visualisation idioms on spherical displays.

In the research conducted by Wang et al. [69], they investigated how 2D displays could be extended to analyse objects in 3D using augmented reality head-mounted displays. They made the observation that these head-mounted displays gave users a better understanding of complex objects. On the other hand, there have also been some investigations on how to project digital information on physical objects. The study performed by Chen et al. [7] in this regard showed that such a system had an overall great user experience and high satisfaction rate among users who said that the system was very easy to understand and use.

Embodied interaction is an important concept that came up due to the need to explore different modes of providing inputs to computer systems other than the well-known interface we use today. This interaction coupled with content from augmented reality arose as a way to map virtual objects with their physical counterpart. It was found that users interact more with the virtual object they see in augmented reality when they have a tangible representation of this object in hand which they can freely manipulate [13, 3]. Bach et al. [1] found in their research that users had a better performance when using visualisations in augmented reality by using head-mounted displays such as hololens while interacting simultaneously with the visualisations' physical counterparts.

Spherical tangible displays have been used widely in the context of education [6]. The use of such displays has been used as input and output devices. Englmeier et al. [14] used a sphere as a way of providing input to a number of applications some of which were virtual globes. They showed the advantages of using tangible spherical displays in their study where they projected 3D bar charts on virtual spheres.

The theory above shows us how tangible spherical displays, augmented reality and virtual spheres can be used in the context of our research topic. In this regard, a work close to this done by Satriadi et al. [51] was taken into consideration. In this study, they investigated how augmented reality can be used for data visualisation purposes using tangible globes or a sphere. A conceptual model of this research is shown in the figure below:

Figure 2.8: Data visualisation on a tangible globe using augmented Reality

As shown above, they tried to investigate 3 ways of displaying geographic data using augmented reality on a tangible sphere. First, they investigated how to display information around the sphere. They also investigated the effect of putting information on the surface of this sphere. Secondly, they investigated the effect of using the sphere's inherent nature as an input to manage the virtual information system space used to display the data under investigation. Lastly, they investigated the effect on user experience when they combine the first and the second scenarios described earlier. The sphere used in this experiment was equipped with readily available hardware devices placed inside the sphere for the purpose of this experiment.

Another study by Satriadi et al. [50] investigated how to perform data visualisation on virtual spheres. In this study, they performed a user study and evaluated five spherical visualisation idioms. They focused on properties related to representing data on spheres which are the well-known primitives: bar charts (3D and 2D) and circles. The second primitive taken into account here is the position. In simpler terms, they examined the most used way of displaying information on spheres which is displaying information using bar charts and they took into account the most used positions of these primitives which are billboarded bars, normal bars and tangential circles. Based on a user study taking into account these two primitives, they came up with what they called *"Geoburst"* which is a system whereby data is presented on virtual globes using radial bar charts. Representing data using the billboard bars makes it easy to compare the bar lengths by just making sure they are aligned in the same direction. One of the major drawbacks of this idiom was the fact that some bars are occluded by others and this caused inconsistencies at the level of perception. Normal bars on their part use 3D bars placed on the surface of the virtual globe. This is widely used in mass media communications but has a similar drawback to billboard bars. Tangential circles make us of 2D circles which we put on the surface of the sphere tangentially. This idiom does not have an occlusion issue like the previous two orientations described here. Circles are sorted from large to small that is the larger circles are first drawn to prevent the occlusion of the smaller ones. The image below can be used to have a better understanding of what was just described with regard to the orientations of primitives.

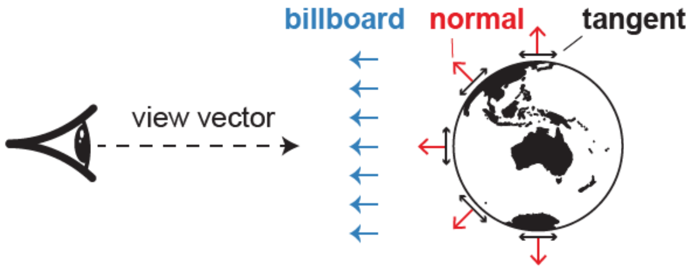


Figure 2.9: Alignment of primitives on a sphere

As mentioned earlier, Geoburst came as a proposed solution to the limitations observed while performing some user studies taking into account what was described earlier above. With Geoburst, the authors propose representing data on globes using radial bar charts which are linked. This proposed solution got much positive feedback and possesses many limitations which we shall discuss further.

The proposed Geoburst is basically a visualisation system using a sphere whereby locations on a sphere or globe are linked to a bar as shown in Figure 2.10:

A very important limitation of this work was found to be: visual clutter caused due to a growing number of links for very large datasets.

Last but not least, Englmeier et al. [16] in another study involving spherical visualisations and head-mounted displays investigated how immersive spherical visualisations can be enhanced with tangible devices.

Their setup consisted of a tangible sphere with its almost exact representation in virtual reality obtained using a head-mounted display. They also tried to find out if the size of the tangible sphere had any impact on the user experience and as such used two different spheres of different sizes. They made an evaluation by giving participants who interacted with their system two specific tasks. The first one was an exploratory assignment whereby a user had to find a country indicated using a marker that was placed on the surface of the virtual sphere. The user had to find this country on the tangible sphere. In the second scenario, the participants were required to view a 360° video that was displayed on both a large, surrounding sphere and a smaller handheld sphere. Following this, they were asked to complete a questionnaire about the environment in these two scenes, as well as the heat map data that was overlaid on top of the video. A general observation made from this study was that users found that using a relatively large sphere made it easier to

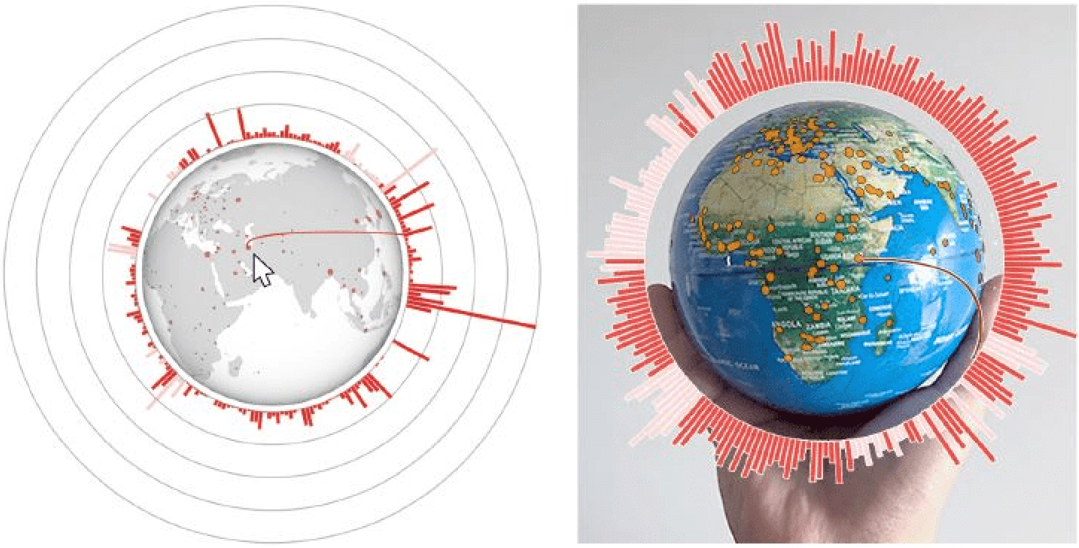


Figure 2.10: The conceptual model of the ideal proposed solution and an expected scenario in the real world using AR

identify areas on the sphere. Using a larger sphere also made the users develop different ways of navigating with it rather than just holding it or just standing in front of it. A major limitation of this research was the head-mounted technology used here which has some disadvantages such as the resolution of the images being displayed in the headset and the fact that the user is completely immersed in the virtual reality world and can no longer see their immediate surrounding.

As shown and discussed in this chapter, there has been some research done on how to represent data on spheres. However, the different scenarios or investigations always focused on how to represent the data on these spheres in digital format either on the surface of a physical sphere with a touch interface [51, 50] or on the surface of a virtual sphere [65]. Since our focus in this thesis is to present an early model or a prototype solution for dynamic data physicalisation on a sphere, we present in the next chapter a proposed solution based on the literature review presented above.

Chapter 3

SphereBurst Solution

Physicalisation in the context of data visualisation comes with advantages and disadvantages. While some argue that the cost of physicalising data is too expensive to invest further in this research field as the outcome is not significant, other scientists who are keen on making data accessible to a wider audience see this approach of making data physical as a means of expanding the audience we can reach when we physicalise data [28]. In this regard, physicalising data can help us make data understandable to communities like the visually impaired.

All the related work with regard to spherical visualisation was centred on data visualisation and not dynamic physicalisation and we can say that our proposed solution is a first attempt to achieve this scenario. Spheres have been used as input devices in the context of data visualisation and we found that users have a tendency to better interact with physical artefacts which we subconsciously or consciously already have an understanding of its layout. Our proposed solution to achieve this is focused on choosing appropriate physical variables described in the introduction chapter to better represent quantitative data being displayed on the surface of the sphere. We propose a robust solution with makes use of off-the-shelf and readily available hardware devices to build our system.

We also use augmented reality which is part of our physicalisation. This proposed solution comes as an early and high-level solution to the research question under investigation and will not be an attempt to do a one-to-one mapping of the data present in our data set.

3.1 Conceptual Design

3.1.1 Ideal Prototype

Since our proposed solution is an early and high-level solution, our objective is to have data physicalisation on a sphere. This sphere is made of individual hexagonal units. We refer to each unit as a module. So we have a sphere that is made up of hexagonal modules. The idea is that these individual modules could represent for example a location on the globe, a region or a street depending on our use case. It should be noted that the individual points on our sphere do not represent the individual location points on a real globe as we know. In more precise terms, our solution is not a one-to-one mapping i.e. the modules at the top do not necessarily represent the northern hemisphere but can be made to represent it based on our use case. For a better user experience, we envision our sphere to be robust and have a diameter of at least 40cm. Each module will have the appropriate hardware to encode the physical variables chosen to represent the properties of the data in our dataset under study. Each of these modules is printed using a 3D printer and will have to be hollow and converge towards its top so that we can affix the individual hardware inside these modules. Our ideal sphere after printing the individual hexagonal hollow modules and sticking or glueing them together to form a sphere will look like the image below:

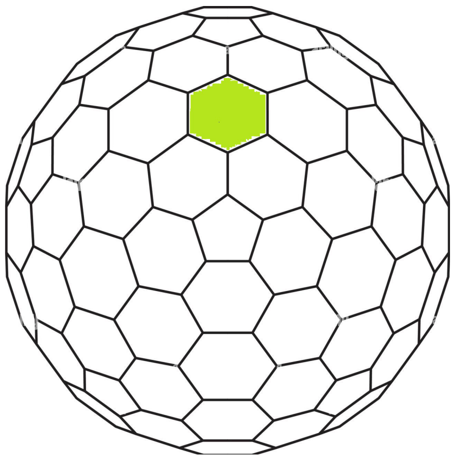
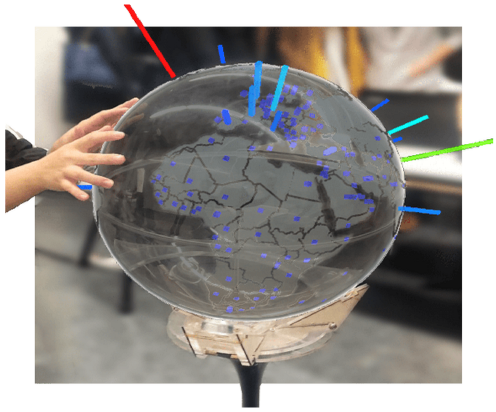


Figure 3.1: Representation of an Ideal prototype of our spherical display. The green spot represents a hexagonal module that will contain hardware to physicalise the data

Ideally, the prototype shown in Figure 3.1 is augmented using a head-mounted display such as a HoloLens so that the user can use both of his hands to explore the tangible sphere at all times. Ideally, a virtual sphere that has the same form factor as the tangible globe will be overlaid on the physical sphere and on which virtual information will be displayed. The user can now see this virtual information and use the corresponding tangible sphere to have haptic feedback which corresponds to the virtual information being displayed. The virtual information seen in augmented reality should move or rotate in the same direction when the physical sphere is rotated. Figure 3.2 is an ideal setup of our envisioned prototype.

(a) User interacting with the tangible globe. The sphere used here is for illustrative purposes. Credit: Arif Bacchus



(b) Expected digital information seen in the head-mounted display overlaid on the tangible sphere

Figure 3.2: A general setup of our ideal data physicalisation on a sphere

Since we want the virtual information displayed in augmented reality to be aligned with the position of the physical sphere when it rotates, we can think of different possibilities of achieving such as:

1. The HoloLens has a program that knows its position and degree of orientation relative to the position of the sphere. It uses this information to determine the position in which it will display virtual information in augmented reality. As such, when the sphere moves, its orientation will be updated and the program uses this new orientation to realign the virtual information in the digital environment.

2. A program that has the position and orientation of both the camera and the physical sphere and uses these coordinates to make sure that they have the same alignment thereby ensuring that the virtual information in augmented reality always matches the position on the physical display

3. External sensor placed in a room to get the position and orientation of the physical sphere and now send these values to our program to make sure the virtual information in augmented reality is aligned accordingly

3.1.2 SphereBurst

Based on our ideal design explained above, we came up with a proposed solution that at a high level has similar functionalities. It should be noted that one of our primary goals is to physicalise data on a sphere and use this for data analysis. Using the hardware we had at our disposal and due to time constraints, we had to find another hardware device (an android device in our case) that would be used for augmenting our physical sphere. The underlying functionality will be the same as it will augment our tangible sphere thereby superimposing digital information on a tangible sphere which will have hardware used to physicalise data. The only drawback here is that since we wanted a virtual sphere with the same form factor in our augmentation, we will not be able to do this using our Android device but we will still be able to overlay digital information based on the dataset under observation and use this for data analysis purpose.

The sphere used here will have a design as shown in Section 3.1 which is made up of hexagonal modules and each of these modules will be augmented using augmented reality technology to give more details about what they represent on the tangible sphere. For example, one module might represent a region on our globe and the users will only know this when they use the augmented reality application. We use marker-based augmented reality to keep track of the position of each of these modules on our sphere.

As we mentioned earlier, each module will hold hardware devices to encode the different physical variables used to represent our data. In our case, we shall be using one pulse-width modulation vibrator motor and one pulse-width modulator fan in each of these modules. By doing so, we expect to use the two hardware devices to encode two dimensions in our data set. We could add more devices for more properties but for aesthetic reasons, we decided to limit our investigation to physicalising two properties of our data set. The idea here is to make use of pulse width modulation to represent the different values in our data set and feel the haptic feedback when our hardware devices will either vibrate for the case of our vibrator or rotate for the case of our fan.

These hardware devices will be connected to the pins of a Raspberry Pico W and will be receiving input signals or values from the master node which is a Raspberry Pi 3. Communication between the master and the individual slave nodes will be done through Wi-Fi. So our setup will consist of a single master node and multiple slave nodes each affixed to the number of modules that constitute our sphere.

Since we are not doing a one-to-one mapping of data points in our data set, we feed a file of aggregated data values into our Raspberry Pi whose job will be to transfer these values to the precise modules. So the Raspberry Pi will be sending two values to each module and these values will drive the respective hardware into motion. Users can feel the haptic feedback by placing their hands over these modules. We expect these hardware devices to rotate at a higher speed for higher values in the case of the fans and to vibrate with a higher intensity for higher values in the case of the vibrators and vice versa.

3.2 SphereBurst Architechture

The architecture of the *SphereBurst* design explained in the previous section is shown in Figure 3.3.

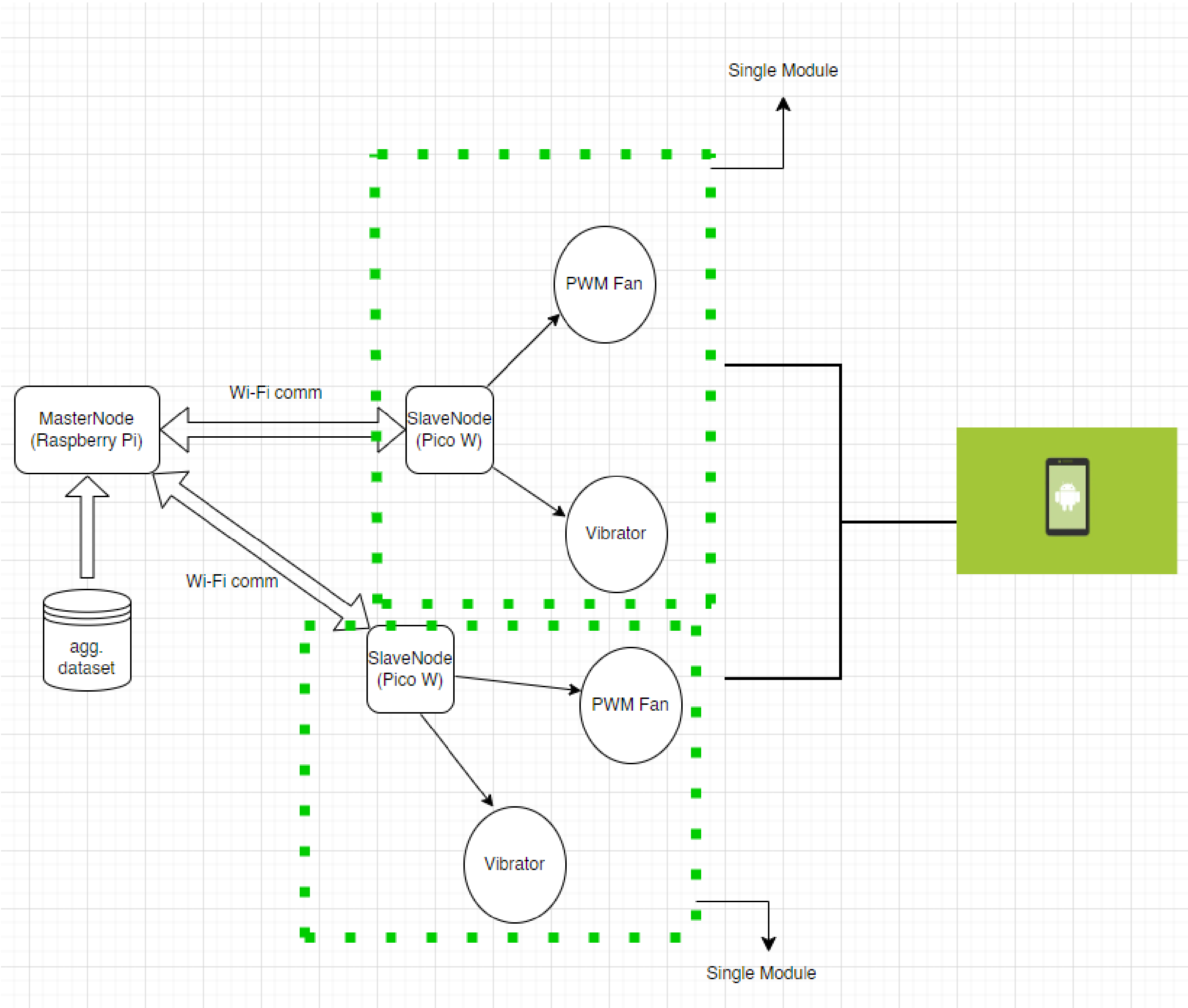


Figure 3.3: Architecture of the SphereBurst prototype

As shown in Figure 3.3, each module (hexagonal unit) of the sphere shown in Figure 3.1 will contain a Pico W and the two pieces of hardware as shown. The user will use the augmented reality application deployed on an Android device to see what the physicalised module represents. More details about how this is implemented are given in the next chapter.

3.3 Interaction and Visualisation Guidelines

As mentioned earlier, we give in this section some guidelines to be taken into account when designing spherical displays like our *SphereBurst* prototype.

Though *SphereBurst* is a physical display, these guidelines are applicable to both physical and virtual displays and are therefore important for researchers who are interested in exploring the design of spherical visualisations.

Englmeier et al. [15] in their study to evaluate the interaction techniques on spherical display made some important observations in this regard. Other studies were equally performed to evaluate these interaction and visualisation techniques such as the work by Bolton et al. [5] where they made a user study to compare interactions between flat and spherical displays. Last, but not least, Soni et al. [56] performed a study in a science museum to observe the way people interacted with physical spherical displays and from these, we make some suggestions on the guidelines to take into account with regard to interaction and visualisation on spherical displays. Based on this previous work mentioned earlier, we establish the guidelines below:

1. **Context:** It is important to consider the target audience of the spherical display, the individual task we expect them to execute, the type of analysis we expect the audience to perform using the display and clearly identify the goals to be achieved once the audience interacts with the display.

2. **360-degree viewpoint:** Since spheres provide a 360-degree surface area, the information display should exploit this by giving the audience the means of interacting with data from every possible angle.

3. **Exploration:** The display should be in such a way that interacting with it is intuitive and not too complex to comprehend. It should have the ability to support physical interactions and free navigation either by rotating the display and also by freely moving around the display.

4. **Scalability:** For virtual spherical displays, the audience should have the ability to observe the data by either zooming in or out to visualise the data in different sizes.

5. **Representation of data:** Since sphere wraps around themselves, we need to make sure that the data displayed at the edges is such that they are not heavily distorted thereby maintaining its clarity and purpose.

6. **Interactions:** The display should be such that they can be explored with both hands. Therefore, they need to be rigid enough to support a certain

weight due to both hands being placed on it, especially at its top without it being deformed.

7. **Size and weight:** Ideally, it was found that when dealing with a spherical display, users have the tendency to rotate the display from right to left and top to bottom and therefore the size and weight should be such that they can enable such interactions.

8. **Consistency in visualisation:** The visualisation paradigm and the way of interacting with the sphere should be consistent throughout to provide a better user experience.

9. **Accessibility:** The display should target a wider audience like people with disabilities. Therefore, users should think about having displays that could easily be moved around and placed at different heights relative to the ground. The data displayed has to be analysed using multi-modal interactions and not only limited to or only visual senses.

10. **User Education:** Users should be given a clear description of how the display is intended to be used and what each section represents especially in the case of data physicalisations where the entire setup is made up of physical hardware without any intuitive way of knowing what each hardware represents.

Chapter 4

Implementation

The *SphereBurst* prototype explained above is a dynamic data physicalisation which we shall give more details about its implementation in this chapter. The implementation is two-fold. Firstly, we have the hardware requirements and how we put them together to constitute our hardware setup and secondly the software implementation to drive this setup. In a nutshell, we will be building a dynamic data phyicalisation which shows how we can physicalise data on a sphere. We will be evaluating our proposed solution in the next chapter where we shall take a use case and conduct a user study.

4.1 Setup

Since we want to physicalise data on our sphere, we need to identify distinct regions on our sphere where we shall place our individual hardware which represents the physical variables used to encode the properties or features of our dataset under observation.

More details regarding the hardware setup of our *SphereBurst* prototype is explained below.

The building block of our prototype is a sphere and 3D-printed hexagonal units shown in Figure 4.1

(a) Seperatable hollow sphere (b) Hexagonal printed module

Figure 4.1: Spherical and hexagonal building block of our system

Once the individual hardware i.e fan, vibrator, pico W and markers are mounted to these hexagonal units, we have a complete module which is then placed in hexagonal holes crafted on our sphere. More details are shown in the Figure 4.2 and Figure 4.3.

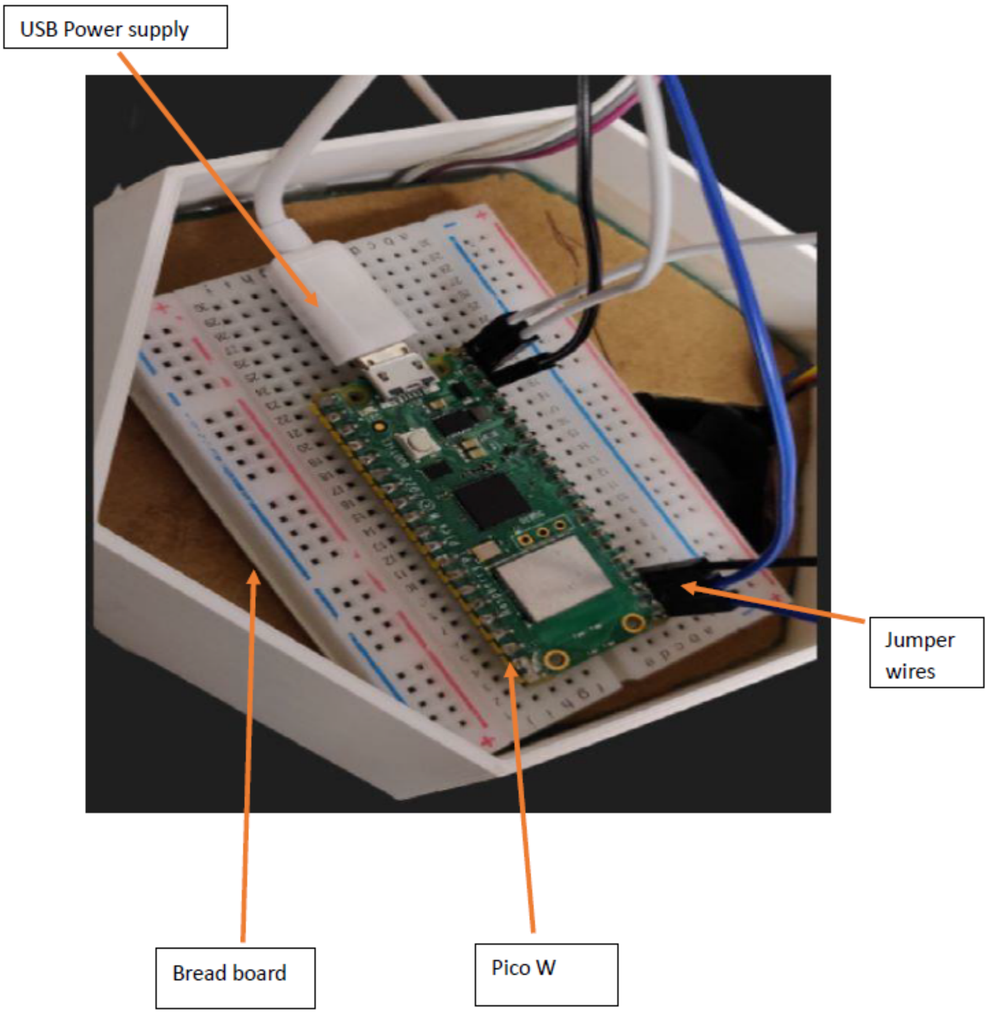


Figure 4.2: Module bottom view

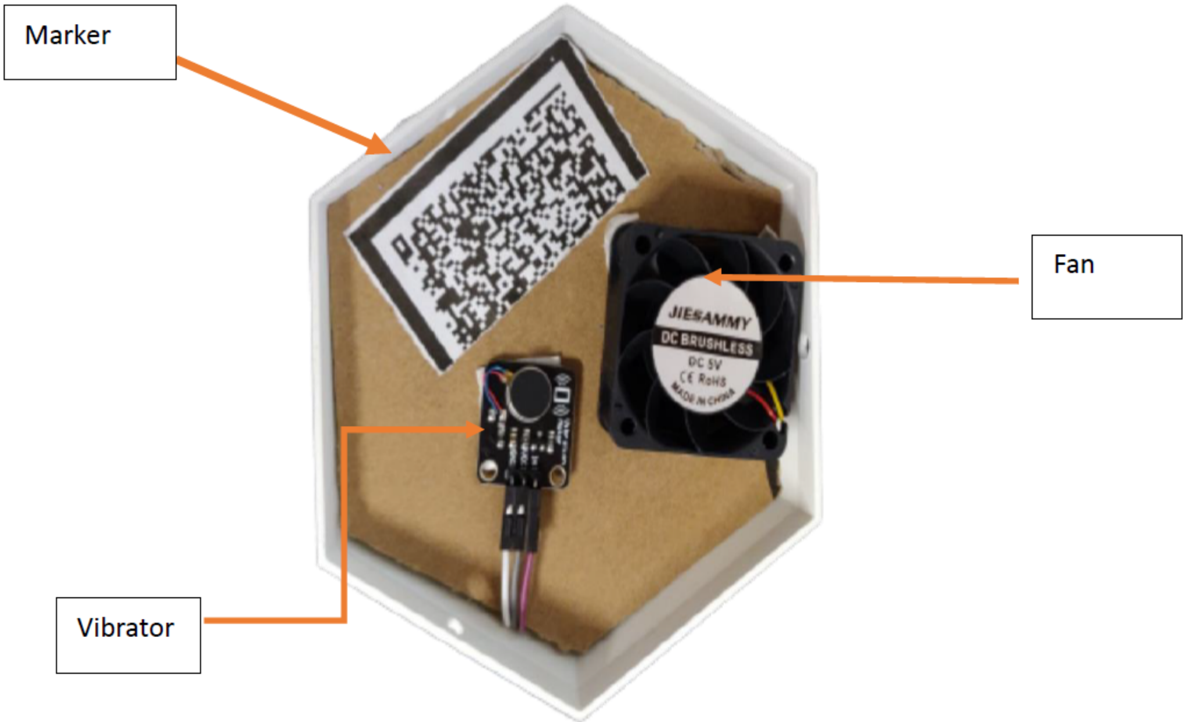


Figure 4.3: Module top view

Each of these modules is used to physicalise data on our sphere. Once they have all been mounted on our sphere. We now set up our server which is done using the Raspberry Pi.

First, we connect the Raspberry Pi to a monitor using the HDMI cable shown in Figure 4.9a. We install the Raspberry Pi OS into the SD card in Figure 4.7 and plug it into the SD card slot of our Pi. When we switch on the Pi, it loads the OS and we can now write the code to set up our server and access the dataset of values which will be sent to our individual clients/modules on our sphere. More on this is covered in the software implementation section of this chapter.

More details on the hardware requirement used in our *SphereBurst* prototype are given in the next section.

4.2 Hardware Requirements

The following hardware devices are necessary to build our system:

1. Raspberry Pi 3b+
2. Raspberry Pi Pico W
3. PWM vibration motor(5V)
4. PWM Fan(5V)
5. Sphere or printed modules
6. MicroSD card
7. PC
8. Android device

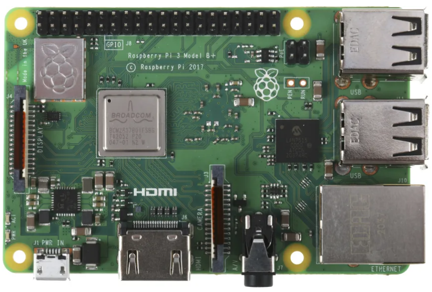
More on the above-listed devices is given in the sections below.

4.2.1 Raspberry Pi

The Raspberry Pi is a small low-cost electronic device developed by the Raspberry Pi Foundation at the University of Cambridge in 2012 [46]. It can be seen as a micro personal computer which can be plugged into a PC monitor. The first ever Raspberry Pi to be released by the Raspberry Pi foundation were the Model A and B which belong to first generation Raspberry Pi's. Subsequently, newer versions were released which were respectively divided into second, third and fourth generations. In the second generation Pi's, we have the Raspberry Pi A+ and B+. Raspberry Pi 2, Zero, Zero W, Raspberry Pi 3 and 3B+ fall in the third generation. In 2019, the Raspberry Pi 4 was released and this falls under the fourth generation.

From one generation to another, functionalities were added to these devices to enlarge their capabilities and make them more powerful.

In our implementation, we will be using the Raspberry Pi 3B+ which was introduced in 2018 and whose image is shown below:



(a) Configuration of Raspberry Pi 3B+

(b) Pin Out diagram of Pico W

Figure 4.4: The different Raspberry Pis used in our setup

The Pi 3B+ shown in Figure 4.4a has many parts and the main ones which are of interest to us are the processor of 1.4GHz, a dual-band Wi-Fi of 2.4/5 GHz, a USB boot, an HDMI port and the USB power supply to power the Pi. Since the Raspberry Pi 3B+ plays the role of our server in our setup, it was important for us to have one that has good processing power and that could connect to Wi-Fi. The Raspberry Pi will run an operating system which loaded into a microSD card and plugged into the Pi. The HDMI port of the Pi will be used to connect the Pi to a computer screen which will provide a GUI and an environment where we will write the script that runs on the Pi and acts as the server in our system. Our dataset of aggregated data values will be on our server and these values will be sent to the individual clients once a connection is established between the client and the server.

4.2.2 Raspberry Pi Pico W

The Raspberry Pi Pico W is another device released by the Raspberry Pi Foundation which is an improved version of the Raspberry Pi Pico[1] which was released in 2021. This device has Wi-Fi capabilities which is crucial in the setup of our system as we wish to establish a client-server connection over Wi-Fi. The Pico W is similar to the Arduino in that they are all microcontroller boards, cheap, small and on which external hardware devices can be added thanks to their GPIO pins. The Pico W differs from other Raspberry Pi developed by the Raspberry Pi Foundation in that they do not run an OS and hence directly run the code that is being stored in its memory. We shall be using each Pico W to represent one client in our system and in an ideal situation, each hexagonal area on our sphere will contain one of these Pico W which shall be used to physicalise the data values being sent by the server. The configuration of the Pico W is shown in Figure 4.5. The Pico W in our system is powered using the USB power supply and the hardware devices used to physicalise the data are attached to its GPIO pins.

[1]https://www.raspberrypi.com/products/raspberry-pi-pico/

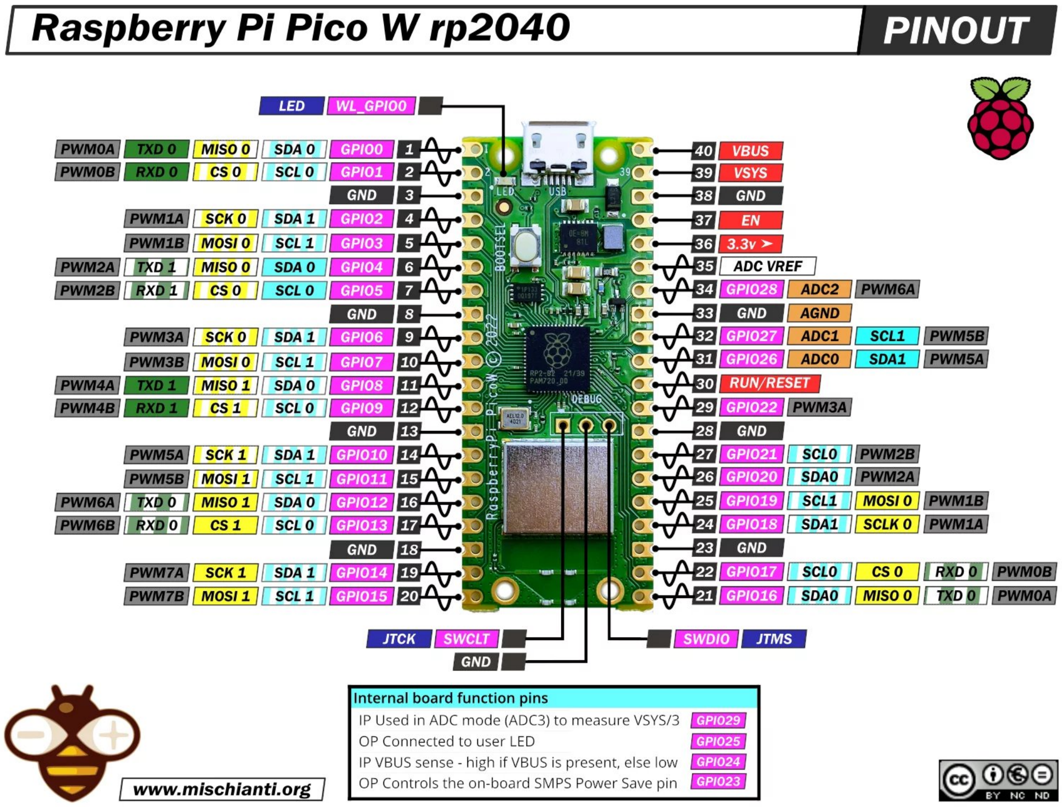
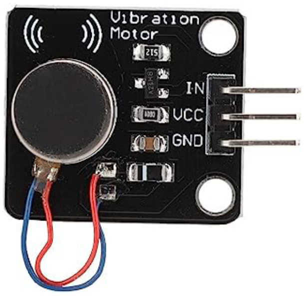


Figure 4.5: Pin Out diagram of Pico W

From this pinout shown in Figure 4.5, we have a number of pins for ground, pins to provide 5V (VBUS and VSYS) when the Pi is powered with a USB power supply and a good number of GPIO pins hence this make this device suitable for our use case as we have to attach two hardware devices with will both require Vcc, GND and Pulse Width Modulated input signals. More on Pulse Width Modulation will be covered in the software implementation section of this chapter.

4.2.3 PWM Vibration Motor and Fan

One of the hardware devices that will be connected to the GPIO pins of our Pico W to physicalise the data in our dataset which will be sent by the server is a vibration motor. The vibration motor used here is a 5V pulse width modulation vibration motor which has the capacity to vibrate at different intensities based on the duty cycle of the signal being sent to it. They are readily available online and are also quite relatively cheap and we can therefore use a number of them in our system. Figure 4.6a shows the vibration module used in our system. It has 3-pins which are Vcc, GND and IN which will be used for the PWM.



(a) Pulse width modulation vibration motor

(b) Pulse width modulation fan

Figure 4.6: The different PWM hardware used in our system

The PWM fan used in our system is shown in Figure 4.6b. This fan equally has Vcc, GND and a PWM pin which will be connected to the respective pins on the Pico W.

4.2.4 MicroSD card

The Raspberry Pi shown in Figure 4.4a runs an operating system. This OS is being fed into a microSD card which is later plugged into our Pi which contains the IDE and the environment for us to write and run our code. We use an 8GB card which can be seen in Figure 4.7

Figure 4.7: microSD card and adapter

4.2.5 Jumper Wires and Cables

In order to connect our hardware devices to our Pico W we will be using jumper wires. The different cables we use are; 1 HDMI cable to connect the Raspberry Pi to a monitor and a USB to micro USB splitter to power on the different Pico W or clients.

(a) Male to female

(b) Female to female

Figure 4.8: Jumper wires

(a) HDMI cable

(b) USB to USB micro splitter

Figure 4.9: Cables used in our setup

4.2.6 Android device

The AR experience is achieved using an Android device. We will build a custom application and deploy it to an Android device to augment our spherical setup to get more insight, especially about the different modules on our spherical display. The image in Figure 4.10 is an example of an Android device.

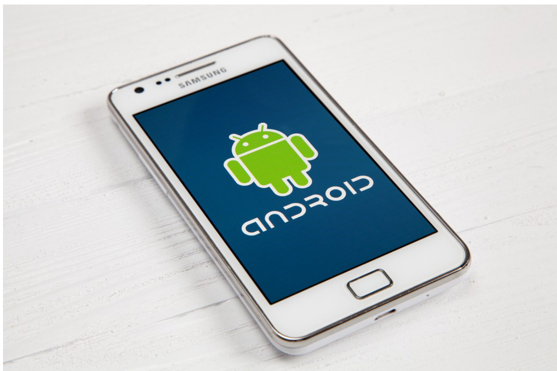


Figure 4.10: Android device

4.2.7 SphereBurst Prototype

Our proposed *SphereBurst* solution which constitutes a sphere on which these modules have been mounted is shown in Figure 4.11.

Figure 4.11: Sphere Burst

4.3 Software Implementation

4.3.1 Client

Since communication between our clients and server will be done over Wi-Fi, the hardware devices we use in our system all have to be connected to the same Wi-Fi for effective communication.

We write the client code which we save in our Pico W. The particularity of Pico W is that it has Wi-Fi capabilities but we need to explicitly write code to connect each of our Pico's to our Wi-Fi. We specify the Wi-Fi name and password and once this is successful, our Pico W will now be connected to Wi-Fi. The code[2] snippet to connect the Pico W to Wi-Fi used in our client code is shown below.

```
import network

# Wi-Fi credentials
Wi-Fi_ssid = 'Wi-Fi name here'
Wi-Fi_password = 'Wi-Fi password'

# Connect to Wi-Fi
Wi-Fi = network.WLAN(network.STA_IF)
Wi-Fi.active(True)
Wi-Fi.connect(Wi-Fi_ssid, Wi-Fi_password)

while not Wi-Fi.isconnected():
    pass
```

We use Thony[3] which is a pythonIDE to write and run code on our Pico W. Thony is installed on our PC and the client code which runs on our Pico W will be executed as we power on our Pico W. In order to achieve this, we save our code as *main.py* in each of our Pico W.

[2]https://projects.raspberrypi.org/en/projects/get-started-pico-w/2
[3]https://thonny.org/

4.3.2 Server

As for the server, we do not need to explicitly write code to connect our Raspberry Pi to the Wi-Fi. Once we connect the Raspberry Pi to the same Wi-Fi as that of the client, we then write the server code which will make our Raspberry Pi act as the server in our system. Below is the code[4] snippet which makes our Pi the server in our system.

```
import socket

# Raspberry Pi server IP address and port
server_ip = 'Enter Raspberry Pi IP address here'
server_port = 'Enter a port number'

# Create a server socket
server_socket = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
server_socket.bind((server_ip, server_port))

# server connects to one client at a time
server_socket.listen(1)
```

This code is written using the Thonny IDE which is already installed in the Raspberry Pi OS we installed on our SD card.

Our server code is run from the IDE, which enables our server which will then be listening to incoming connection requests from the individual clients on our sphere. Below is a snippet of the message from the server when we executed our code whereby it is waiting for a connection to be established.

Once the connection is established with a client, we get a confirmation message and the server now sends the respective data values to the client to drive the fan and vibrator which are attached to this client.

These values in reality drive these hardware devices as they represent duty cycle values which are used to change the pulse of the signal being fed into these hardware.

[4] https://projects.raspberrypi.org/en/projects/get-started-pico-w/2

4.3.3 Marker-based AR app

Since we will be using an Android application to augment our tangible sphere, we use Unity[5] and Vuforia[6] to develop our AR application which will be deployed to any compatible Android phone.

We created a model target[7] of our tangible sphere and imported it to our unity project. This model target is a digital representation of our physical sphere which assumes the same form factor and which helps the AR application recognise the actual physical sphere when the AR camera points at the physical sphere in our real environment.

However, at the moment of implementing our *SphereBurst* solution, it is not advised and recommended to augment symmetrical physical objects like spheres, cubes and cylinders[8] etc as they do not have enough distinct features. For research purposes and since we wanted to explore how to physicalise data on a sphere, we decided to add some features to our sphere in order to make them have quite some features such as colours which will be recognisable by our AR camera. The features we added were not sufficient to let us use only the model target of our sphere for our augmented reality application. Due to this, we had to make image targets using markers to have our early prototype of *SphereBurst.*

We create different image targets[9] for our markers using the Vuforia image target generator and create a database that contains these image targets. This database is now imported into our Unity game engine where we then wrote some script to overlay information over these markers based on the data being read.

The markers we use to augment our tangible spheres were generated using an online marker generator tool[10]. An example of markers used in our Augmented reality application is shown

These markers are used for tracking the position of the virtual information displayed using our augmented reality application. We used 5 of such markers in our prototype and wrote a script in c which tracked the position of these markers on our sphere. By doing so, we ensured that the information overlaid on these markers will move as the sphere will be rotating as the individual markers will also be rotating since they are fixed on the sphere.

In order to generate the model target we mentioned earlier, we made a 3D scan of our tangible sphere using the Lidar[11] technology. We made use of an

[5]https://unity.com/
[6]https://developer.vuforia.com/
[7]https://library.vuforia.com/model-targets/how-create-model-targets-3d-scans
[8]https://library.vuforia.com/model-targets/model-targets-supported-objects-cad-model-best-practices
[9]https://library.vuforia.com/objects/image-targets
[10]https://shawnlehner.github.io/ARMaker/
[11]https://en.wikipedia.org/wiki/Lidar

Figure 4.12: Example of a Marker used in our Augmented reality application

iPhone 12 pro-Max to record a clear 3D scan of our sphere using the Polycam[12] app downloaded from the Apple Play Store. The 3D scan obtained in Polycam is shown in 4.13.

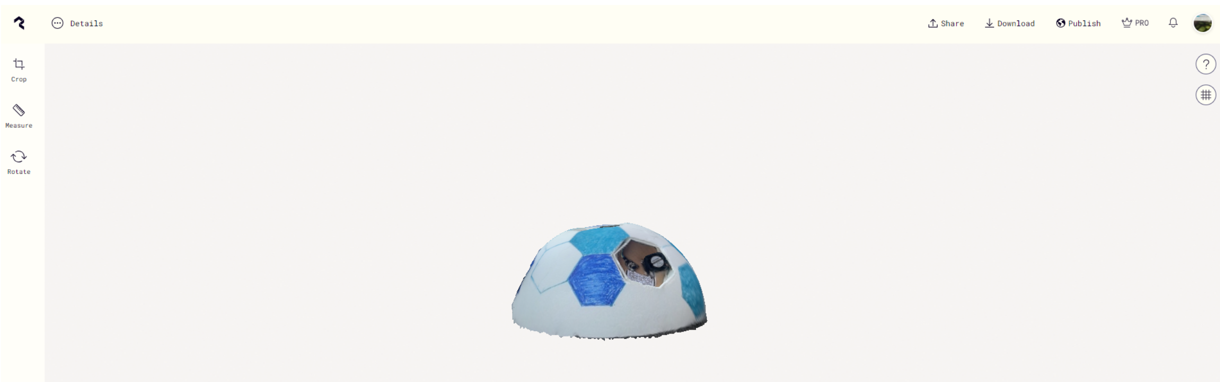


Figure 4.13: 3D scan of the tangible sphere in Polycam

[12]https://poly.cam

Once we have this 3D scan model of our tangible sphere, we use the Vuforia model target generator to generate a suitable model target to be used in our Augmented Reality application.

Our model is now trained for approximately 4 hours using the deep learning technology provided by the Vuforia model target generator. By doing so, it makes our object recognisable from every angle by our AR app. This training process which makes our object recognisable from every angle is shown in Figure 4.14.

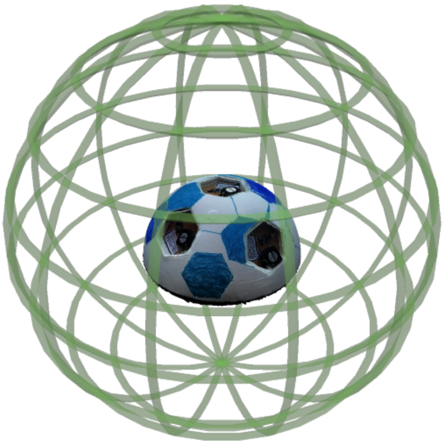


Figure 4.14: Process of recognising our target in a 360-degree view

Once the model target has been imported into our Unity program, we wrote some scripts and added assets to our scene which handles the behaviour of our AR application once we point our AR camera to our target.

In order to make sure that the virtual information that is overlaid using our augmented reality application behaves as intended, that is, appears where and when intended, is stable, and rotates as we rotate our tangible sphere, we wrote some code in CSharp which makes sure the AR camera focuses on a marker only when the entire marker is in its view. The script tracks the position of the marker and once the marker is no longer in the camera view, the overlaid information disappears.

We equally have a script that can change the dataset to be analysed. This way, we want to achieve our goal of having a dynamic system that is not only specific to a single use case. This new dataset can be uploaded using an interface in the AR application where new values can be added and saved. These values are saved locally within the application and can now be overlaid on the sphere by the augmented reality application

The code base for our application is provided together with the submission of this thesis paper. A snippet of the development environment we used to build our application is shown in Figure 4.15

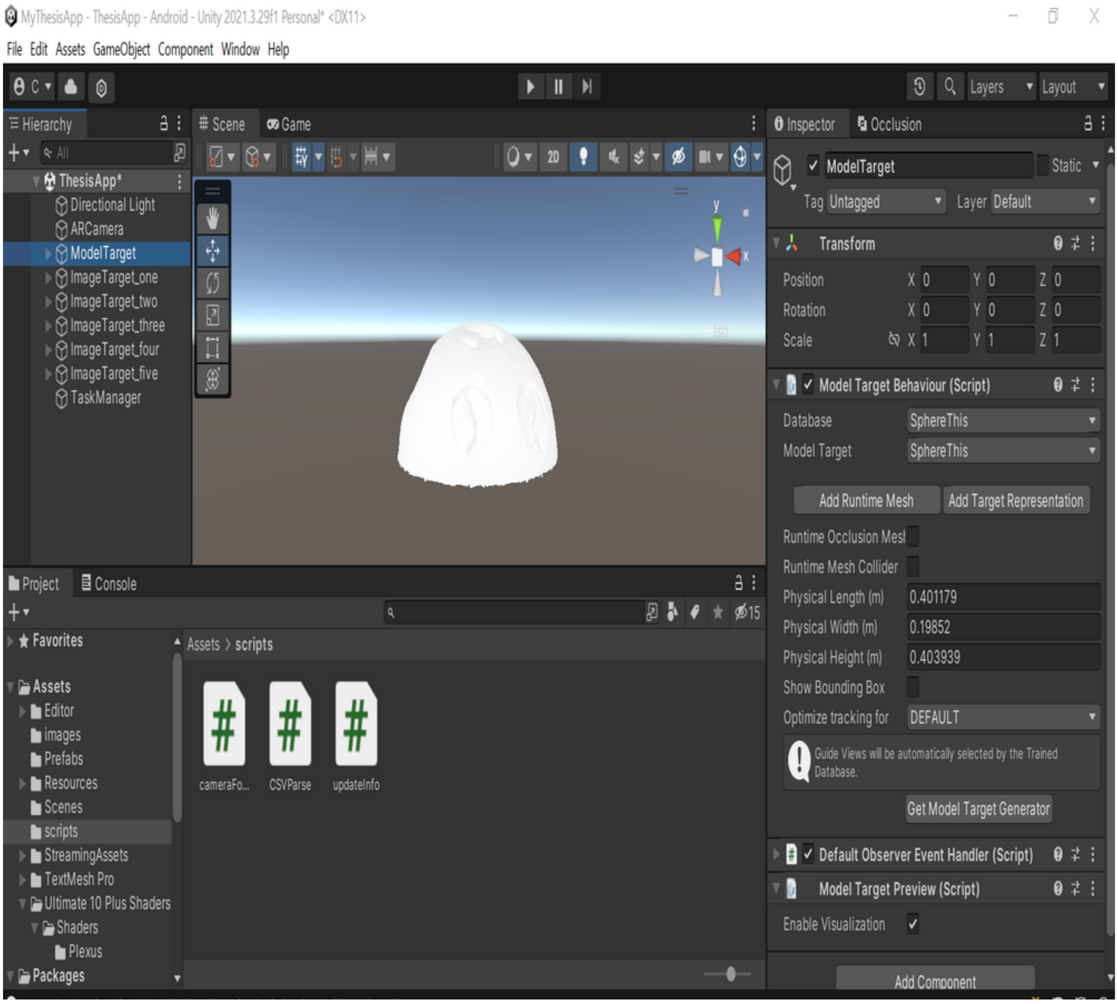


Figure 4.15: Unity development Engine

Once this was done, we deployed it to an Android phone and we can now use our *SphereBurst* to perform some data analysis tasks.

When we use our AR application to augment our tangible sphere, we have an augmented sphere as seen below:

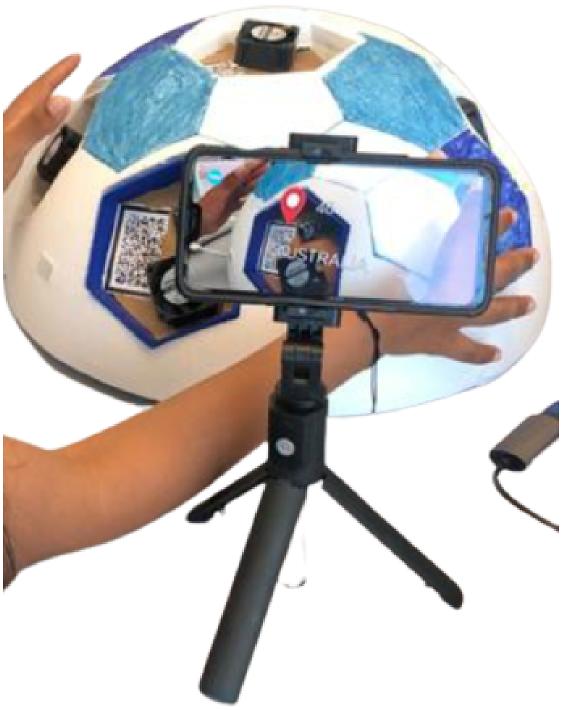


Figure 4.16: Actual setup of a user using our AR application to augment our tangible sphere.

Below is a zoom in to the different views observed by our AR application on different areas of our tangible sphere

(a) Augmented Sphere in an initial position.

(b) Augmented Sphere after rotating it at a given degree.

Figure 4.17: Demonstration of the use of our AR application to augment our tangible sphere. We can notice that the virtual information displayed using our AR application moves as we rotate the tangible sphere which was one of the goals of our ideal prototype

In the next section, we will be evaluating our *SphereBurst* prototype and make observations based on the feedback obtained by the audience who tested our prototype.

Chapter 5

Evaluation

We present in this chapter an evaluation of the *SphereBurst* prototype. Data physicalisation as a whole is a concept with stems from information visualization and as such, one of its goals among others is to communicate information being represented by the underlying data.

In this section, we evaluate our prototype to see its ease of use and appreciate its novelty. We do this by conducting a survey among users who interacted with our prototype. In this survey, they were asked to fill in a questionnaire to provide us with more insights about the features that they like or dislike on our prototype. We equally collect feedback on how to improve our prototype and also if it is a research area that is worth investigating further. This is done using a User Experience Questionnaire (UEQ)[1].

The UEQ tool used for this purpose is a standard tool that is widely used to evaluate products. It has 26 adjectives and each user who participates in the evaluation process has to give a review on a scale from one to seven to say if they agree or disagree with the adjective used to describe a scenario regarding the product being evaluated.

Furthermore, since data physicalisation allows multi-modal data exploration, we also evaluate if and how efficiently our prototype can be used for this purpose. Jansen et al. [28] observed that data physicalisation has huge potential in making it possible for the visually impaired to interact and make data analysis using physicalizations thereby expanding the target audience and taking into account important features in design such as accessibility.

It is known that once we design a solution, it is always good to take into account a wider audience and not forget those with disabilities [39]. As such, in this evaluation phase, we also explore if the audience could rely on visual senses to effectively make data analysis.

[1]https://www.ueq-online.org/

We also conduct a user study where we take a use case and have our selected user perform data analysis using our prototype. They were later asked to fill out an online questionnaire to evaluate their answers and validate the effectiveness and efficiency of our prototype in performing data analysis. We ensured that the users who participated in our evaluation phase all had basic knowledge about information visualisation and interacted with spheres either virtually or physically. We achieved this by conducting a pre-survey where users had to answer some questions regarding information visualisation, data physicalisations, sphere and basic information about their profile in general.

All the data collected in this evaluation phase is used as a ground to make observations and provide insights for improvements which we shall highlight in our next chapter. More details on this evaluation procedure are provided below.

5.1 Selection of participants

Ideally, we wanted to have participants who have some basic knowledge about concepts such as information visualisation, data physicalisations or data analysis as a whole. In order to achieve this, we sent out an online form and performed interviews online and in person to collect data and filter out participants who had some prior knowledge of these concepts. By doing this, we wish to increase the probability of having more critique and unbiased feedback on our proposed solution and its use as a data analysis tool.

However, we also included participants who didn't have prior knowledge of these concepts as we gave a brief overview of the goal of the experiment during the user study phase.

From the result of our online questionnaire and interviews, we interviewed a total of 14 participants. Out of this, 8 participants agreed to participate in our user study. However, we were only able to perform this user study with 3 participants due to time constraints and also due to the fact that we had to transport our prototype to have users evaluate it.

Therefore, we had 2 male and 1 female participants. All of our participants were between the ages of 26 and 50. All of our participants were familiar with data analysis as a whole which was good for the context of our research.

5.2 Use Case

Since our prototype is a high-level solution to data physicalisation on spheres, we decided to examine and make an analysis of a dataset of aggregated data values that represent the average weather conditions per continent. The data for our user study and eventual data analysis was obtained from the trading economics website[2]. The aggregated data values obtained here were stored on our server which gives us an overview of the average temperature and CO_2 emission rate per continent. The vibrator in our modules was used to physicalise the average temperature values while the fan was used to physicalise the CO_2 emission rate for each continent.

5.3 User Study

Before we conducted the user study, we introduced our topic under research to our participants and explained to them what each hardware in our prototype represents. The fans were used to physicalise the CO_2 emission values while the vibrator was used to physicalise the temperature.

Once we switched on our server and powered our individual hardware on our sphere, the user had to stand in front of our spherical display and navigate over our sphere by placing their palms over the different hexagonal modules. Based on the haptic feedback perceived from the different hardware devices on the individual modules and with the help of our AR application that is placed on a phone stand in front of our prototype, they were asked to answer some questions and these answers were evaluated to see if our proposed solution was efficient in making data analysis.

The participants were asked to determine using our *SphereBurst* prototype the following:

1. The region with the highest CO_2 emission rate
2. Between Europe and Australia, which region has the highest average annual temperature?

[2]https://tradingeconomics.com/country-list

5.4 Result

We found that all the 3 participants rightfully determined that Asia was the country with the highest CO_2 emission rate. For the second question, 2 out of 3 participants rightfully determined after interacting with our prototype and from the haptic feedback they could perceive from the hardware that Australia was the country with the highest annual temperature while 1 participant said it was Europe.

It should be noted that, for the second data analysis task, we noticed that participants took more time to make a conclusion. This was due to the fact that the hardware devices used vibrate and rotate at almost similar intensities and speeds for values within the same range and this was one of the drawbacks of our prototype.

All 3 participants said that the design of our prototype made them focus more while performing the data analysis task thereby increasing user engagement. They all were fascinated by this new way of analysing data as it was the first time that they all had to use more than just their visual sense to perform data analysis.

All 3 participants intuitively rotated the sphere when interacting with our prototype and they all mentioned that they wished they had the option to rotate the sphere in all directions.

All 3 participants said that they found our system more performant than just analysing data using visual senses as using haptic feedback increases memorability. One participant said *"Asia is really loud"* when referring to the haptic feedback perceived when placing their hand over the fan used to physicalise data for this region. This way of interpreting data definitely has an effect on the way we perceive data.

After the user study, they filled out a user experience questionnaire with the results shown in the appendix section of this thesis. However, we present below some statistics based on the input from the user experience questionnaire that was filled out by the participants.

2	Items																									
3	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
4	5	5	2	2	2	6	6	6	2	3	6	2	6	6	6	6	4	2	2	6	2	6	2	2	2	6
5	7	6	1	2	1	7	7	6	1	1	7	1	6	6	6	7	1	1	1	7	1	6	1	1	2	7
6	4	5	3	3	3	4	4	3	4	2	5	2	5	5	5	6	4	2	4	5	2	6	3	3	1	5

Figure 5.1: Data filled in the User Experience Questionnaire

Each row in Figure 5.1 represents the inputs by the participants. Since we had 3 participants, we therefore have 3 inputs. Each column represents an adjective used to get the participants' appreciation of the prototype. More on this can be seen in Appendix B.

The goal of this UEQ tool is to provide insights on the basis of six properties which are: *attractiveness, perspicuity, efficiency, dependability, stimulation and novelty.* This tool performs calculations based on the values filled in the questionnaire and presents results (mean values) on a scale ranging from -3 to +3 with -3 representing a very bad evaluation and +3 a very good evaluation. Figure 5.2 is the result obtained from this UEQ tool in the evaluation process of our prototype.

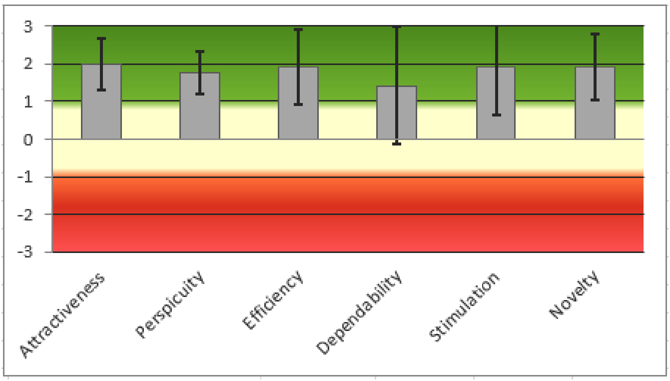


Figure 5.2: UEQ result graph showing the mean value of the six properties used to evaluate our prototype

From the graph shown in Figure 5.2. We noted that the properties that had the highest positive reviews were attractiveness, Novelty, stimulation and Efficiency. This shows that it is important to have physicalisations that are visually appealing as they have a positive impact on user engagement. We also mentioned in the introduction of this thesis that we were proposing a one-of-a-kind and novel prototype which could be used for data analysis and the result from this UEQ form confirms our claim. Our prototype was also found to be efficient in performing data analysis and we believe that the multi-modal exploration of the data, coupled with the aesthetics of our prototype played a major role in this since all the users who evaluated our prototype said it made them really focus more while they were performing the data analysis task.

We can conclude that our *SphereBurst* prototype was found to provide a positive user experience and was appreciated by our audience in its ability to perform the task for which it was designed though we acknowledge some of its drawbacks which we shall mention in the next chapter.

Chapter 6

Future Work and Conclusion

In this section, we present what we believe are improvements to our *SphereBurst* prototype. We based ourselves on the feedback we got in our evaluation phase and also some ideas which we eventually got during the implementation of our prototype and which due to time constraints, were not able to implement. Finally, we conclude by giving an overview of our contribution to the broad area of data physicalisation we examined in this thesis based on our *SphereBurst* prototype and the evaluation performed in the user study.

6.1 Future Work

Although our *SphereBurst* prototype received positive feedback based on the evaluation done in the previous chapter, we are aware of the probability of this result being affected if we had many more participants who evaluated our prototype. Based on what was observed during the design and evaluation of our prototype, we present below some points on which we could make our prototype better and which due to time restrictions, we were not able to look further into and which could serve as a basis for future research.

6.1.1 Improvement on Augmented Reality

Our prototype makes use of an augmented reality application deployed on an Android phone. By doing so, the form factor of virtual information that appears in the augmented reality application is reduced to fit the size of the phone screen. However, when we physicalise data, one of the objectives is to have the physical representation match as much as possible the actual data in size, shape, texture and so on and that is why our ideal solution makes use of a head-mounted display. Using a head-mounted display such as holoLens will make our virtual information displayed by our AR application appear in our real-world environment with the possibility of having the same form factor as the sphere.

More visual encodings could also be made in our augmented reality application whereby we display a virtual globe in augmented reality with the physical counterpart providing haptic feedback based on the data displayed on the virtual globe.

6.1.2 Choice of Hardware Devices

During our evaluation process, we noticed that for values in a similar range or which are close to each other (for example 21, 22), it was difficult to make a difference in these values using the hardware devices used in our prototype. In future, we think of a scenario where we could use more than one hardware device to physicalise a data value even though this might give rise to some drawbacks such as the complexity in the setup of our prototype. However, more investigations have to be done in this regard.

6.1.3 Improvement on the setup

Our current setup makes use of a phone placed on a phone stand. With this, the user will have to remove their hands from the sphere from time to time to reposition the phone while interacting with the sphere. This changes the overall interaction and time taken to analyse data on the sphere. Going for an approach where the user doesn't have to reorientate the AR camera from time to time will help the user save time while interacting with our system. This can be achieved using a head-mounted display as the user will not have to reorientate the AR camera but just focus on navigating and interacting with the sphere.

6.2 Conclusion

We introduced in this thesis *SphereBurst* which is an early prototype that explores how to display data on a physical sphere. Displaying data on a sphere is best suited for some type of data and making such visualisations physical does not only increase the audience that can benefit from these visualisations but also increases the performance of such visualisations especially due to the fact that users can explore data using multi-modal interactions.

We demonstrated how such a system can be used to perform data analysis and how users interact with such systems. We established guidelines that can be used for designing similar projects.

Furthermore, we showed that physicalising data on a sphere comes as a solution to some commonly known issues in digital spherical visualisation such as reducing the distortion of data being displayed at the edges of a sphere as the physical variables used to physicalise data have a rigid structure and can be placed on a sphere at all angles without it being distorted as is the case of our *SphereBurst* prototype.

Due to the growing amount of complex data generated daily, physicalising data on a sphere opens the way in providing alternate ways through which we explore and understand complex information.

The work presented in this thesis is a cross-boundary between scientific inquiry, innovation and creativity in demonstrating how more than just being a scientific research topic, data physicalisation is an art that when well crafted opens the door for new visualization idioms.

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Appendix A

Survey Questions

Participants selection for a user study on the Master Thesis: A Novel approach for data physicalisation on spheres

* Indique une question obligatoire

1. Adresse e-mail *

____

Informed Consent
This is an invitation for you to participate in a user study conducted in the context of my master thesis on data physicalisation on spheres. The goal of this user study is to evaluate our prototype solution, the user experience and also explore the effectiveness and efficiency of using our proposed solution for data analysis.

If you agree to participate, you will be invited to the Lab at VUB campus, Brussel and asked to interact with our prototype. This experiment will take approximately 10 minutes to be completed and you will later be asked to fill a user experience form.

Information about your interactions with our prototype will be collected during the study. This may include video recordings. However, your personal information will be confidential and we will anonymize any publicly shared data. All the data collected during this study will solely be used in the context of this master thesis and your identity will not be released in any publication published as a result of this study.

By proceeding with this study, you confirm that you have read and agreed to the information provided above.

By clicking on 'Yes', you give your acknowledgement and consent to participate in this survey.

Thanks,
Aubin

2. Do you agree to participate in this study? *

Une seule réponse possible.

- Yes
- No

Participants selection for a user study on the Master Thesis: A Novel approach for data physicalisation on spheres

14 réponses

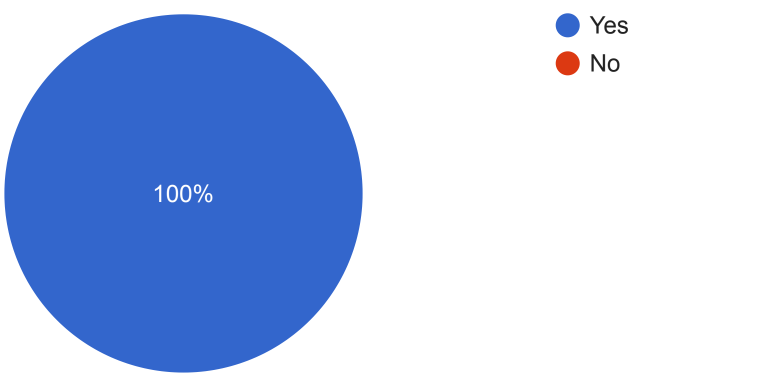
Publier les données analytiques

Informed Consent

Do you agree to participate in this study?

Copier

14 réponses



Survey Questions

Gender

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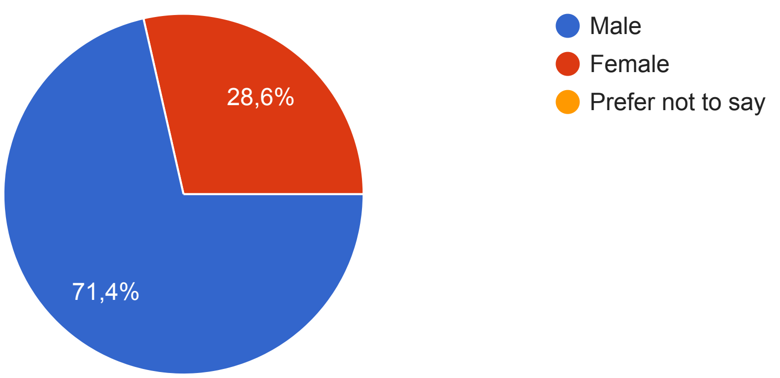
14 réponses



Age

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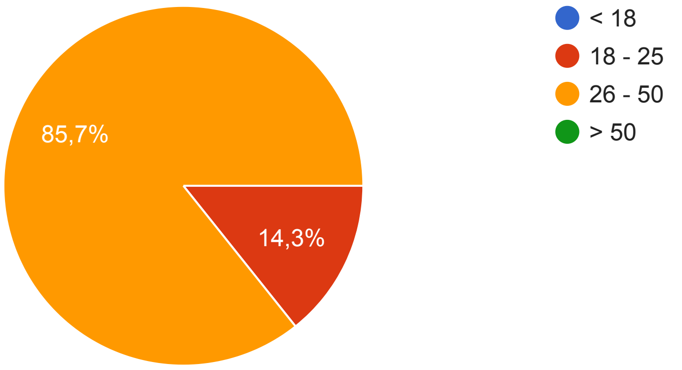
14 réponses



Are you familiar with the concept of Information Visualisation?

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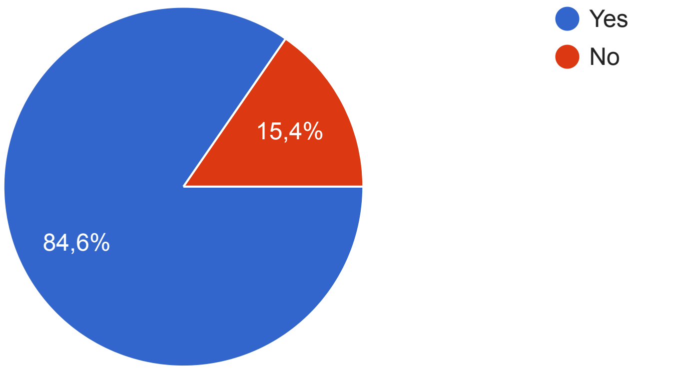
13 réponses



Are you familiar with the concept of Data physicalisation?

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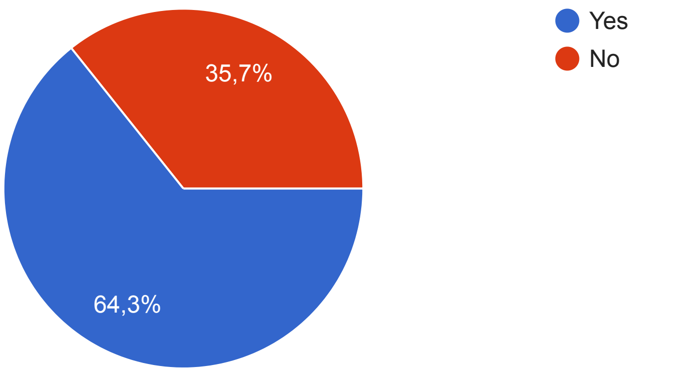
14 réponses



Have you ever used any Augmented Reality device or Application?

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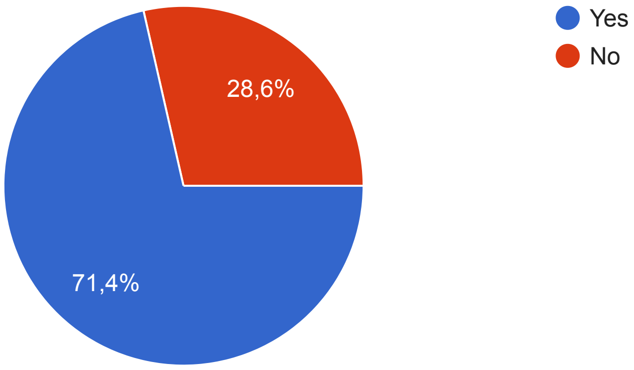
14 réponses



Have you ever interacted with spheres (ex. a globe) either physically or virtually?

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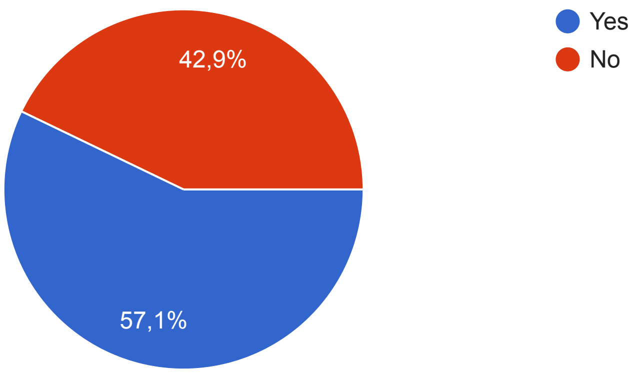
14 réponses



Have you ever performed any data analysis task?

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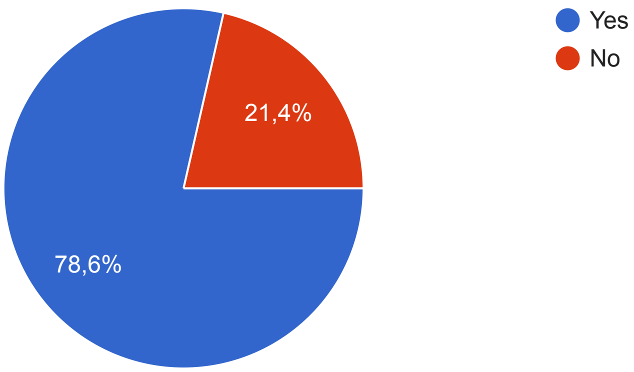
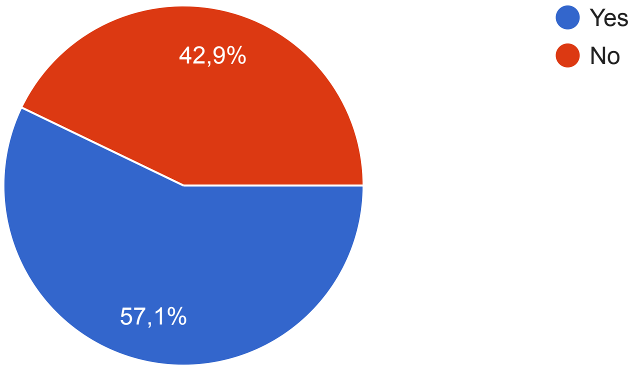
14 réponses



We expect to run this experiment between the 14-22 August 2023. Are you able to come to the VUB campus in Brussel during this period?

Copier

14 réponses



Appendix B

User Experience Questionnaire Answers

Please make your evaluation now.

For the assessment of the product, please fill out the following questionnaire. The questionnaire consists of pairs of contrasting attributes that may apply to the product. The circles between the attributes represent gradations between the opposites. You can express your agreement with the attributes by ticking the circle that most closely reflects your impression.

<u>Example:</u>

attractive	○	⊗	○	○	○	○	○	unattractive

This response would mean that you rate the application as more attractive than unattractive.

Please decide spontaneously. Don’t think too long about your decision to make sure that you convey your original impression.

Sometimes you may not be completely sure about your agreement with a particular attribute or you may find that the attribute does not apply completely to the particular product. Nevertheless, please tick a circle in every line.

It is your personal opinion that counts. Please remember: there is no wrong or right answer!

Please assess the product now by ticking one circle per line.

	1	2	3	4	5	6	7		
annoying	○	○	○	⊗	○	○	○	enjoyable	1
not understandable	○	○	○	○	⊗	○	○	understandable	2
creative	○	○	⊗	○	○	○	○	dull	3
easy to learn	○	○	⊗	○	○	○	○	difficult to learn	4
valuable	○	○	⊗	○	○	○	○	inferior	5
boring	○	○	○	⊗	○	○	○	exciting	6
not interesting	○	○	○	⊗	○	○	○	interesting	7
unpredictable	○	○	⊗	○	○	○	○	predictable	8
fast	○	○	○	⊗	○	○	○	slow	9
inventive	○	⊗	○	○	○	○	○	conventional	10
obstructive	○	○	○	○	⊗	○	○	supportive	11
good	○	⊗	○	○	○	○	○	bad	12
complicated	○	○	○	○	⊗	○	○	easy	13
unlikable	○	○	○	○	⊗	○	○	pleasing	14
usual	○	○	○	○	⊗	○	○	leading edge	15
unpleasant	○	○	○	○	○	⊗	○	pleasant	16
secure	○	○	○	⊗	○	○	○	not secure	17
motivating	○	⊗	○	○	○	○	○	demotivating	18
meets expectations	○	○	○	⊗	○	○	○	does not meet expectations	19
inefficient	○	○	○	○	⊗	○	○	efficient	20
clear	○	⊗	○	○	○	○	○	confusing	21
impractical	○	○	○	○	○	⊗	○	practical	22
organized	○	○	⊗	○	○	○	○	cluttered	23
attractive	○	○	⊗	○	○	○	○	unattractive	24
friendly	⊗	○	○	○	○	○	○	unfriendly	25
conservative	○	○	○	○	○	○	⊗	innovative	26

Please assess the product now by ticking one circle per line.

	1	2	3	4	5	6	7		
annoying	○	○	○	○	○	○	●	enjoyable	1
not understandable	○	○	○	○	○	●	○	understandable	2
creative	●	○	○	○	○	○	○	dull	3
easy to learn	○	●	○	○	○	○	○	difficult to learn	4
valuable	●	○	○	○	○	○	○	inferior	5
boring	○	○	○	○	○	○	●	exciting	6
not interesting	○	○	○	○	○	○	●	interesting	7
unpredictable	○	○	○	○	○	●	○	predictable	8
fast	●	○	○	○	○	○	○	slow	9
inventive	●	○	○	○	○	○	○	conventional	10
obstructive	○	○	○	○	○	○	●	supportive	11
good	●	○	○	○	○	○	○	bad	12
complicated	○	○	○	○	○	●	○	easy	13
unlikable	○	○	○	○	○	●	○	pleasing	14
usual	○	○	○	○	○	●	○	leading edge	15
unpleasant	○	○	○	○	○	○	●	pleasant	16
secure	●	○	○	○	○	○	○	not secure	17
motivating	●	○	○	○	○	○	○	demotivating	18
meets expectations	●	○	○	○	○	○	○	does not meet expectations	19
inefficient	○	○	○	○	○	○	●	efficient	20
clear	●	○	○	○	○	○	○	confusing	21
impractical	○	○	○	○	○	●	○	practical	22
organized	●	○	○	○	○	○	○	cluttered	23
attractive	●	○	○	○	○	○	○	unattractive	24
friendly	○	●	○	○	○	○	○	unfriendly	25
conservative	○	○	○	○	○	○	●	innovative	26

Please assess the product now by ticking one circle per line.

	1	2	3	4	5	6	7		
annoying	○	○	○	○	●	○	○	enjoyable	1
not understandable	○	○	○	○	●	○	○	understandable	2
creative	○	●	○	○	○	○	○	dull	3
easy to learn	○	●	○	○	○	○	○	difficult to learn	4
valuable	○	●	○	○	○	○	○	inferior	5
boring	○	○	○	○	○	●	○	exciting	6
not interesting	○	○	○	○	○	●	○	interesting	7
unpredictable	○	○	○	○	○	●	○	predictable	8
fast	○	●	○	○	○	○	○	slow	9
inventive	○	○	●	○	○	○	○	conventional	10
obstructive	○	○	○	○	○	●	○	supportive	11
good	○	●	○	○	○	○	○	bad	12
complicated	○	○	○	○	○	●	○	easy	13
unlikable	○	○	○	○	○	●	○	pleasing	14
usual	○	○	○	○	○	●	○	leading edge	15
unpleasant	○	○	○	○	○	●	○	pleasant	16
secure	○	○	○	●	○	○	○	not secure	17
motivating	○	●	○	○	○	○	○	demotivating	18
meets expectations	○	●	○	○	○	○	○	does not meet expectations	19
inefficient	○	○	○	○	○	●	○	efficient	20
clear	○	●	○	○	○	○	○	confusing	21
impractical	○	○	○	○	○	●	○	practical	22
organized	○	●	○	○	○	○	○	cluttered	23
attractive	○	●	○	○	○	○	○	unattractive	24
friendly	○	●	○	○	○	○	○	unfriendly	25
conservative	○	○	○	○	○	●	○	innovative	26

Appendix C

Data Analysis Answers

Data Analysis Using Sphere Burst

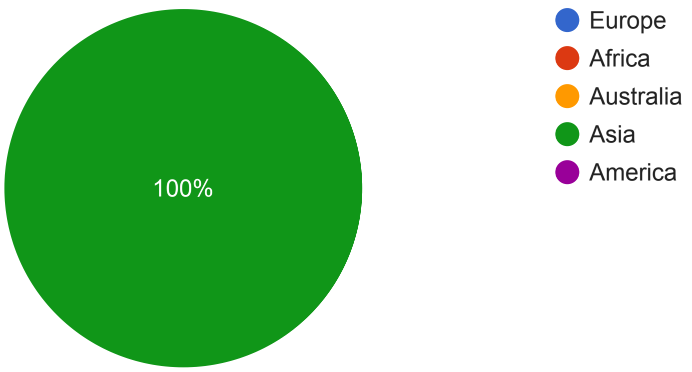
3 réponses

Publier les données analytiques

What is the region with the highest Co2 emission?

Copier

3 réponses



Between Australia and Europe, which region has the highest average annual temperature?

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3 réponses