FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Application of Multisensory Interfaces in Immersive Analytics

Miguel Silveira Rosa

Mestrado em Engenharia Informática e Computação

Supervisor: Daniel Castro Silva

Co-supervisor: Daniel Garrido

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Abstract

Current data is increasingly expanding in both quantity and diversity. But data alone is not enough. Data needs to be processed and analyzed so that knowledge can be extracted from it.

This thesis discusses immersive analytics, more specifically an implementation of immersive analytics that uses a multisensory interface to make a more immersive experience.

Immersive analytics is a field that uses virtual reality to analyze data. The main objective of the multisensory interface is to transform data into different senses. The interface uses sound and vibrations to communicate data.

The sound part of the interface uses sonification. Sonification uses sound as a means of transmitting information. In this work, the data is transformed into instrument notes or the duration of each note, encoding the data into sonified data.

The vibrations encode binary variables and transmit a short or long pulse of vibrations.

An experience comparing the interface with a visual-only interface was made to test the interface. In the end, the participants experienced both the interfaces and gave their subjective experiences.

With the results of the experience, the multisensory interface had a better performance than the visual-only interface in the subjective evaluation of the participants. The data also suggests that multisensory interfaces make the person's interaction with the data more engaging, making it a type of interface with much potential to make the analysis more interactive and stimulating.

Keywords: Immersive Analytics, Multisensory, Sonification

Resumo

Os dados atuais estão se expandindo cada vez mais em quantidade e diversidade. Mas os dados por si só não são suficientes. Os dados precisam ser processados e analisados para que o conhecimento possa ser extraído deles.

Esta tese discute a análise imersiva, mais especificamente uma implementação de análise imersiva que usa uma interface multissensorial para tornar uma experiência mais imersiva.

A análise imersiva é um campo que usa a realidade virtual para analisar dados. O principal objetivo da interface multissensorial é transformar dados em diferentes sentidos. A interface usa som e vibrações para comunicar dados.

A parte de som da interface usa sonificação. A sonificação usa o som como meio de transmissão de informações. Neste trabalho, os dados são transformados em notas de instrumento ou na duração de cada nota, codificando os dados em dados sonificados.

As vibrações codificam variáveis binárias e transmitem um pulso curto ou longo de vibrações.

Uma experiência comparando a interface com uma interface somente visual foi feita para testar a interface. Ao final, os participantes vivenciaram ambas as interfaces e deram suas experiências subjetivas.

Com os resultados da experiência, a interface multissensorial teve melhor desempenho do que a interface somente visual na avaliação subjetiva dos participantes. Os dados também sugerem que as interfaces multissensoriais tornam a interação da pessoa com os dados mais envolventes, tornando-se um tipo de interface com muito potencial para tornar a análise mais interativa e estimulante.

Plavras chave: Análise imersiva, Multissensorialidade, Sonificação

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U. PORTO

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Miguel Silveira Rosa

"Until I began to learn to draw,
I was never much interested in looking at art."

Richard P. Feynman

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Abbreviations

2D	Two dimensional
3D	Three dimensional
HMD	Head-mounted display
IATK	Immersive Analytics Toolkit
PC	Personal computer
RQ	Research question
UEQ	User experience questionnaire
VRTK	Virtual Reality Toolkit
VR	Virtual reality

Chapter 1

Introduction

Existing data is increasingly expanding in both quantity and diversity. But data alone is not enough. Data needs to be processed and analyzed to extract knowledge from it. To that end, analysts need new and better ways to analyze data.

The first step to analyzing data is to do a visualization of it. It is possible to see the data and its distribution with a good visualization. Sometimes, a simple visualization cannot offer every piece of information about the data, especially in complex datasets. To mitigate this problem, we need analytics.

Analytics is a computational analysis of data. But even with analytics and a good 2D visualization of the data, understanding data and its relations and retrieving conclusions from it can be challenging. When analyzing high dimensional data, a part of the information can be obstructed by the natural limitations of the 2D environment [Ens et al., 2021]. To overcome this problem, we can use Immersive analytics.

Immersive Analytics ([Marriott et al., 2018]) is an area of analytics that uses an immersive environment for better performance, usually using virtual or augmented reality, consisting of 3D visualizations to better understand the data and its relations. These visualizations typically rely on sight exclusively, potentially causing visual overloads. To reduce the possibility of causing visual overloads, we can reduce the amount of data presented visually by utilizing other ways of showing this data. Using the other senses like sound and touch is a method already used in virtual reality (as later described in the state of the art section). Still, it does not have many developments in the field of immersive analytics.

Sonification, as described in [Hermann et al., 2011],

> "is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation."

Sonification uses sound as a means of transmitting specific information. To this end, the sound can be decomposed into variables. Usually, the sound variables used to encode data are intensity, frequency, pitch, and time. Sound can also be used to localize an object in an immersive environment

[Kuppanda et al., 2015].

Haptic interfaces utilize touch as a means of interacting with the system. They are normally used in systems that require the simulation of object manipulation. The haptic interfaces can give information about the form and the object's location, and some can even provide information about the temperature and texture of the object. A branch of haptic interfaces is the vibrotactile interface. This interface uses a motor or, more recently, Linear Resonant Actuators [Dementyev et al., 2020] to create vibrations. These can have different amplitudes, frequencies, and duration. These variations make it possible to transmit information through touch [Han and Schulz, 2020].

1.1 Objective and research questions

The main focus of this thesis is further the field of immersive analytics by integrating other senses (such as sound and touch) in a multisensorial interface. Using sonification and the vibrotactile capacities of the head-mounted display and hand tracking controllers makes it possible to create a an improved immersive analytics interface. The main objective of this new interface is to better the performance and be easier to use.

This thesis intends to answer the main question about the application of generic multisensorial interfaces and if and how they can improve immersive analytics. With this main question in mind, several research questions were defined. The following list contains the main research questions that this thesis intends to answer:

RQ01: Does multisensorial analytics provide a better analysis? The main objective of this new interface is to better the immersive analysis. So the first question that needs to be answered is if the new interface does add value to immersive analytics. The new interface can obtain value by having a faster analysis or a better one. An analysis can be better in multiple ways, including the quantity or quality of data and the time needed to analyze that data. If the user takes more time to analyze the data but can find and retain more information, it can signify that the interface incentivizes the exploration of the data.

RQ02: Can an unfamiliar user extract knowledge from the multisensorial interface? Multisensorial interfaces utilize an unorthodox way of transmitting information. This method will be something new for many users, so understanding their difficulties and how the interface helps teach these new concepts is very important to the new interface.

RQ03: Is it better to use the multisensorial interface to add information to the graph or to reinforce the data shown by it? One of the main points of using a multisensorial interface is to increase the amount of information that can be transmitted to the user. However, how to better use this potential is still unknown. The new information given by the interface can disturb the visual analysis done by the user. The capacity of the user to use the visual information and the information given by the other senses needs to be tested. If the new information is detrimental to the analysis, the interface should be used to reinforce the visual data instead of adding new information.

RQ04: Does the multisensorial interface provide immersion? One of the main points of using an immersive environment is to permit the user to immerse himself in the analyses. If the user dislikes the experience of the interface, it is very unlikely that he uses the interface to the point of being engaged. For this reason, it is important to see if the multisensorial interface is a pleasant interface that engages the user.

1.2 Methodology and Contributions

The multisensorial interface can be decomposed into three components: the visual, the sonification, and the haptic. The three components have the same objective, to help the user explore data by giving information to the user. To do this, the components need to transmit data to the user. The primary method for this task is mapping data to some characteristics of the components.

In the visual component, these characters are varied and depend on the type of graph used. For example, a line graph can have an x-axis, y-axis, z-axis (location of the point), color (value and hue), size, shape, and orientation, among others [Roth, 2017]. This interface uses the location of the point and color as the visual variables.

In the sonification component, the sound can be mapped for different sound characteristics as pitch, timber, volume, duration, harmonics, and envelope (these components are later explained in further detail in section 2.2). This interfaces uses pitch, timber and duration of the notes as the sound variables.

The haptic interface can have amplitudes, frequencies, and duration as haptic variables. The interface uses amplitude and duration as the haptic variables.

A comparison between the multisensorial and older interfaces is needed to test the new multisensory interface. The main aspects that are tested are subjective metrics, more precisely, how useful and engaging the interface is when compared with a visual-only interface.

Two test groups were designated, one that started the analyses in the visual-only scene and one in the multisensory scene, to make the comparison more reliable.

In the test, the participants were exposed to different types of datasets, some with time as variable and different sizes. Some of the graphs had more information on the multisensory than the one present by visual means. These datasets hinted at the graph type that benefits more from the interface.

1.3 Document organization

This dissertation is organized in the following way:

Chapter 2 is state of the art, being this chapter is divided into four sections: immersive analytics, sonification, haptic interfaces, and multisensorial interfaces. Chapter 3 is the implementation.

It contains the actual implementation and is divided into three sections: sound, touch, and vision. Chapter 4 is the experimental setup. It describes the experience setup, scenes, and datasets used. Chapter 5 is the results and discussion. It contains the information gathered during the experiment. Chapter 6 is the conclusion and future work.

Chapter 2

State of Art

This chapter is divided into four sections, visual, sound, touch and summary. The first three of these sections contains information about the sense, how it was explored in previous works. The final section gives an overview of the senses and how they can be used in a interface.

2.1 Visual

Vision is the most researched of the senses. In the book of [Marriott et al., 2018] chapter three, the vision is described as having three main stages, parallel processing, rapid serial processing, and visual working memory.

These stages increase in complexity and happen sequentially. The low-level properties (color, texture, lines, and movement) are extracted in parallel processing. After this, similar color and texture regions are grouped in rapid serial processing and recognized surfaces, boundaries, and relative depth of proto-objects. The visual working memory achieves conscious control, having object recognition and attention.

The book of [Marriott et al., 2018] also describes the visual elements and variables. Visual elements were originally points, lines, and areas, with more recent elements identified surfaces and volumes in 3D spaces. Visual variables are location, size, color, opacity, orientation, texture, and shape. These variables vary in effectiveness, ordering by decreasing order: size, color, motion, and shape to show categorical attributes; linear position, length, angle, area, depth, color and curvature, and volume to show ordinal attributes.

Using vision to simulate a 3D environment requires many considerations. Although vision has many variables, using them in a 3D environment can lead to misinterpretation of the data. For example, if size and position are used, a large object far away can be interpreted as a small but close object. This can happen because the visual system relies on depth cues to ascertain depth perception.

As defined in the book [Marriott et al., 2018], there are many depth cues such as data occlusion, relative size, relative density, and height in visual field. Data occlusion happens when data covers other data. Relative size occurs when two objects of the same size and in separate positions appear to have different dimensions to the user. Relative density describes the phenomenon that patterns and visual features of objects appear to be denser the more distant they are. Height in visual field refers to the ability to retrieve the distance of an object based on its relative position to the horizon. These four depth cues are often clustered as linear perspective.

2.1.1 Immersive Analytics

Immersive analytics uses Virtual or Augmented reality. It can provide the usual features of a standard visualization and it has the added benefit of immersing the user in analyzing information. Immersion helps the user to be present and emotionally engaged in the analysis. Emotional engagement and presence help when recalling information and communicating the analysis findings. [Marriott et al., 2018]

In the work of [Roberts et al.,], it is suggested to use immersive analytics to create a visual representation of archaeological sites. It is not always easy to discover the truth in archeology, requiring several theories and interpretations to conclude. Furthermore, to have a coherent picture of events, many data of different types are needed. The motive for using immersive analytics is to visualize it and interact with it collaboratively and build a spatial narrative, a story where the viewer can become part of it.

Immersive analytics does not require an expensive setup to be used correctly. As demonstrated in the work of [Butcher et al., 2016], a good experience can be achieved by using Google Cardboard and web technologies (Fig. 2.1). Web technologies were used instead of game engines because they provide efficient mechanisms for loading complex data. Using Google Cardboard (Fig. 2.2), a platform that uses a smartphone in virtual reality, allows the simulation to be experienced without specialized equipment.

In the work of [Wagner Filho et al., 2019], to minimize the sickness that commonly happens with movement in virtual reality, the simulation utilizes the desk to create the workspace. Utilizing gestures to execute commands and reducing the necessary movement to perform the tasks in the simulation (Fig. 2.3). Gestures were utilized instead of standard input to permit the utilization of different commands and facilitate the user's abstraction of these.

In the work of [Lee et al., 2021], the work uses data visceralization to give a better perception of some events. Data visceralization is the transportation of data to restore the basic understanding of units and measurement. Using VR can transmit the data in a move intuitive and immersive way. In this work, users tested many prototypes of data visualization. One of the prototypes was the speed of the 100-meter Olympic race (Fig. 2.4), where the users were inserted in the stadium to experience the athletes' speed, increasing the immersion and enriching the experience. In this work, participants experienced both the original data and the version with data visualization, and it was found that the users spent more time in the data visceralization.

In the end, it was concluded that data visualization facilitates understanding the data.

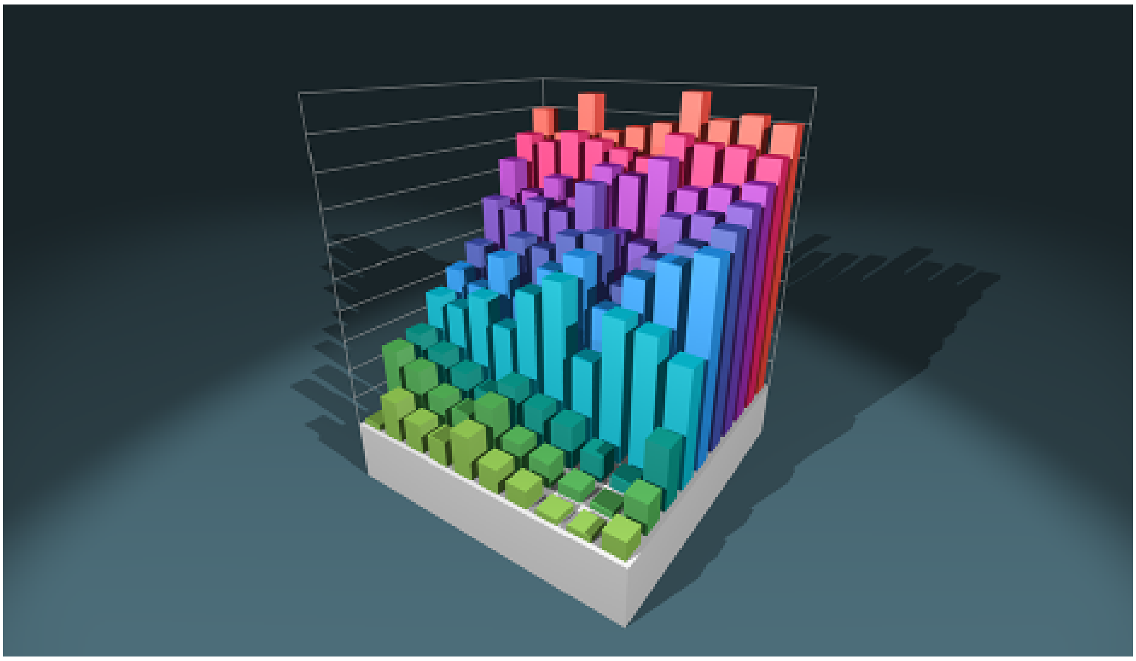


Figure 2.1: 3D visualization, retrieved/adapted from [Butcher et al., 2016]

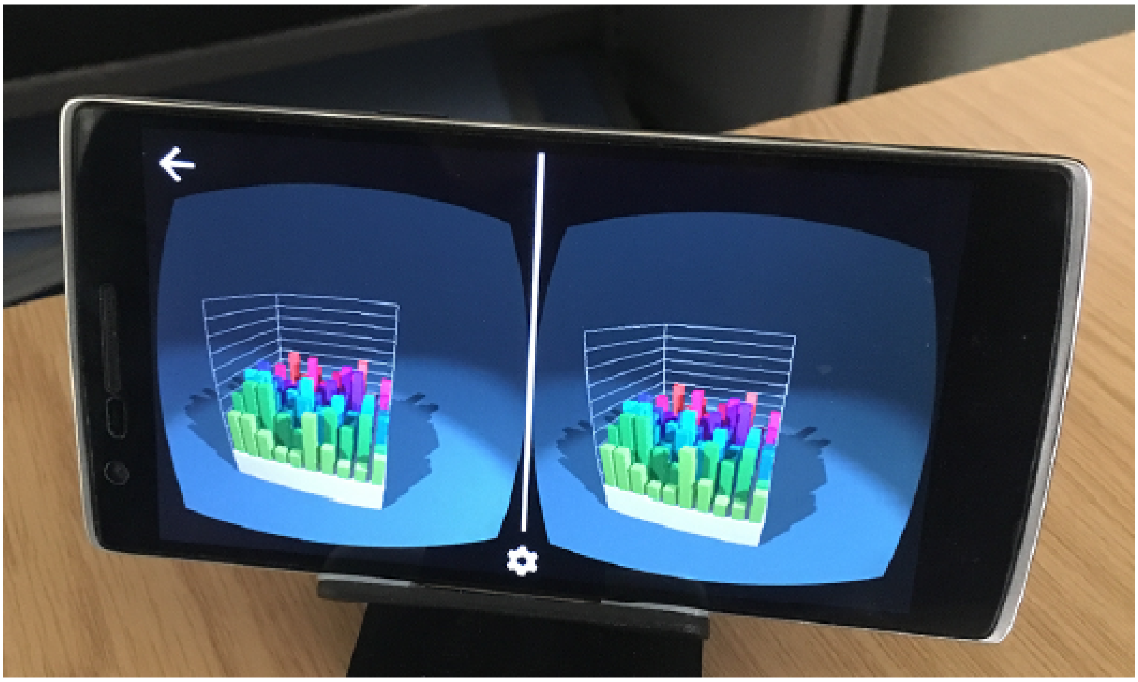


Figure 2.2: Google Cardboard, retrieved/adapted from [Butcher et al., 2016]

Figure 2.3: VitrualDesk uses gestures to interact with the visualisation, retrieved/adapted from [Wagner Filho et al., 2019]

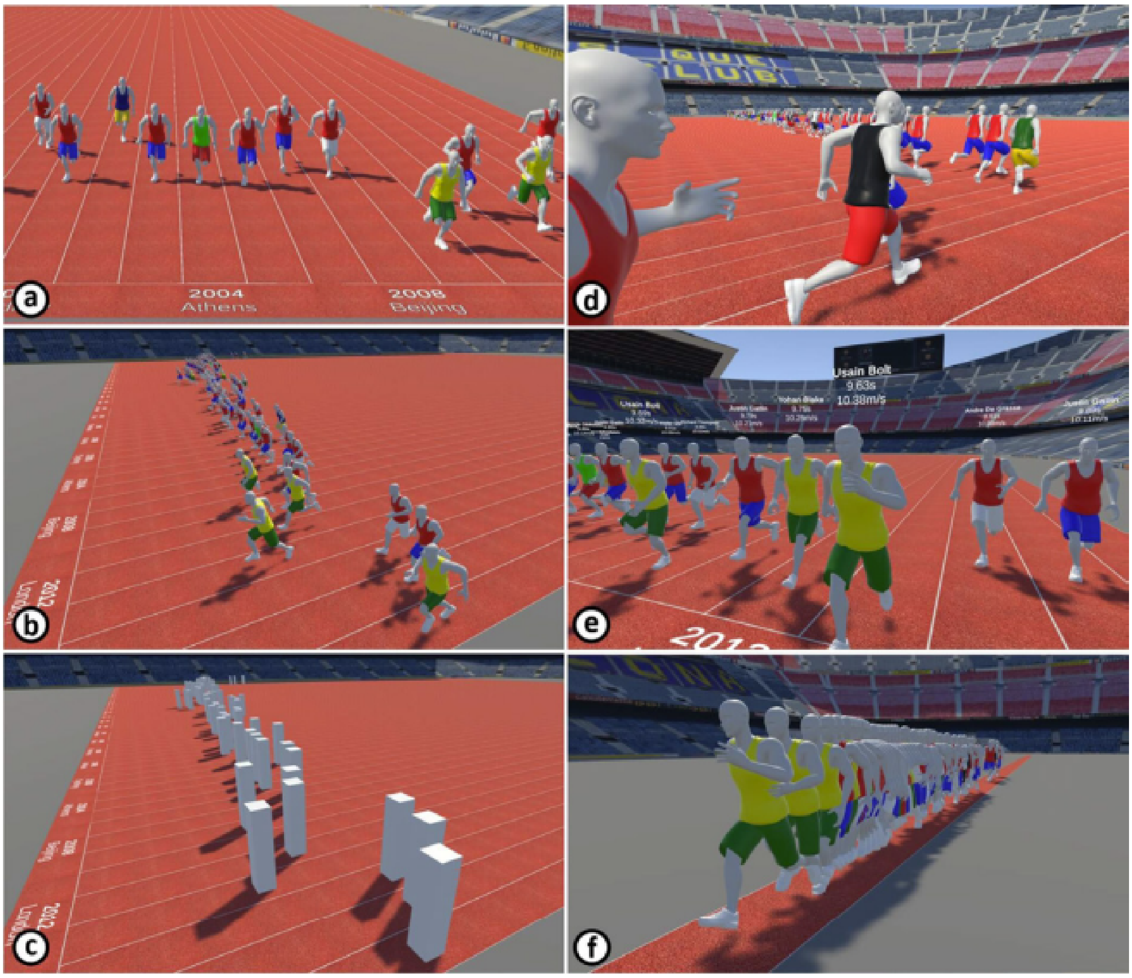


Figure 2.4: Data Visceralization of a 100-meter Olympic race, retrieved/adapted from [Lee et al., 2021]

2.1.2 Immersive Analytics toolkits

There are already many frameworks and toolkits made for immersive analytics. These can work either for game engines or websites and focus on developing graphs for the 3D environment. Some of the toolkits for the development on the web include VR-Viz [Saifee et al., 2018] and VRIA [Butcher et al., 2021], and game engines have IATK [Cordeil et al., 2019] and DxR [Sicat et al., 2019]. VR-Viz and VRIA use javascript to program a predefined set of visualizations. DxR is designed for rapid prototyping. IATK is designed for large datasets.

2.2 Sound/Sonification

Sound was one of the first senses to be explored as an alternative to visual input in data analytics. It was initially explored due to sound equipment being available and inexpensive. It also had the advantage of being a familiar structure and already having technical terms to discuss sound. [Bly, 1982]

Interfaces that use sound as the primary way of transmitting information, like the Geiger counter, the sonar, medical, and cockpit auditory displays, are great examples of sound potential. [Kaper et al., 1999] [Bonebright et al., 2010]

Sound has several parameters: pitch, volume, duration, envelope, and harmonics. Each of these variables can be used to encode information. Pitch, volume, and duration are properties that can encode a continuous variable. Envelope (that in music is described by how the sound changes over time) and different harmonics (that in music represent frequencies, musical tones, or pure tones in which each frequency is an integer multiple of a fundamental) can encode categorical variables due to their limited options. Due to time being one of the sound characteristics, sound can be used to highlight the changes in time-varying data. [Bly, 1982]

Sound also has the advantage of working regardless of the listener's position.[Bly, 1982] Contrary to Visual input that requires the full attention of the user to be utilized, sound frees the user to multitask while still receiving information.

Sound is also used to transmit information to the visually impaired. Some work has been done to transform visual graphs into sonification graphs. [Ramloll et al., 2000, Bonebright et al., 2001, Franklin and Roberts, 2003]

2.2.1 Sound in an immersive environment

When implemented in an immersive environment, sound is mainly used to localize objects or notify events in the environment.

In the work of [Rau et al., 2015], they use virtual reality to visualize a simulation of molecules and their activity. The sound is implemented to notify the users of the simulation of some events and their location during the molecular simulations. The sound increases the level of immersion in the simulation and helps users by directing their attention to events in the simulation.

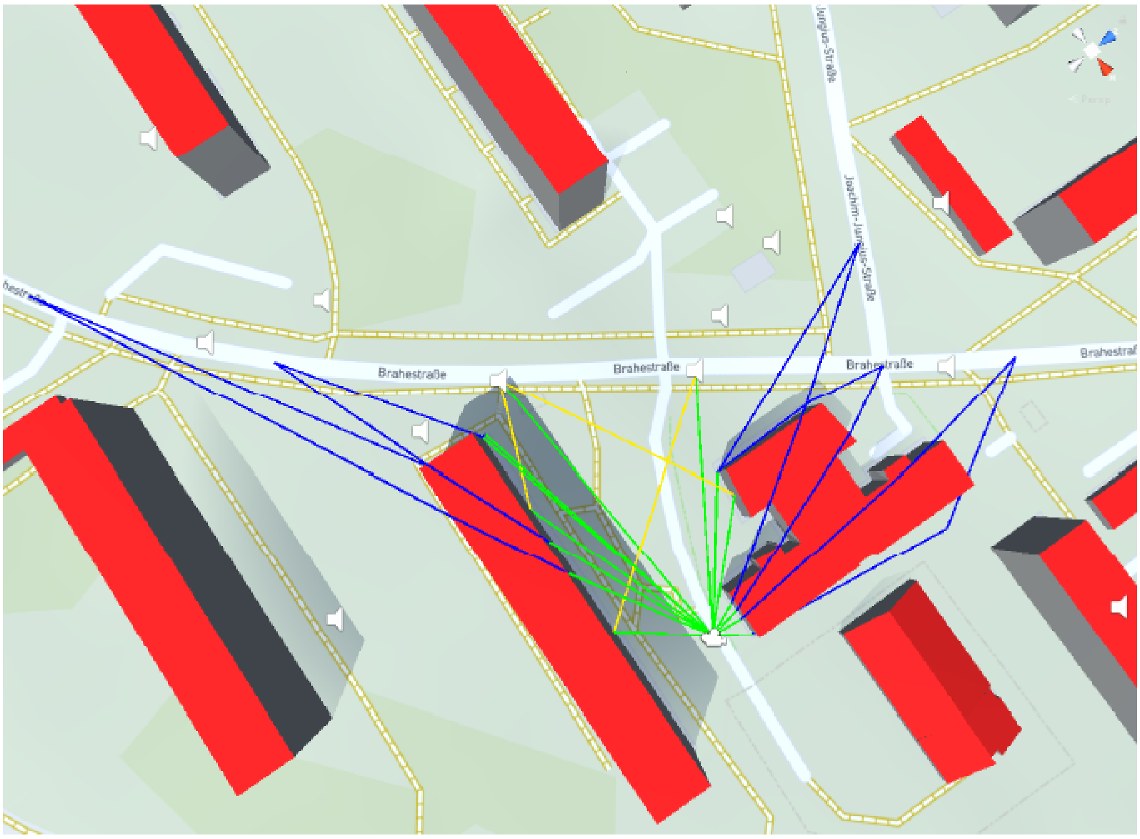


Figure 2.5: Noise propagation, retrieved/adapted from [Berger and Bill, 2019]

The work of [Kuppanda et al., 2015] tests the capacity of the sound in object localization tasks. The test was conducted in two different scenarios, one where the participant has visual stimuli and another where he is without visual feedback. In this experiment, they used three types of sound a pure tone, white noise, and a plucked sound which is "somewhat in-between the pure tone and the noise." The authors also utilized jitter, which is a simulation of the movement of the head ("Humans tend to ascertain the direction of sound source by moving their head" [Kuppanda et al., 2015]). Jitter was produced by oscillating the object, and it had a positive effect while the subjects were not blindfolded. The results were favorable, showing that sound can be utilized for this kind of task. The results also suggest that visual stimuli improve the effect of sound.

In the work of [Berger and Bill, 2019], virtual reality and sonification are used to create an immersive exploration of urban noise standards. The sound indicates the noise level in the environment and its location. Multiple calculations need to happen to simulate the sound bouncing between the walls in the environment for this feature to occur (Fig. 2.5). As a result of this, the performance of the simulation is not ideal.

2.2.2 Sonification toolkits

The available sonification toolkits were not created with immersive analytics in mind. Despite that, these tools' interfaces and functionalities are similar to the ones intended in this work. Some examples of these toolkits are SONART and SONIFICATION SANDBOX. [Walker and Cothran, 2003, Ben-Tal et al., 2002]

SONART is open-source and platform-independent. SONIFICATION SANDBOX is a cross-platform application authored in Java. Both have a collection of methods to map data to sonification parameters.

2.3 Touch

Touch is an essential sense to every human being. From brief contact to continuous touch, from different textures and temperatures to pain, touch is critical to comprehending the world and how to interact with it. In the book of [Marriott et al., 2018], the haptic sense is divided into four types of receptors: mechanoreceptors, thermoreceptors, proprioceptors, and nociceptors.

Mechanoreceptors detect indentations and vibrations on the skin, capable of sensing pressure, vibrations, and texture. Thermoreceptors detect the temperature of the objects. Proprioceptors give information about the body by providing information about the limbs and other body parts' position. Nociceptors are the receptors responsible for pain.

Haptic interfaces can be divided into two categories, data physicalization, and haptic devices. [Marriott et al., 2018]

Data physicalization is the creation of a haptic object that presents the data. Simple, tangible objects are very effective. In immersive analytics, they can become miniatures or substitutes for simulated objects. The main weakness of data physicalization is its lack of flexibility since a change in the type of data can require the creation of a new haptic object. [Marriott et al., 2018]

Haptic devices can create haptic stimuli, such as force, vibration, texture, temperature, and even pain. Due to their flexibility, they can be used for multiple purposes, such as perceiving the shape of an object and notifying an event that happened in the simulation. The following sections will focus on two types of haptic devices: force feedback and vibrotactile interfaces. [Marriott et al., 2018]

2.3.1 Force feedback interfaces

Force feedback interfaces utilize force to transmit information. This force can simulate the height and shape of an object. This interface can be used in simulations that require the manipulation of objects. This interface can be found in different hardware, such as the PHANToM arm (Fig. 2.6) and haptic glove (Fig. 2.7). [Burdea, 1999]

In the work of [Suebnukarn et al., 2009], the haptic interface is used with the purpose of bettering the education of health professionals, especially prosthodontics. To achieve this, they simulate a crown preparation task and compare the performance of professional and novices prosthodontics. They compared the time to task completion, the force used, and angulations of the bur. In the results of the tasks, the performance of the professional is better than the novices. It was possible to detect patterns between the force and angles used by professionals. The simulation has the potential to measure the clinical skill performance of prosthodontics.

Figure 2.6: PHANToM arm, retrieved/adapted from [Suebnukarn et al., 2009]

Figure 2.7: Haptic glove, retrieved/adapted from [Burdea, 1999]

In the work of [Gonzalez-Badillo et al., 2013], he uses HAMMS architecture (Haptic Assembly, Manufacturing and Machining System) to build an assembly planning and evaluation system. The HAMMS architecture comprises three elements, haptic rendering, physics simulation, and visualization module. In this implementation, various aspects of the haptic interface, such as stiffness, damping, cursor size, and friction, can be changed in real-time. This haptic interface was used to test the physics of the simulation.

2.3.2 Vibrotactile interfaces

A branch of haptic interfaces is the vibrotactile interfaces. This interface uses motor crate vibrations. These can have different amplitudes, frequencies, and duration. These variations make it possible to transmit information through touch. [Han and Schulz, 2020]

In the work of [Cheng et al., 1997], vibrotactile interface was used in virtual reality operations instead of force feedback due to it being cheaper, lighter, and easier to assemble. To test the vibrotactile interface, it was created a control group that used only visual/audio feedback. In this work it was possible to conclude that the vibrotactile/visual/audio feedback improved the performance when compared with just visual/audio feedback.

In the work of [Sziebig et al., 2009], a vibrotactile glove was created using different motors (one in each finger and one in the palm). This glove was tested in 3 capacities sensing of power, reaction time, and distinction of vibrating motors. It was discovered that a slight increase in power was noticeable, and the reaction time was almost instant, although the distinction between the motors was not an easy task.

2.4 Summary

From the done from previous works, some conclusions can be made. Vision, sound, and touch are already used in virtual reality but typically not used simultaneously. Haptic interfaces are not usually used in immersive analytics. Sound is usually used to replace the vision and not to enhance the experience.

With all the previous work done with the senses is possible to conclude that information can be encoded in the senses and that the senses can be used to transmit information. Vision has multiple variables that can be used, such as the location of the point, color, size, shape, and orientation, among others. Sound has multiple variables that can use pitch, volume, duration, envelope, and harmonics. Vibrotactile interfaces can use the vibration of the motors and their features (amplitude, frequency, and duration). With all these variables is possible to create an interface that uses these senses to transmit information to the user.

Chapter 3

Implementation

This chapter will focus on the implementation and design choices made throughout the development of this thesis. Some will compare the section 3.1 and what was realized. This chapter comprises four sections. One section is a planned solution and three detail what was done to utilize each sense.

Some parts of the implementation will specify how the user can interact with the feature. The buttons the interface uses can be found in the controller scheme, seen in Fig. 3.1.

3.1 Planned Solution

A solution can be defined with all the previous work done in the respective senses. This section is divided into two subsections: technological choices, where the technologies chosen for the project are defined, and planned features, where the initial proposal of how to integrate the other senses on the interface is described.

3.1.1 Technological choices

In terms of hardware, this interface will be developed for PC Virtual Reality, more specifically, to be used with a Head-Mounted Display. A Head-Mounted Display was chosen because of its accessibility, making it a more impactful interface. Using Google Cardboard was also considered, but it was discarded due to its weak performance. This interface will also focus primarily on conveying information to the user. Expanding how the user can use the system is beyond the scope of this dissertation. This interface will also focus primarily on sound and touch, partly because these are the most accessible with no specialized equipment needed and because these areas are already being explored in more detail than smell and taste.

In terms of software, it was planned to use a game engine to develop the interface, more specifically Unity. This decision was made due to the other works being done in Unity and easy

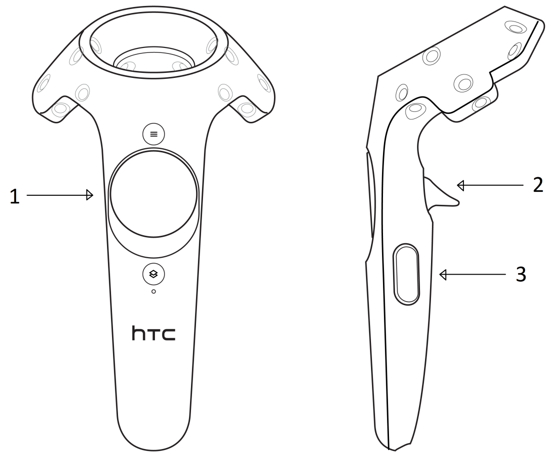


Figure 3.1: The interface uses three buttons from the controller: 1 trackpad, 2 trigger button, 3 grip button

integration with virtual reality. Also, some of the frameworks referred in state of the art (2.1.2 and 2.2.2) were planned to be used.

3.1.2 Planned features

The planned solution presented in this section is composed of a set of features that the interface must have to be capable of answering the research questions presented in the introduction. The proposed features are the following:

The main feature of this dissertation is the ability to map which information the interface transmits in each channel. The interface has visual, sonorous, and haptic channels. This feature can be further enhanced to allow the user to choose which data and components of the multisensorial interface are used to analyze the information.

Sound synthesis is one of the central points of this work. The interface needs to turn dimensions of data into sound. This task can be challenging given all the distributions that the data can have. It is expected to transform at least two data dimensions into sound, by encoding them into pitch and volume. Pitch and volume were chosen because of their extensive range and the familiarity that an average person has with these concepts (contrary to envelope and harmonics, pitch and volume are characteristics that do not require extensive musical knowledge).

Another central aspect of this work is the haptic interface. This interface needs to turn dimensions of data into vibration. At the end of this stage, the system is expected to transform one data dimension into vibration variables (amplitudes, frequencies, and duration). [Han and Schulz, 2020]

The capacity to see which dimension of data is now being used to create the multisensorial experience. This is a fundamental feature to help the user know what information they is receiving. This feature can be further improved by displaying which dimension is being used and its progression.

The user must stop, restart and rewind the shown data. This feature is essential if the user wants to reanalyze the data. Another helpful feature is being able to "jump" between the progression of the data. For example, when analyzing various categories, the user can choose which categories they wants to perceive instead of restarting.

The ability to filter or "zoom" the data. Filtering is achieved by removing some of the experience. But "zoom" requires the reprocessing of the experience so that small changes can now be more noticeable.

The ability to change the graph's position and rotate the graphs to see different angles is a relevant feature related to the visual side of the simulation.

If implemented, there are more features that will be beneficial to the immersion of the user, but they are not essential to the dissertation's main focus. Therefore the following features are considered optional:

Creating new graphs and multisensorial experience is a feature that requires a new user interface that allows the user to make the experience from the ground up.

3.2 Sound

This section describes the implementation of the sound in the interface, from the transformation of the data into sound to how the user can manipulate and interact with the sound.

3.2.1 Mapping

Some libraries and packages were used in the project to expedite the process of creating a multisensory interface. One of these libraries is jsmidgen[1] that helps in converting data into a MIDI file.

The first step of transforming the data is to confirm that all the variables have the same number of elements. After this verification, the variables' information is normalized and mapped to a specific instrument or the duration of the notes.

The information mapping depends on the number of variables to be encoded. If there are one or two variables, they are each encoded into one instrument. If there are three variables, two variables are encoded into an instrument, and one is encoded into the duration of the notes.

The number of instruments used varies with the number of variables encoded in the sound. The instruments used were a piano and an organ. Each instrument plays its notes (the value of the variable encoded in the instrument), which varies from c1 to bb5 (30 notes).

The note's duration is specified in the library as ticks, where 128 ticks represent a quarter note. It was defined as five values to the duration of the notes: sixteenth (32 ticks), eighth (64 ticks), quarter (128 ticks), half (256 ticks), and whole notes (512 ticks).

A function from jsmidgen was used to add each data point to the MIDI file. The function addNote has channel, pitch, and duration as variables, and received the note (pitch) and the note

[1] jsmidgen, a Java Script MIDI file library: https://github.com/dingram/jsmidgen

duration was variables. The channel was not changed during the mapping and was always the first channel 0. The function setInstrument was used to change between the different instruments in the track. This function has channel and instrument as variables. The instrument was changed each time a different variable needed to be represented (except if the variables were encoded in the length of the note). It was necessary to use the functions addNoteOn and addNoteOff to determine when the notes start and end to play notes simultaneously.

The original solution to mapping the sound used pitch and volume as sound variables. There were two reasons to replace the volume with timber and note duration. One of the reasons was the potential of timber to encode more variables in the future. The second reason was that volume was a variable more challenging to work with (during development, some tools/libraries, mainly the toolkits in the section 2.2.2, were tested to transform information into sound, but none of the tested permitted the change in the volume).

After the MIDI file is created, it is added in the library created by the toolkit Maestro[2]. This toolkit is used for the sound manipulation done by the sound interface described in the next subsection.

3.2.2 Sound interface

A sound interface (soundboard) was created to help the user with sound exploration and manipulation. This interface includes basic operations, the ability to focus on a specific part of the song, manipulating the song's speed, and enabling or disabling the song animation.

Basic operations (Fig. 3.2) include play, pause, stop, and restart. The play also works as an unpause if the sonified data is paused; this redundancy was made to create a more intuitive interface. With the objective of helping immerse the user, an animation of the buttons being pressed was made.

The focus and speed manipulation utilize a slider to give a better range of values. The speed (Fig. 3.3a) has five speed values: a quarter, a half, normal, one and half times, and two times speed. The focus (Fig. 3.3b) has an upper and lower handle that can be adjusted from values from zero to one. These values correspond to the various moments of the song, being zero at the beginning and one at the end. This feature was implemented to allow the user to access a more selective part of the data.

The basic operations and the focus and speed manipulation were achieved by using functions available in the toolkit Maestro. This toolkit contains functions that allow the manipulation of the sound of the midi file.

The sound animation (Fig. 3.4) is the bridge that connects the sound to the visual. The animation changes the colors of the graph to display the points that were played and the current point being played in the song (Fig. 3.4a). This feature was developed to help the user connect the audio with the visual in one congruent experience. To activate or deactivate the animation, the user need to interact with the animation board (Fig. 3.4b). The animation is on by default. When

[2]Maestro, MIDI player tool kit https://assetstore.unity.com/packages/tools/audio/maestro-midi-player-tool-kit-free-107994

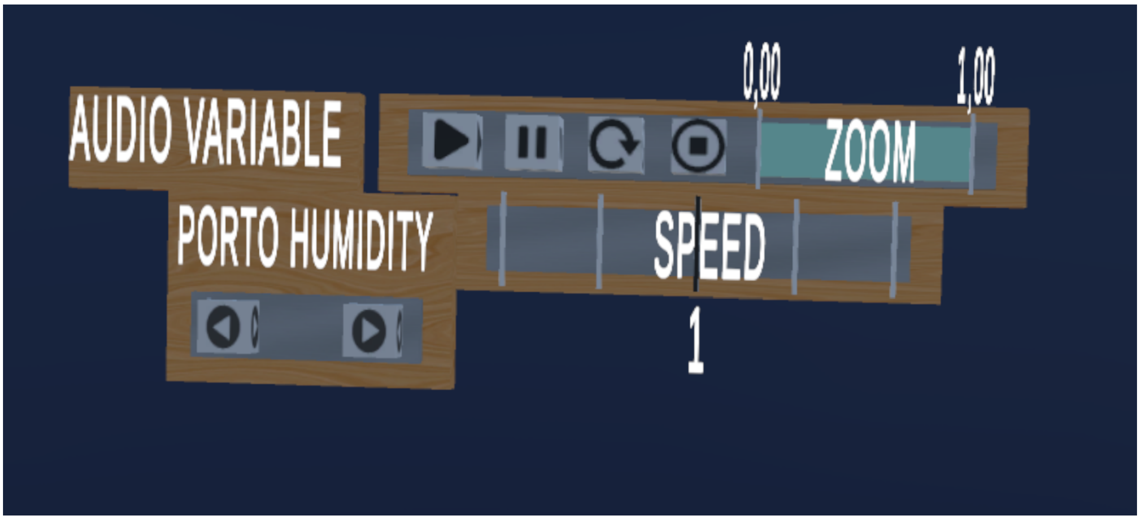


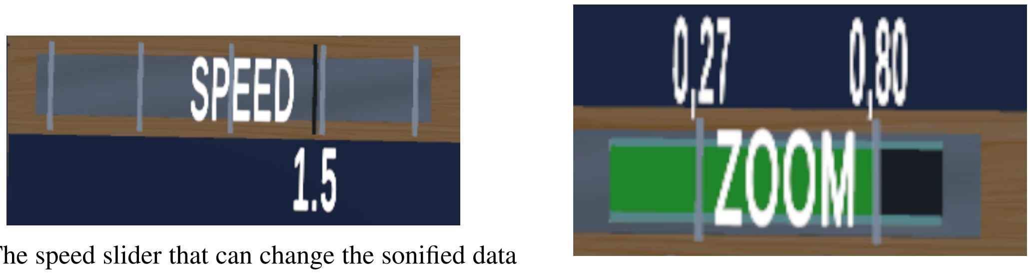
Figure 3.2: The soundboard has four basic buttons from left to right: play, pause, reset and stop.

deactivated, only the point that is being played changes color; this allows the user to analyze the rest of the graph while also receiving some information about what data point is being transformed into sound.

3.2.3 Portable soundboard

The soundboard is one of the main objects of the multisensory interface. After some testing in the final scenes, it became evident that the soundboard needed to be more easily accessible. To this end, it was implemented the portable soundboard (Fig. 3.5). As the name implies, the portable soundboard is a portable version of the soundboard. This soundboard follows the left command of the player, always available to change the sound experience.

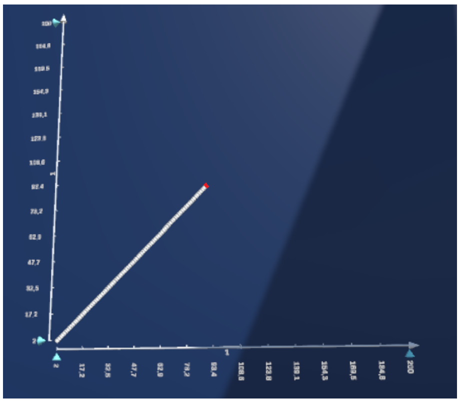
To activate or deactivate the portable soundboard, the user has to point to the graph using the trackpad (Fig. 3.6) and then press the trigger button.



(a) The speed slider that can change the sonified data speed

(b) The sonified data stopped because it reached the upper limit of the focus sliders

Figure 3.3: The soundboard has a speed slider a), and a focus slider b)



(a) Sound animation, the red point is the point being played

(b) Animation board

Figure 3.4: The sound animation a) can be deactivated or activated by the animation board b)

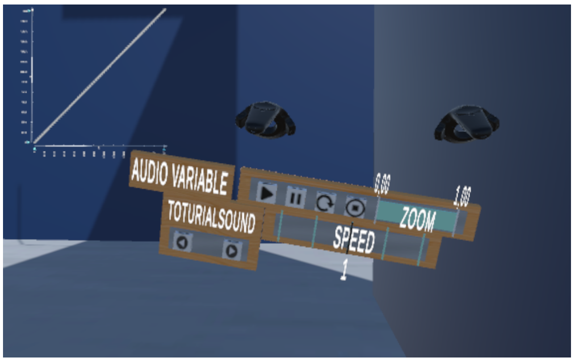


Figure 3.5: Portable Soundboard

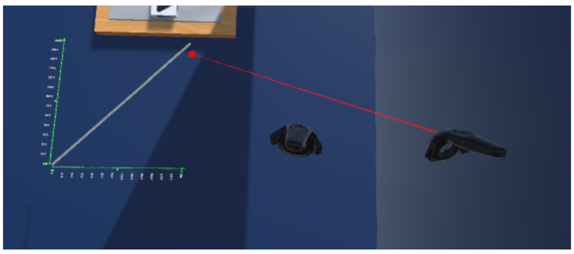
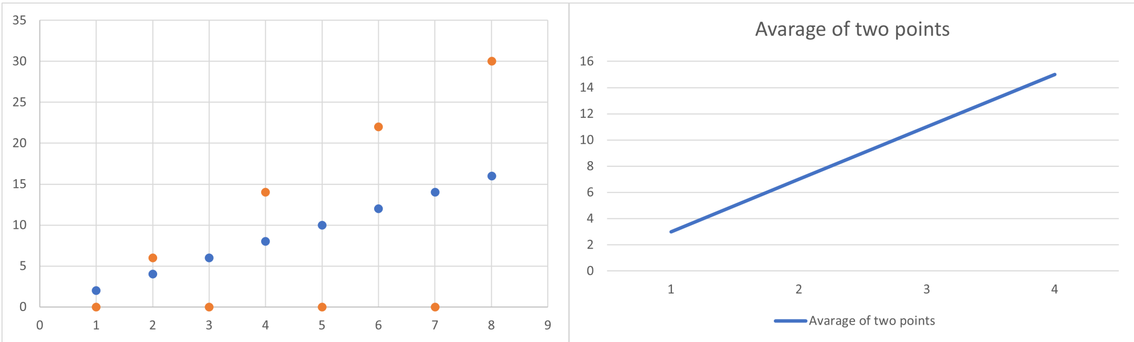


Figure 3.6: To activate the portable soundboard, first the user need to point to the graph while pressing the trackpad



(a) Example of two variables

(b) Result when making the average of two points

Figure 3.7: Although the two variables in a) are different, both have the same result in b)

3.3 Touch

In the planned solution, it was stated that the interface would use three variables to encode data: amplitudes, frequencies, and duration. The implementation diverges from this initial solution primarily due to the controllers' motor.

The motor available on the commands had less power than was initially expected. For this reason, using the force of the vibrations as a variable was not feasible. The primary variable used in the haptic experience is the vibrations' duration.

To program the vibrations values VRTK[3] was used.

It was created two types of haptic experiences: general experience encoding a variable similar to what was done with sound and a point by point or specific experience.

3.3.1 General experience

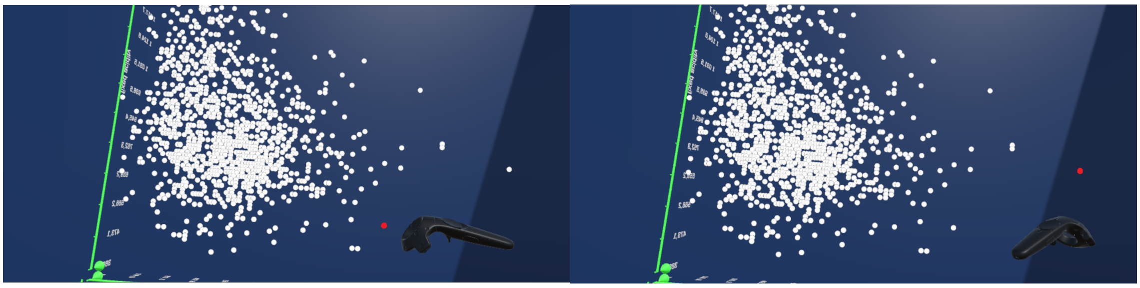
The general experience was done by normalizing the points of the variable. Due to time being a part of the haptic experience, the haptic experience was too long, especially in datasets with a lot of data. We used the average of points instead of all data points; this created a shorter experience but a less accurate one.

The general experience was not used in the experiment because it may lead to many errors while analyzing data. For example, if we group the points, many graphs with different points can create the same haptic experience, as seen in Fig. 3.7.

3.3.2 Specific experience

The specific experience was done by choosing a binary variable of the dataset. A binary variable was used due to the limitations of the motor. The main stimulus was the time of the vibration, 0.1 seconds to 1 second. In the specific experience, the user can interact with the graph choosing the particular point to be analyzed (Fig. 3.8). After selecting a specific point is possible to retrieve more information about the point, by using the trigger button.

[3]VRTK - Virtual Reality Toolkit: https://vrtoolkit.readme.io/



(a) (b)

Figure 3.8: The haptic feedback gives information about the closest point to the controller (the red point)

The VRTK allows changing three parameters of the vibration, the strength, the duration, and the interval of the vibration. The values used in the binary version were 0.6 strength, 0.1 duration, and 0.01 interval for the value of 0; and one strength, one duration, and 0.01 interval for the value of 1. The changes in strength try to differentiate the vibrations even more. These values create a short and long duration of vibrations making their distinction more manageable.

3.4 Visual

The IATK toolkit (talked about previously in the section 2.1.2) was used to create the graphs of the interface. The graphs of IATK can use the X, Y, Z-axis, and color to represent data.

To move the graphs, VRTK was used. There are two ways of moving the graph. If the user is close enough to the graph, the grip button is enough to grip the graph. The user can also use a combination of the trackpad and the grip button to move the graph from a distance.

In the experience, the graph only uses the x and y-axis and color to represent variables. The graphs are 2D instead of 3D to avoid data occlusion and permit graphs analyses from a distance.

3.4.1 Interaction visual feedback

After some testing with the interface, it was discovered that the average user could have problems knowing when to interact. For this reason, visual feedback and visual indicators were added. Visual feedback was implemented in the soundboard buttons (Fig. 3.9), the soundboard sliders (Fig. 3.10), and the graphs (Fig. 3.11). These visual indicators informed the user when the action was done (in the case of the buttons) and when the user could initiate an interaction (in the case of the slider and the graphs).

3.4.2 Haptic Details

To allow the user to retrieve specific information about a point, Haptic Details were added. The details on-demand function by giving the specific information of the closest point of the right hand, displaying this information on top of the left hand (Fig. 3.12). This feature works together

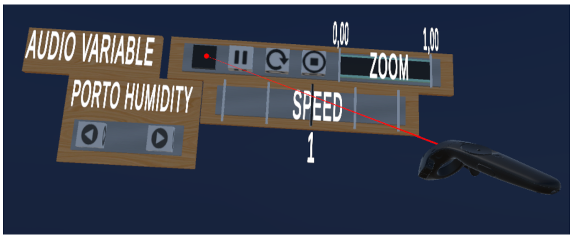


Figure 3.9: When the interaction with the button starts, the button changes color

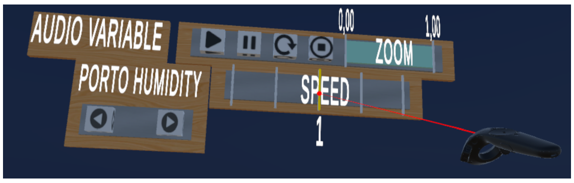


Figure 3.10: When pointing to the slider, it changes color to inform that interaction is possible

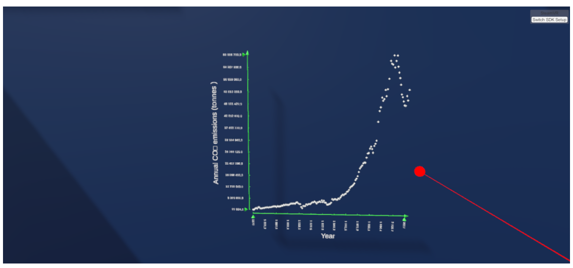


Figure 3.11: When pointing to the graph, it changes color to inform that interaction is possible

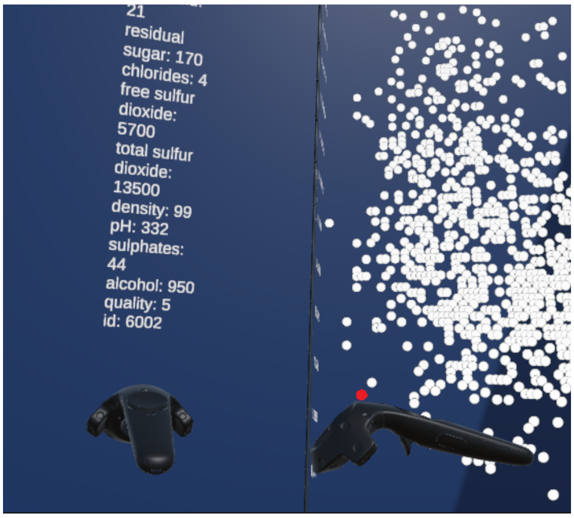


Figure 3.12: The point's information is displayed on the left hand

with the specific experience (Fig. 3.3.2) to give a complete picture of each point. To activate or deactivate the haptic details, the user can interact with the haptic details board (Fig. 3.13).

Figure 3.13: Haptic Details Board

Chapter 4

Experimental Setup

The experiment involved three scenes, one tutorial scene and two test scenes. The test scene shares the same datasets, with eight total datasets. The experiment has two versions depending on which test scene is presented first. In this experiment, to prevent the participants from becoming nauseous with the virtual reality, the experiment was done on a chair, and the sessions were kept relatively short. The experience had an estimated time of approximately 50 minutes and had the following plan:

First, the participant completes part of the experiment form. This part is relative to the participant's demographic information and consent to be in the experiment. Then the user goes to the tutorial scene to learn how to interact with the interface. This part has no time limit, and it was expected to last, on average, 15 to 20 minutes.

After this, the user goes to the first test scene to analyze and interact with the datasets. This part has a time limit of 10 minutes. A time limit was imposed to prevent the user from spending too much time in one test scene and learning all about the datasets, leaving the other test scene useless for the user.

The participant gets a little pause from the virtual reality and completes another part of the experience form. This part concerns the participant's subjective experience of the first test scene.

After the pause, the participant goes to the last test scene. The time limit and the objective are still the same as in the last test scene.

To finish the experiment, the participant completes the final part of the form. This last part is comprised of the subjective evaluation of the last scene and some open questions about the multisensorial interface.

4.1 Scenes

The experiment involves three different scenes: the tutorial scene, the visual-only scene, and the multisensory scene.

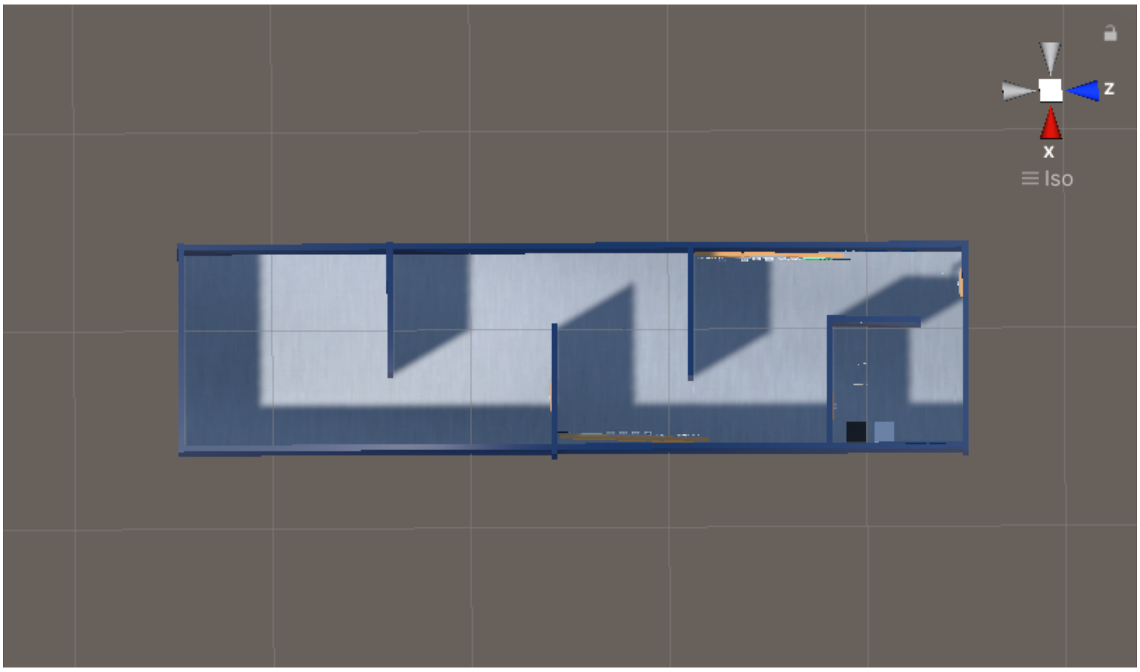


Figure 4.1: The tutorial is composed of multiple corridors, each having a lesson about components of the interface

4.1.1 Tutorial scene

This scene's primary purpose is to help the user familiarize themself with virtual reality and interact with the multisensory interface. The tutorial scene is divided into different aspects so as not to overwhelm the user with all the information simultaneously, as seen in Fig. 4.1. It first starts by explaining how to move in virtual reality and how to analyze a small graphic. Then it explains how to use the soundBoard, the animation board, and the haptic experience.

4.1.2 Visual Scene

The visual scene is one of the primary test areas. This scene comprises eight datasets (later described in this section), and each dataset can have multiple graphs. The scene is divided into two squares, each having 1 dataset per wall. The two squares are connected by tiny openings in one of the walls (Fig. 4.2).

4.1.3 Multisensory scene

The multisensory scene is the other main test area. The scene shares the same datasets and layout as the visual scene (Fig. 4.2). This decision has been made so that the datasets are not an issue while analyzing the different reactions between the two scenes. This scene also has multisensory objects that provide the user the interface necessary to analyze the datasets differently.

Figure 4.2: The test is composed of two rooms, each having one dataset in each wall

4.2 Datasets

All the datasets were acquired in Kaggle, but some were modified before being used. The main modifications were the deletion of incomplete lines and the round of the number for easier representation. The datasets belong to different categories: biological-related, weather-related, or climate-related datasets.

The rest of this section describes each dataset in its' category, number of points, number of variables, the variable's type, graphs used to describe the dataset, and which variables are transformed into sound. The graphs were composed to expose every variable of the dataset (except the mammals' sleep dataset), and the graphs of the dataset that have a time scale use the time on the x-axis (to make the analysis and sonified data easier to understand).

The graphs in this section will be described by the variables encoded in the x-axis, y-axis, and color variables (the color is optional). For example, one of the graphs in the Mammals' sleep dataset can be described as total speed time, danger, and species, meaning that the graph has encoded the total speed time on the x-axis, danger on the y-axis, and species in color.

The sonified data files' names represent what variables are represented and how they are encoded. For example, the sonified data file "Mammals body and brain weight" is a sonified data file from the Mammals' Sleep dataset and has encoded two variables, the body weight (represented in piano sounds) and brain weight (reprinted in organ sounds). If it were only one variable, it would only have piano sounds; if it had three variables, the final variable would be represented in the note length.

The original datasets are in footnotes in each dataset description. The datasets were chosen because of their size in terms of data points and having or not having time as a variable.

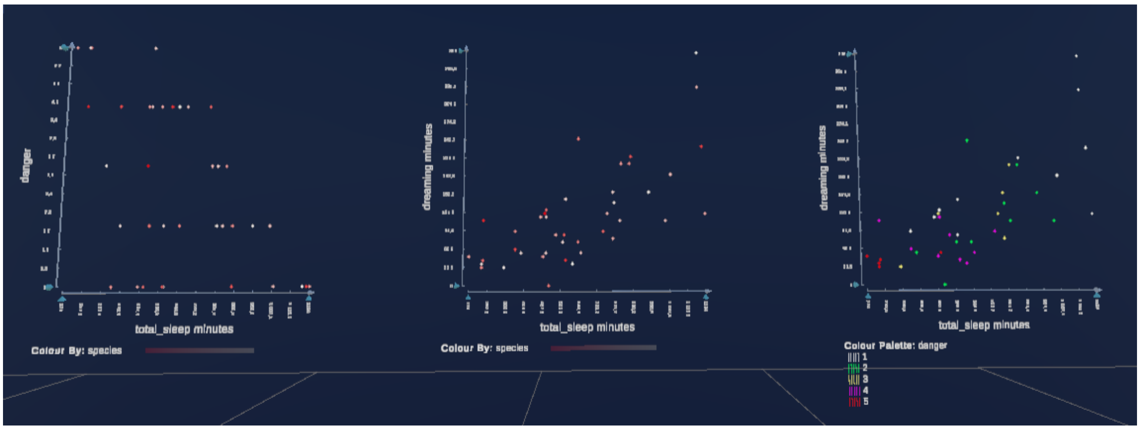


Figure 4.3: Mammals' Sleep graphs

4.2.1 Mammals' Sleep

This is a dataset[1] containing information about the mammals' sleep. It contains seven variables, of which five are continuous (weight, brain weight, dreaming time, sleep time, life span), one is Discrete (danger level), and one is nominal (the specie name). This is a small dataset counting only 43 points.

The dataset has three graphs describing it (Fig. 4.3). The first graph can be described as total sleep time, danger and species; the second as total speed time, dreaming time, and species; and the final as total sleep time, dreaming time, and danger.

The dataset has eight sonified data files containing information that is not available in the graphs. The sonified data files of this dataset are the following: Mammals body and brain weight, Mammals dreaming and danger time, Mammals sleep and body weight, Mammals sleep and danger level, Mammals sleep and life span, Mammals sleep life span and danger level, Mammals time dreaming, Mammals total sleep time.

This dataset has been chosen to be presented to see the participants' reactions with a scatter plot with a low volume of data points.

4.2.2 Penguins

This is a dataset[2] containing information about various penguin specimens. It contains 14 variables, of which one is discrete (date egg), four are continuous (culmen length, culmen depth, flipper length, and body mass), seven are nominal (study name, species, region, island, stage, sample number, and individual identification), and two are binary (clutch completion and sex). This is a medium-size dataset with 325 data points.

[1] Original dataset retrieved from: https://www.kaggle.com/datasets/volkandl/sleep-in-mammals

[2] Original dataset retrieved from: https://www.kaggle.com/datasets/parulpandey/palmer-archipelago-antarctica-penguin-data

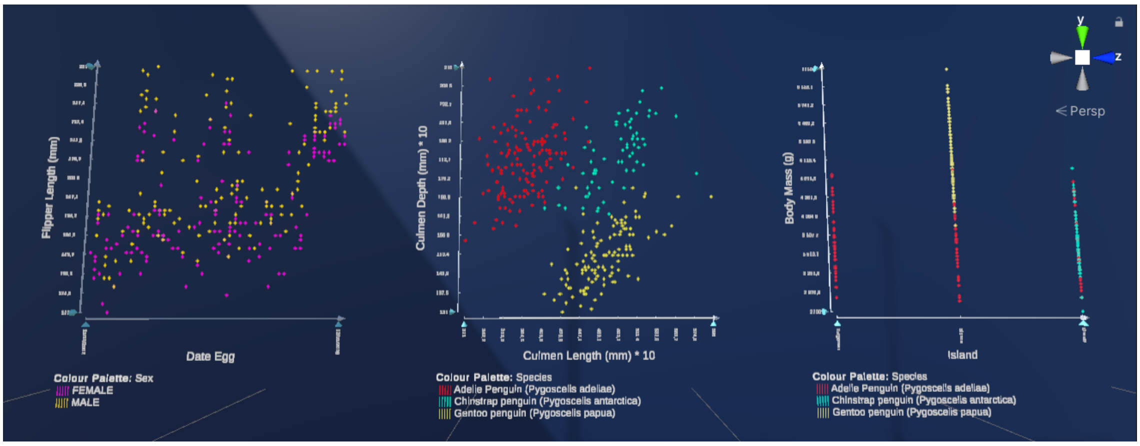


Figure 4.4: Penguins graphs

The dataset has three graphs describing it (Fig. 4.4). The first graph can be described as data egg, flipper length, and sex; the second as culmen length, culmen depth, and species; and the final as island, body mass, and species.

This dataset has six sonified data files. The sonified data files of this dataset are the following: "Penguins culmen length", "Penguins culmen depth", "Penguins culmen depth and length", "Penguins flipper length", "Penguins weight", "Penguins weight and flipper length".

This dataset has been chosen because it is a medium-size dataset containing binary variables. These variables are essential because the haptic information can only encode binary variables.

4.2.3 Iris

This is a dataset[3] containing information about various iris specimens. It contains four variables, of which four are continuous (sepal length, sepal width, petal length, and petal width) and one nominal (species). This is a small size dataset with 151 data points.

The dataset has two graphs describing it (Fig. 4.5). The first graph can be described as sepal length, sepal width, and species; the last as petal length, petal width, and species.

This dataset has six sonified data files. The sonified data files of this dataset are the following: "Iris petal length", "Iris petal length and width", "Iris petal width", "Iris sepal length", "Iris sepal length and width" and "Iris sepal width".

This dataset was chosen because it has few variables, and the distinction between iris species is clear (there is little overlap in the species traits).

4.2.4 Sloths

This is a dataset[4] containing information about various sloths specimens. It contains seven variables, four continuous (claw length, size, tail length, and weight) and three nominal (specie, subspecies, and endangered level), This is a large dataset with 4584 data points.

[3] Original dataset retrieved from: https://www.kaggle.com/datasets/uciml/iris

[4] Original dataset retrieved from: ttps://www.kaggle.com/datasets/bertiemackie/sloth-species

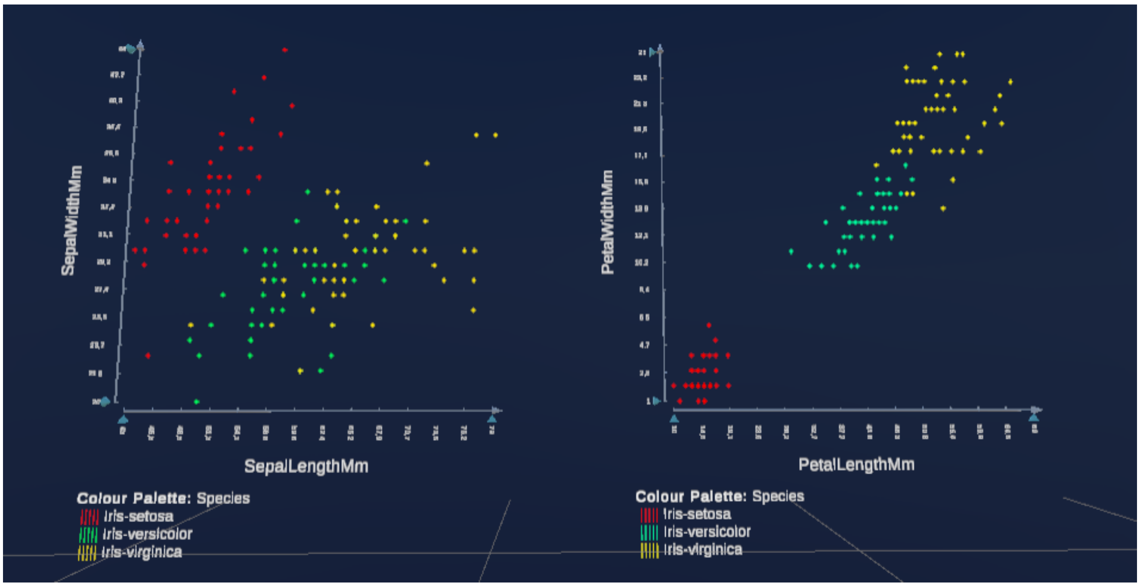


Figure 4.5: Iris graphs

The dataset has three graphs describing it (Fig. 4.6). The first graph can be described as weight, sloth size, and subspecies; the second as tail length, claw length, and subspecies; the final as subspecies, endangered level, and species.

This dataset has six sonified data files. The sonified data files of this dataset are the following: "sloth claw and tail length", "sloth claw length", "sloth size", "sloth size and weight", "sloth tail length" and "sloth weight".

This dataset was chosen because it is a large dataset.

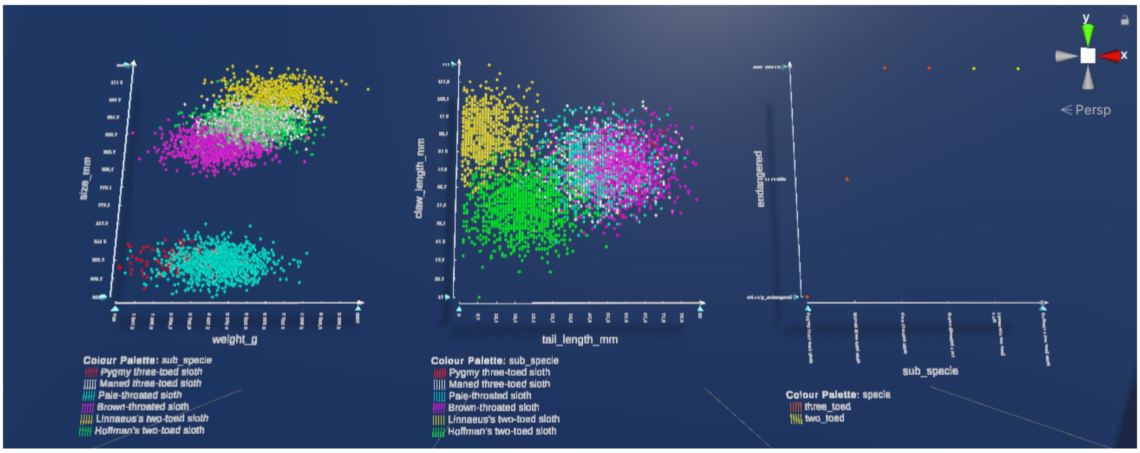


Figure 4.6: Sloths graphs

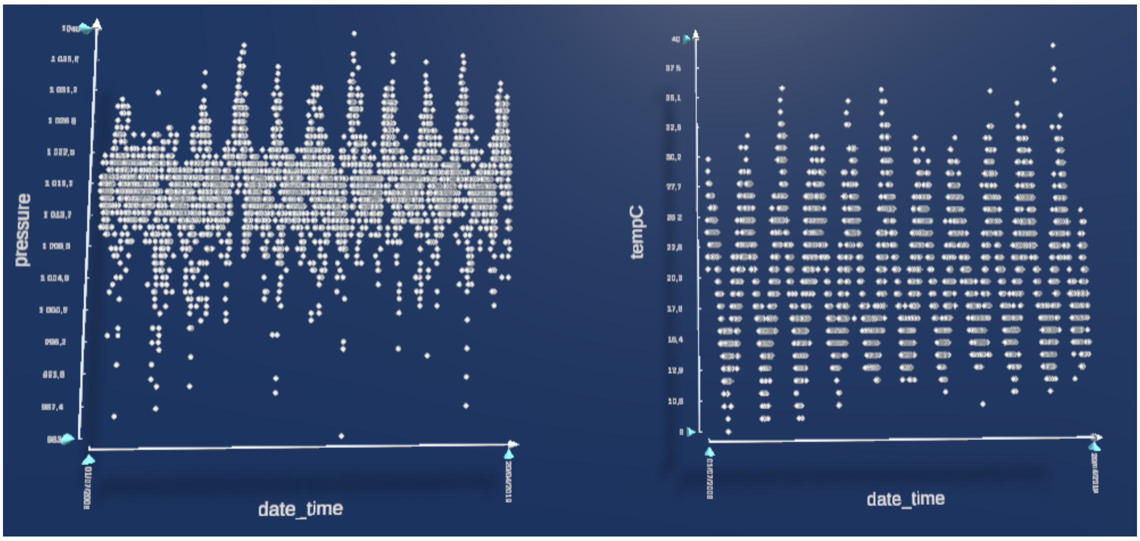


Figure 4.7: Lisbon graphs 1

4.2.5 Lisbon

This is a dataset[5] containing information about the weather in Lisbon each day. It contains five variables, and all of them are continuous (date, humidity, pressure, temperature, wind speed). This is a large dataset with 3947 points of data.

The dataset has four graphs describing it (Fig. 4.7 and Fig. 4.8). The first graph can be described as date and pressure; the second as date and pressure; the third as date and humidity; the final as date and wind speed.

This dataset has four sonified data files. The sonified data files of this dataset are the following: "Lisbon humidity", "Lisbon pressure", "Lisbon temperature," and "Lisbon winds speed".

This dataset was chosen because it is a large dataset with time as a variable. It was also chosen to allow the participant to compare this dataset with Oporto's weather dataset.

4.2.6 Oporto

This is a dataset[6] containing information about the weather in Oporto each day. It contains five variables, and all of them are continuous (date, humidity, pressure, temperature, wind speed). This is a large dataset with 3947 points of data.

The dataset has four graphs describing it (Fig. 4.9 and Fig. 4.10). The first graph can be described as date and pressure; the second as date and temperature; the third as date and humidity; the final as date and wind speed.

This dataset has four sonified data files. The sonified data files of this dataset are the following: "Porto humidity", "Porto pressure", "Porto temperature," and "Porto winds speed".

[5] Original dataset retrieved from: https://www.kaggle.com/datasets/luisvivas/spain-portugal-weather?select=lisbon.csv

[6] Original dataset retrieved from: https://www.kaggle.com/datasets/luisvivas/spain-portugal-weather?select=porto.csv

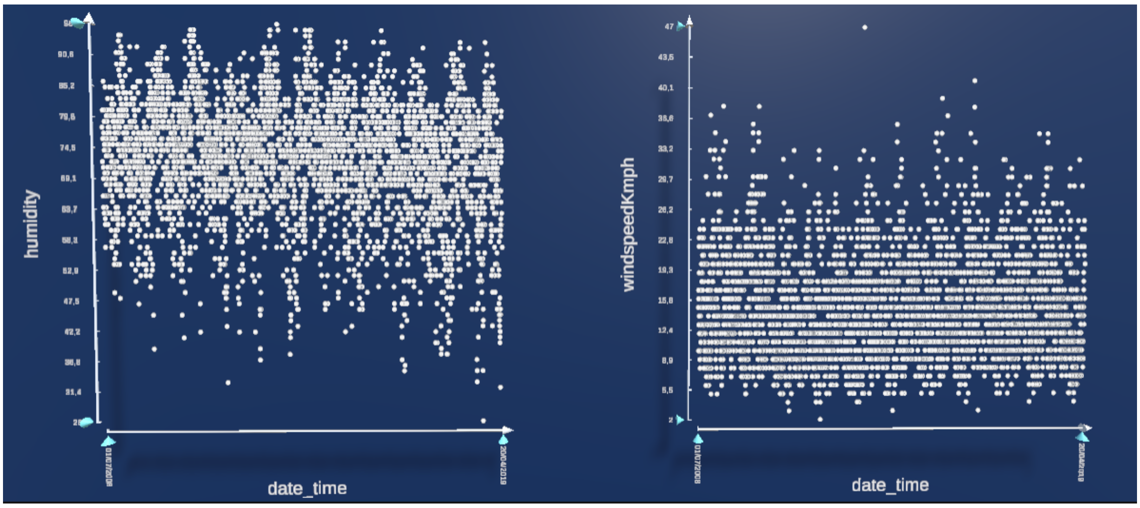


Figure 4.8: Lisbon graphs 2

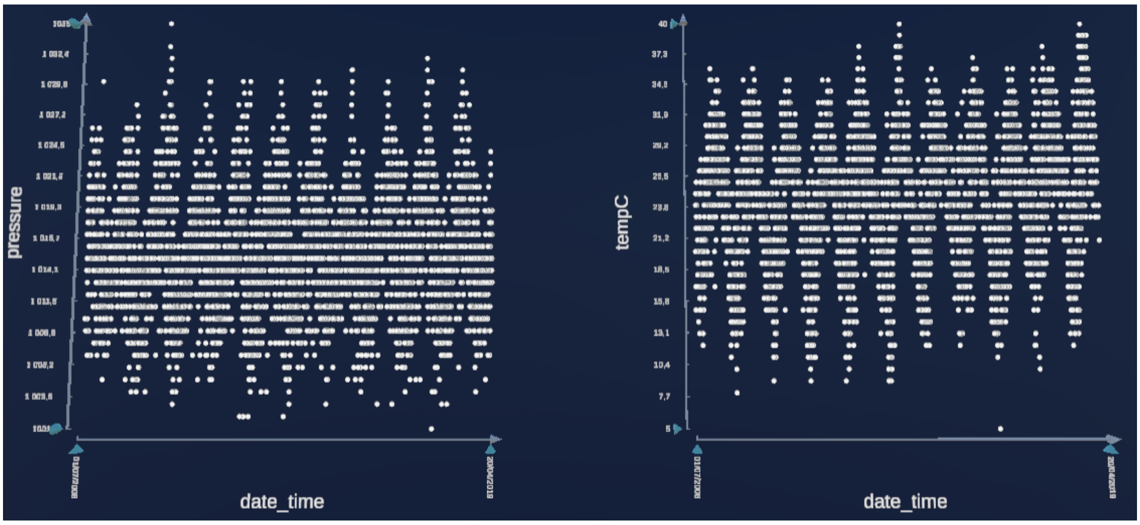


Figure 4.9: Oporto graphs 1

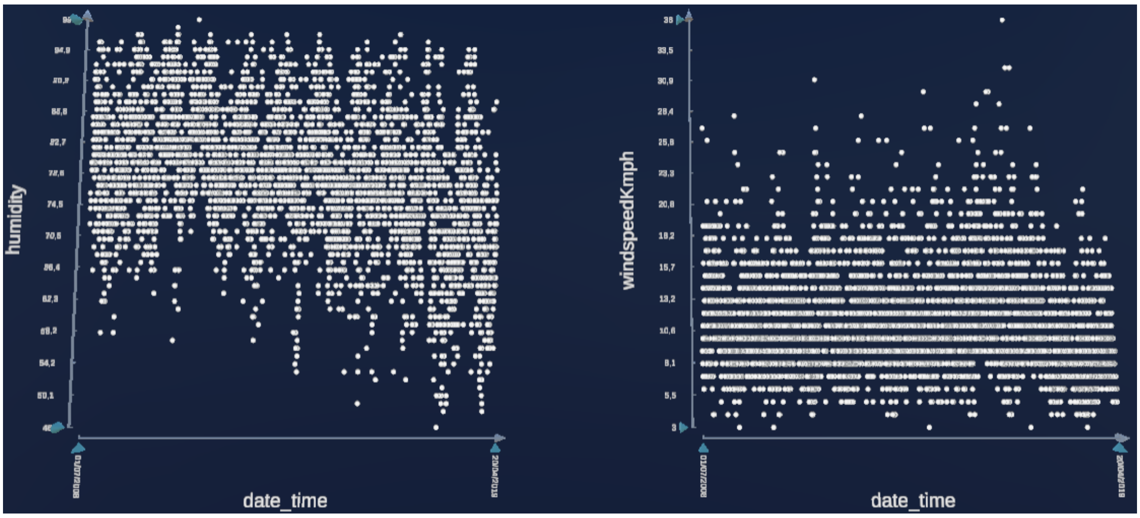


Figure 4.10: Oporto graphs 2

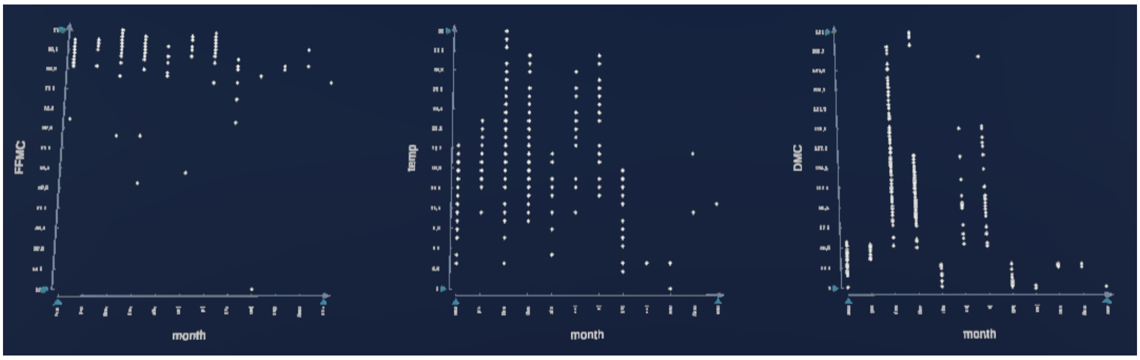


Figure 4.11: Forest fires graphs

This dataset was chosen because it is a large dataset with time as a variable. It was also chosen to allow the participant to compare this dataset with Lisbon's weather dataset.

4.2.7 Forest fires

This is a dataset[7] containing information about Portugal forest fires. It contains seven variables, one is discrete (month), and six of them are continuous (fine fuel moisture code, duff moisture code, drought code, initial spread index, relative humidity, and temperature), This is a medium-size dataset with 518 data points.

The dataset has three graphs describing it (Fig. 4.11). The first graph can be described as month and fine fuel moisture code; the second as month and temperature; the last as month and duff moisture code.

The dataset has six sonified data files, some of them contain information that is not available in the graphs. The sonified data files of these datasets are the following: "forest fires drought code", "forest fires Duff moisture code", "forest fires fine fuel moisture code", "fores initial spread index", "forest fires relative humidity", and "forest fires temperature".

This dataset was chosen because it is a medium-size dataset with time as a variable.

4.2.8 Carbon dioxide emissions

This is a dataset[8] containing information about Portugal's Carbon dioxide emissions. It contains two variables, both of which are continuous (year and annual emissions of carbon dioxide). This is a small size dataset with 149 data points.

This dataset has one graph describing it (Fig. 4.12). The graph can described as year and annual emissions of carbon dioxide.

This dataset has only one song. The song of this dataset is the "CO2 levels".

This dataset was chosen because it is a small dataset with time as a variable.

[7] Original dataset retrieved from: `https://www.kaggle.com/datasets/vikasukani/forest-firearea-datasets`

[8] Original dataset retrieved from: `https://www.kaggle.com/datasets/mathchi/co2-intensity-of-electricity-generation`

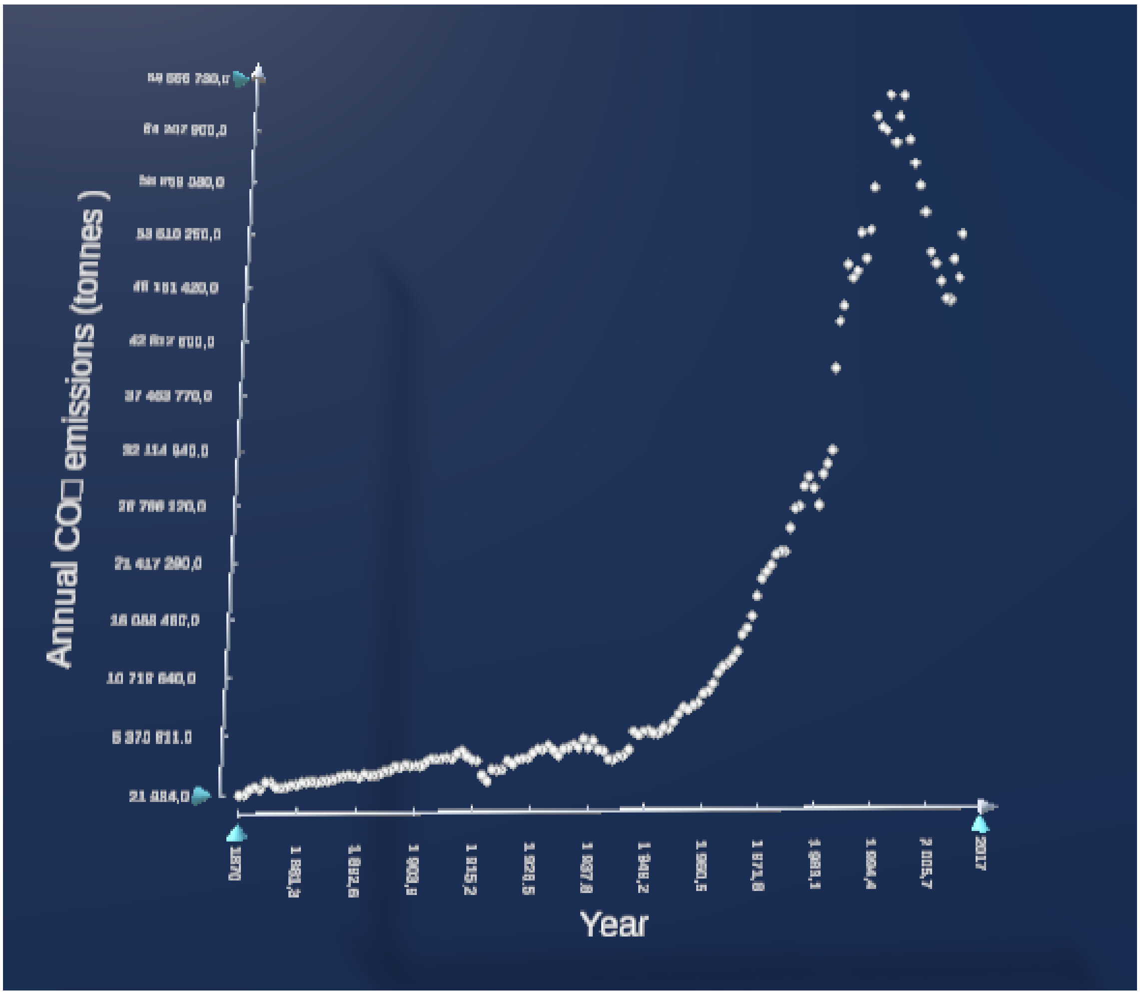


Figure 4.12: Carbon dioxide emissions graph

Chapter 5

Results and discussion

This section will explore the data collected during the experiments and discuss its meaning to the interface performance. This section is divided into three parts; the first will talk about the participants' demographic, the second will discuss the subjective evaluation of the interface, and the final will talk about the comments made about the interface.

The raw data and the results can be found in Appendix A.

5.1 Participants

There are a total of 23 participants in the experience.

Of these participants, eight were between the ages of 10-20 and 15 between the ages of 20-30,

Sixteen of the participants identifies themselves as male and seven as female.

Regarding education, 10 participants have completed high school or equivalent, nine completed Bachelors' degree, and 4 have a Master's degree.

In terms of experience with virtual reality, most participants had no prior experience, with 10 having no experience, 11 had experienced one or two times, and 2 having some experience but are not recurrent users.

Most participants did not have hearing problems, and only one had this kind of problem.

In terms of vision problems, most participants had some vision problems. Some even said that the images were a bit blurry during the experience, 15 participants had some vision problems, and 8 had no problems regarding vision.

As stated in section 4, the experience has two versions depending on which test scene the participants experience first. Eleven participants experienced the vision-only scene first, and 12 participants experienced the multisensory scene. The results of the versions will be described in the next section.

5.2 Scenes evaluations

This section will compare the subjective questions about each test scene. The experience's form has seven aspects of the interface. The participant rated the aspect from totally agree to totally disagree (5- totally agree, 4- somewhat agree, 3- indifferent, 2- somewhat disagree, and 1- totally disagree).

The aspects are the following:

1. I like the interface used.
2. The interface was engaging.
3. The interface was useful.
4. The interface help in the data analysis.
5. The data presented was interesting.
6. The data presented was hard to analyze.
7. I understand the data presented and its relations.

Each aspect will be compared in three aspects. The first two are comparisons between the participants that experience the test scene first and last to see if the order of the scenes changed the participant's subjective experience. The last aspect is a comparison between the two test scenes. These aspects were chosen to help discover the subjective performance of the interface (aspects 1, 2, 3, and 4) and if the interface changed the user perception of the datasets (aspects 5, 6, and 7).

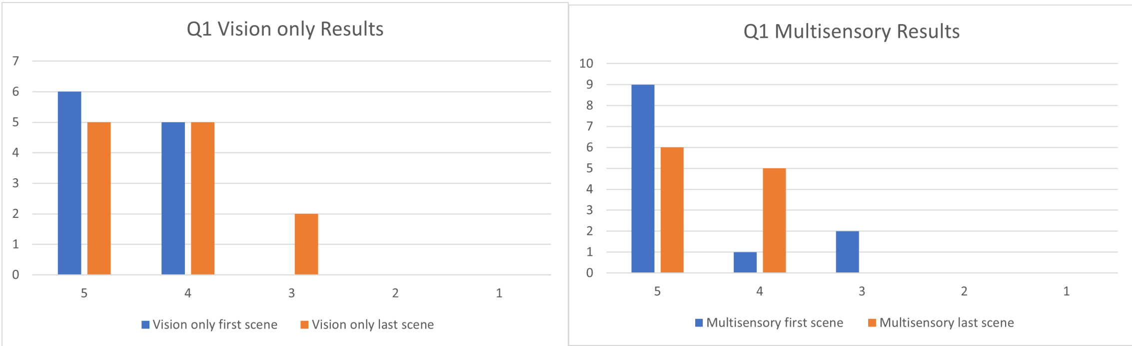
The performance of the two scenes in the first question, *I like the interface used*, can be seen in the 5.1. The vision-only test scene (Fig. 5.1a) had similar results in the two cases, although it was better when presented first. The multisensory test scene (Fig. 5.1b) had a more significant discrepancy, and the participants liked the scene when it was presented first more than when it was presented in last place.

Between the two scenes (Fig. 5.2), the multisensory was more liked than the vision-only.

The performance of the two scenes in the second question, *The interface was engaging*, can be seen in the (Fig. 5.3). In this question, the vision-only (Fig. 5.3a) was a significant discrepancy between the two scenarios; it had outstanding results when it was the first scene and mixed results when it was the last scene. The multisensory scene (Fig. 5.3b) had the inverted result; in the first, it had good results, but when presented last, it had even better results.

The two scenes were perceived as engaging (Fig. 5.4), but the multisensory performance was better than the vision-only.

The performance of the two scenes in the third question, *The interface was useful*, can be seen in the (Fig. 5.5). The vision-only scene (Fig. 5.5a) had positive results in both scenarios, although when presented first, the results were better. The multisensory scene (Fig. 5.5b) had a negative response in both scenarios, but the results overall were positive; the results when presented first were better than when presented last.



(a) Performance of the vision only scene (b) Performance of the multisensory scene

Figure 5.1: Performance of the two test scenes in the question 1

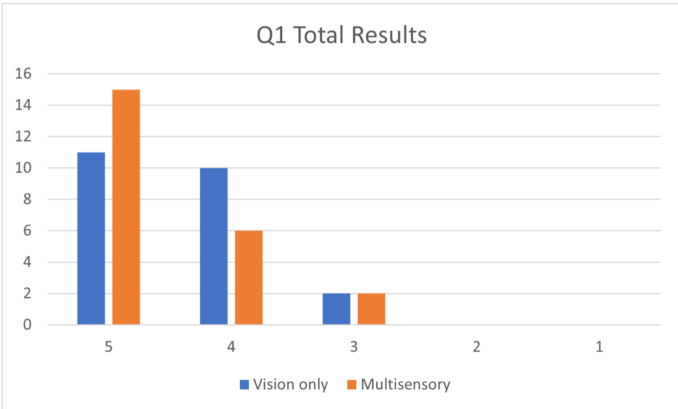
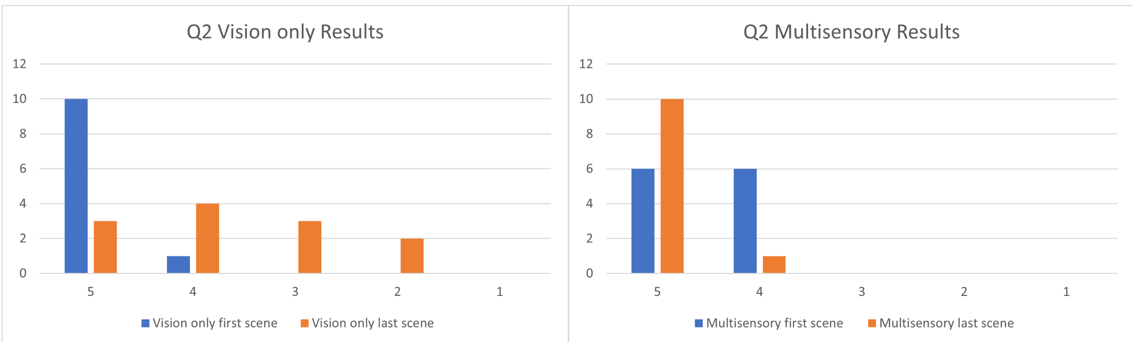


Figure 5.2: Comparison between the two test scenes in the question 1



(a) Performance of the vision only scene (b) Performance of the multisensory scene

Figure 5.3: Performance of the two test scenes in the question 2

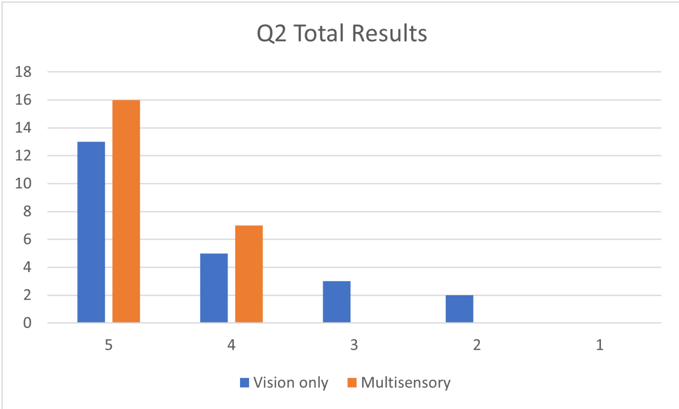


Figure 5.4: Comparison between the two test scenes in the question 2

The two scenes were perceived as useful (Fig. 5.6). The multisensory has more people that agree completely with this aspect but is also the only test scene with people disagreeing with the statement.

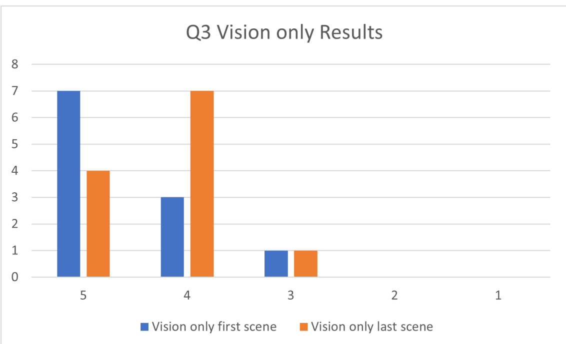
The performance of the two scenes in the fourth question, *The interface help in the data analysis*, can be seen in the (Fig. 5.7). The vision only (Fig. 5.7a) had few changes in the two scenarios, and it had favorable results. The multisensory (Fig. 5.7b) has more dispersed results but also had few changes in the two scenarios.

Comparing the two test scenes (Fig. 5.8), the vision-only had more consistent results while the multisensory scene had more dispersed answers.

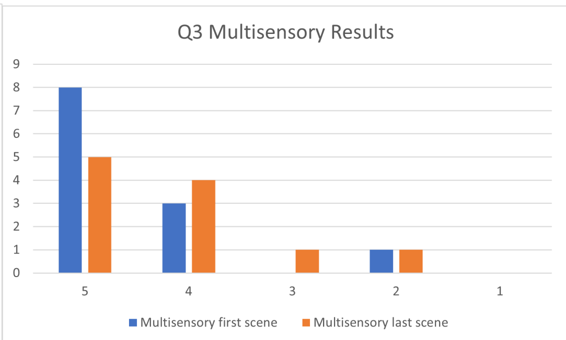
The performance of the two scenes in the fifth question, *The data presented was interesting*, can be seen in the (Fig. 5.9). The vision-only scene (Fig. 5.9a) had better results when presented last. The multisensory scene (Fig. 5.9b) had better results when presented first.

Comparing the two scenes (Fig. 5.10), the vision-only has a better result than the multisensory one.

The performance of the two scenes in the sixth question, *The data presented was hard to analyze*, can be seen in the (Fig. 5.11). This question was the most dispersed result and was



(a) Performance of the vision only scene



(b) Performance of the multisensory scene

Figure 5.5: Performance of the two test scenes in the question 3

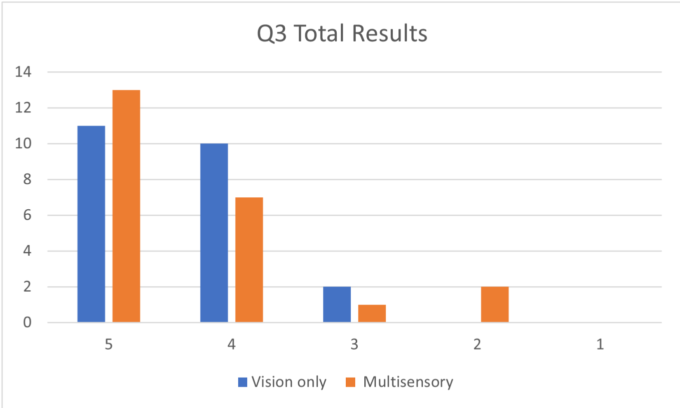
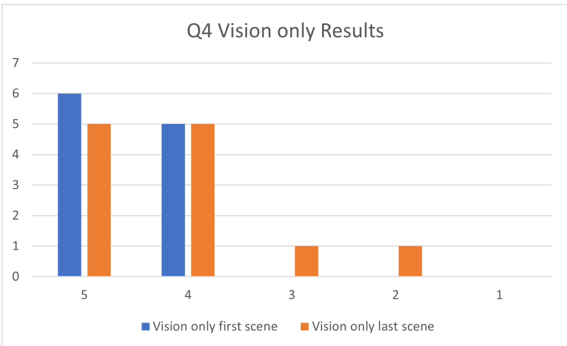
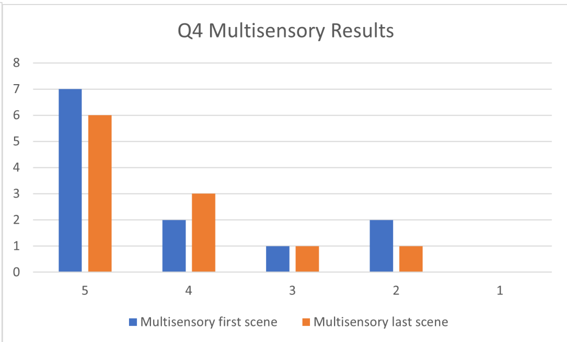


Figure 5.6: Comparison between the two test scenes in the question 3



(a) Performance of the vision only scene



(b) Performance of the multisensory scene

Figure 5.7: Performance of the two test scenes in the question 4

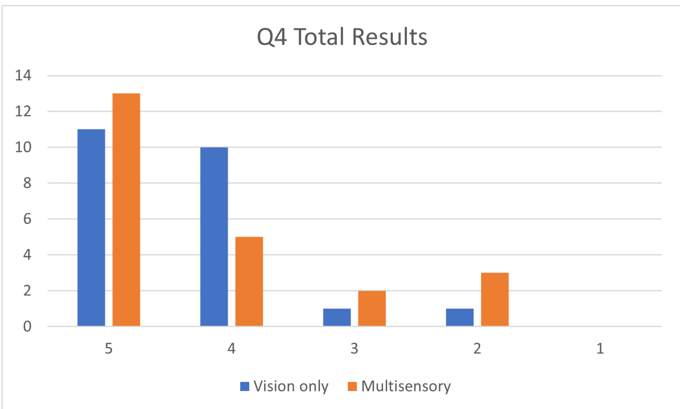
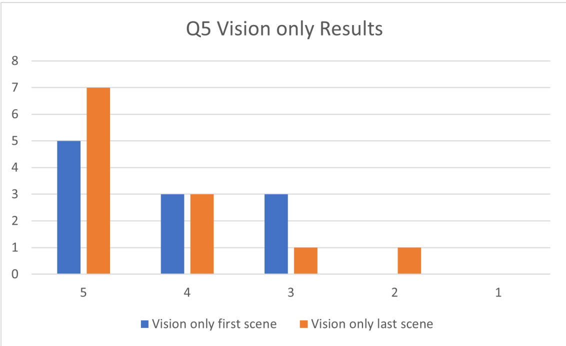
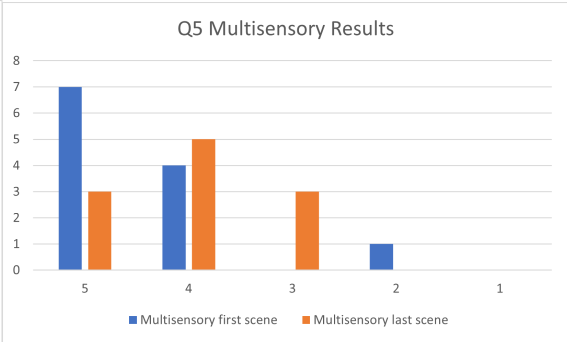


Figure 5.8: Comparison between the two test scenes in the question 4



(a) Performance of the vision only scene



(b) Performance of the multisensory scene

Figure 5.9: Performance of the two test scenes in the question 5

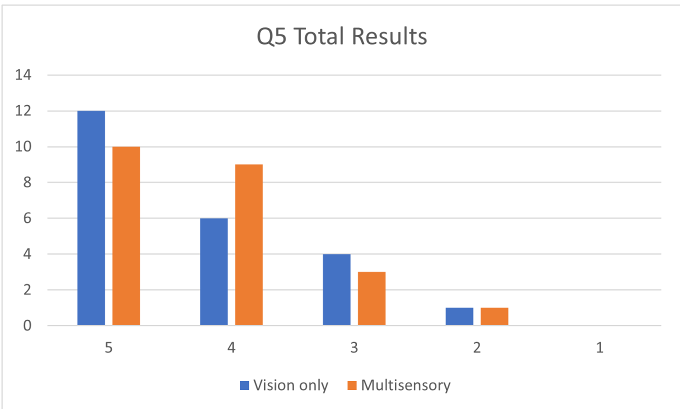
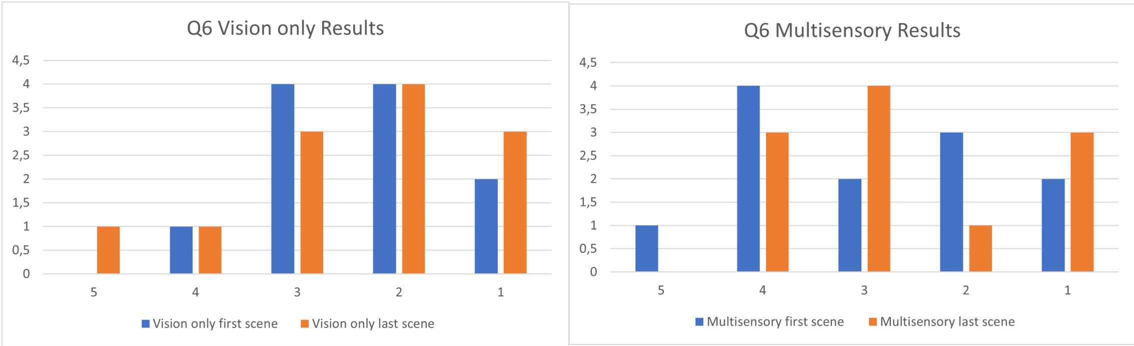


Figure 5.10: Comparison between the two test scenes in the question 5



(a) Performance of the vision only scene (b) Performance of the multisensory scene

Figure 5.11: Performance of the two test scenes in the question 6

the only question when disagreeing with the statement was positive. The vision-only scene (Fig. 5.11a) and the multisensory scene (Fig. 5.11b) had better results when presented last.

Comparing the two test scenes (Fig. 5.12), the vision-only scene has better results than the multisensory scene. This may indicate that the participants did not have time to fully prepare to use the new interface making the analyses more complex instead of making them easier.

The performance of the two scenes in the seventh question, *I understand the data presented and its relations*, can be seen in the (Fig. 5.13). The vision-only scene (Fig. 5.13a) had better results when presented last. The multisensory scene (Fig. 5.13b) had better results when presented first.

Comparing the two scenes (Fig. 5.14), the vision-only scene had better results than the multisensory scene.

5.3 Open comments

The last section of the experience's form has open-ended questions about the multisensory interface. The answers were categorized, and the most interesting questions will be translated and

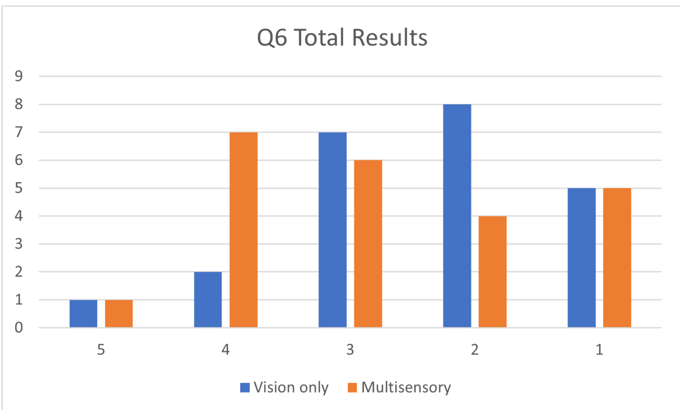
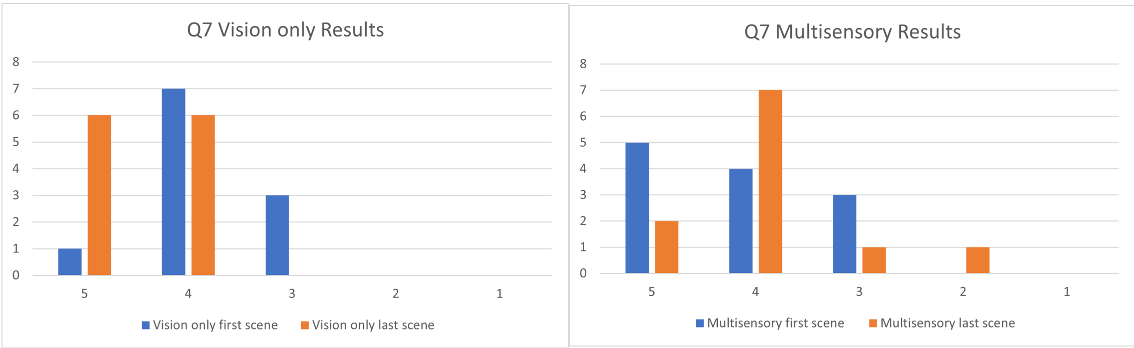


Figure 5.12: Comparison between the two test scenes in the question 6



(a) Performance of the vision only scene

(b) Performance of the multisensory scene

Figure 5.13: Performance of the two test scenes in the question 7

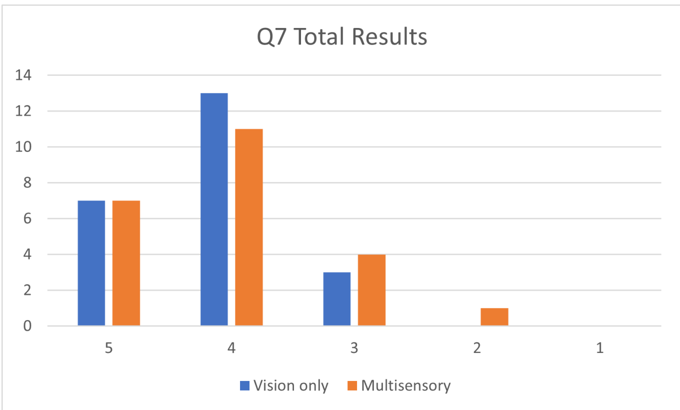


Figure 5.14: Comparison between the two test scenes in the question 7

discussed in this section (most of the original answers are in Portuguese).

The original answers can be found in Appendix A.

The three questions that the participants had to respond to are the following:

1. Was there an advantage to using the multisensory interface? What was it?
2. What type of graph worked best with the multisensory interface?
3. Ways to improve the multisensory interface (feedback)

5.3.1 Advantage to using multisensory interface

The first question regards the advantages of using the multisensory interface. The answers to the first question were analyzed and categorized into the following categories. The answer of the participant can have multiple categories.

1. The interface makes analysis more immersive/fun (8 participants).
2. The interface makes analysis easier (12 participants).
3. The interface does not help the analysis (3 participants).
4. The interface disturbs the analysis (2 participants).
5. The interface helps find patterns in the data (3 participants).

Eight participants said that the interface was more immersive and engaging than the vision-only scene. Many participants noted that the interface was more immersive because it was more interactive than the vision-only interface.

One participant stated that the interface's advantage was "More engaging and more didactic".

Another participant also referred to the interface's potential to make the data analysis more interesting and interactive. "More engaging and interactive. the non-multisensory could be very useful; however, the multisensory one could bring huge applications and make things more interactive and interesting."

Twelve participants said that it made the analysis easier but did not specify the reason that made the interface help them.

One participant stated that interacting with the data made their interpretation easier. "Yes. The interactions with the graphs help in their reading and interpretation."

Another participant stated that the interface was notably helpful when the sonified data had the information of the graph the participant was analyzing. "When it was music for both axis, it was easier to understand the date."

Another participant said that the possibility of having more dimensions present at one time was helpful in complex datasets. "Yes, it permits greater dimensionality in the analysis and makes it easier to analyze complex datasets."

Three participants said that the interface did not help the analyses.

One participant stated that visual stimuli make the information easier to retrieve, making the interface useless. "No, as I take most of the data out of visual interaction with commands and graphics."

Two participants said that the interface disturbed the analyses. Both participants stated that the visual stimulus was enough and that sound was a hindrance.

One participant stated that the interface was chaotic. "No, the visuals were enough; the sound added chaos."

Three participants stated that the interface helped them perceive patterns in the data.

One participant stated that the interface helps find patterns in the data, specifically in the datasets that used time as a variable. "It is possible to identify certain patterns, namely when we are talking about temporal scales (time series) that you possibly didn't notice only visually. However, for the rest of the scenarios, a paper view is more useful. Virtual reality makes it difficult to read the subtitles of the graphs, and in most cases, the audio does not guarantee a great advantage and even hinders the amount of time needed to analyze a graph."

Another participant stated that it helped to perceive the evolution of the graph. The participant also referred that the animation helped interpret the more dense graphs. "Better understand the evolution of a variable over time, have feedback on each value entered, which helps in the graphs that are more loaded."

5.3.2 Better graphs to use with the interface

The second question regards the best type of graph to use with the interface. The answers to the second question were analyzed and categorized into the following categories. The answer of the participant can have multiple categories.

1. Time series (6 participants)
2. Penguins (6 participants)
3. All (5 participants)
4. Forest Fires (2 participants)
5. Iris (2 participants)
6. Small datasets (1 participant)
7. Sloths (1 participant)
8. CO2 emmissions (1 participant)
9. Animals datasets (1 participant)

Six participants stated that time series were the best graphs to use with the interface.

Some participants also stated that time series were good with the interface because they could see the evolution of the graph over time. "Time series data to "feel" the evolution, the change of pitch was really useful."

Six participants stated that the penguins' dataset worked best with the interface. One participant pointed out that the penguins' dataset was the only one that used the haptic part of the interface, and that part helped in the analysis of the graph.

"The penguins' dataset because it contained more data, it would be more difficult to analyze and understand without the multisensory interface."

"The dataset that included the information in the right hand control" (haptic part of the interface) ", as it facilitated the visualization of its evolution."

Five participants said that all the datasets were good fits for the interface.

Two participants stated that the forest fires dataset worked best with the interface.

Two participants said that Iris was the dataset that worked best with the interface. "The petals" (Iris) "because the data was quite different and I could see the difference; however, I could not explore all the data so there could have been a better dataset."

One participant said that the forest fires dataset could obtain more detailed data. "Forest Fires, we were able to obtain more detailed data."

One participant said small datasets take more advantage of the interface. "I believe that datasets that have less information take better advantage of the interface."

Large datasets take more time to hear all the data points, making the analysis take more time. Larger datasets also have the disadvantage of having many points with the same values making the sonified data less enjoyable.

One participant stated that Sloths was the dataset that worked best with the interface.

One participant stated that the carbon dioxide emission dataset was the one that worked best with the interface. "I think it was the carbon dioxide emission dataset. In my opinion, it was kind of funny since it was one of the easiest to analyze."

One participant chose the biological datasets as the datasets that worked best with the interface. "The animal kingdom, but for personal reasons - because it is something that captivates me."

5.3.3 Ways to improve the interface

The third question regards how the participants would improve the multisensory interface. The answers to the third question were analyzed and categorized into the following categories. The answer of the participant can have multiple categories.

1. Feedback about the interface (9 participants)
2. Feedback about the scene (5 participants)
3. Feedback about the tutorial (2 participants)
4. Feedback about the experiments (2 participants)

Nine participants gave feedback about the interface, some were corrective and other gave some suggestions about possible future features and interactions.

The sound animation used yellow as the color of the point being sonified, but in some graphs, the color pattern used yellow in some categories. "Better color selection and separation of different tools by color"

One participant stated that large datasets made the analyses difficult because the points overlapped. One possible solution to this problem is to create a visual zoom for the graph or increase its size. "In the datasets with more information, the points overlapped in different ways depending on the perspective, which makes it difficult to read the graph."

One participant talked about the possibility of grouping data points. This is a possible solution to large datasets, to make the sonification take less time, although grouping points may lead to incorrect assumptions. "Group points by species, check which notes/sounds used are 'good to hear'"

Another participant stated that using a dataset with fewer data points to make sound takes less time. This can be a solution for large datasets, to segregate the large datasets into more minor, easier-to-analyze samples. "Maybe decrease the amount of data in a single graph because the sound part is long even at speed 2."

One participant suggested one interesting feature for the interface. A way to retrieve the graphs to the user, similar to the portable soundboard 3.2.3. "Move graphs without teleport, have a way of stretching or compressing the "laser" hit point to bring stuff closer without moving from the place."

One participant suggested using different types of graphs, more specifically bar graphs. "(...) Adding a bar chart would be interesting."

One participant pointed to the fact that the haptic interface has only capable of indicating binary values. "The haptic part is not very indicative, especially as they only have binary indications. If you have a way to change the intensity, maybe it's more indicative."

Five participants gave feedback about the test scenes. Some state the need for larger graphs and more comprehensive labels. "Graphics should be larger, and use colors with greater contrast to be able to visualize more easily." "Add the unit used in the graphs (eg C^{o} or years). (...)"

One participant referred to the use of 3D graphs instead of 2D. 3D graphs were not used because of data occlusion and the necessity of the user to move the graph to see the occluded information. "(...) Sometimes it is difficult to read the plot because it requires the constant movement of the person in the virtual world; combining this with the letters blurred by the lens makes the visual interpretation of the graphics a little difficult. I think multi-dimensional (3D) graphics would benefit more from this type of analysis than 2D plots as it brought a unique advantage that VR brings that is not possible on paper."

One participant referred progression of the sonified data. In the experiment, the sonified data was in alphabetical order, and the participant described a more comprehensive order that followed the composition of the graphs. "The analysis of the graphics (sound issue) has a more specific order, that is, follow the evolution along with one of the axes instead of being so random."

Two participants gave feedback about the tutorial. One suggested a controls scheme at the beginning of the tutorial, and the other suggested less text in the tutorial explanations.

"(...) In the tutorial, show a caption of command with all its purposes."

"The tutorial was good; however, it seemed like an overload of text on certain occasions, a shorter explanation would benefit the user, but it is important to note that it was possible to understand everything without major problems. (...)"

Two participants gave feedback about the experience. One suggested fixing the order of the test scenes so that the scene with more interactions (the multisensory) was the last. Another participant stated that the 10 minutes to analyze the test scene was insufficient for a more thorough analysis.

"Start with visual and then multisensory, as the latter is more interesting. (...)"

"Little time for a complete analysis of all data."

Chapter 6

Future work and conclusion

This chapter will answer the research questions and discuss the results obtained in the previous section. This chapter will also talk about the future that can be done to improve the interface.

6.1 Conclusion

Throughout this thesis, a multisensory interface was developed, using sight, sound, and touch to transmit information to the user. Despite some concessions made during development, the goal of making a multisensory interface was achieved.

From the experience made, it is possible to extract some conclusions. The multisensory interface made the experience more engaging, and the participants spent more time on the multisensory scene. The participants could extract information from other senses, but some had a better experience when the sound transmitted the same information as the graph. Some participants had problems using the interface, but it may be attributed to the short exposure to the interface. The interface was particularly useful for analyzing patterns and tendencies. With a more prolonged time with the interface, the participants can possibly extract more information from the interface.

In terms of responding to the initial presented reached questions:

The first RQ: *Does multisensorial analytics provide a better analysis?* The data does suggest that the majority of the users think that the multisensory interface was more helpful in analyzing data when compared with the visual-only scene. However, some of the users stated that the interface was a hindrance to the analysis. More objective data is needed to make a conclusive statement about the interface's efficiency.

The second RQ: *Can an unfamiliar user extract knowledge from the multisensorial interface?* The data suggest that some users were capable of extracting knowledge from the interface. Nevertheless, this was not true for all participants, and some participants stated that the interface was ineffective. This claim can be attributed to the inability to extract knowledge from the interface. It is possible that with more time, the users could learn to extract more knowledge from the interface, but this theory was not tested.

The third RQ: *Is it better to use the multisensorial interface to add information to the graph or reinforce the data shown?* There is not enough data to make a conclusive statement for this RQ. Regardless, one participant stated that the interface was more useful when the data presented reinforced the data shown by the graph.

The fourth RQ: *Does the multisensorial interface provide immersion?* The second question answered by the participants (section 5.2) was referent to this question, and the data suggest that the multisensory interface was more engaging than the visual-only scene.

Overall multisensory interfaces can make the person's interaction with the data more interesting and have the potential to make this task more interactive and stimulating.

6.2 Future work

In this work, it was only taken subjective metrics about the interface. Taking objective metrics to evaluate the performance of the interface would be an interesting addition to the work done in this thesis.

Although this thesis's main objective was achieved, many functionalities can still be added to a multisensory interface. This section is composed of all the ideas not implemented in the interface but has great potential to enrich the data analysis experience.

One of these functionalities is zoom audio. Zoom audio consists of using the focus functionality to limit the sonified data to a specific part and to see the relations of the points in that part. This would require dynamic sonified data that could change with the change of focus. This sonified data would only use the points of the interval to normalize the data. This functionality would be great for analyzing graphs that have a significant variability between the points that have points with similar or identical sounds. The new sound using only a selection of the points with lower variability between the point allows the sound of the points to be more distinct.

Dynamic sound is another functionality that has great potential. Instead of using only the sonified data available in the selection, the user would be able to create a song and assign the variables to the respective music parameters. This would involve the user in the analysis and give more freedom to the user to explore the dataset.

Another functionality is the visual zoom. The visual zoom would accompany the focus of the sonified data only to show the points being played.

One of the problems, that became apparent after the experiences, is that a graph with too many points hinders the analysis. Although there are some ways to bridge this problem, a feature that groups the points according to the user would reduce the points while maintaining some resemblance to the original progression of the graph. This functionality, in conjunction with the audio and visual zoom, would make analyzing a dense dataset easier.

Another problem that emerged during the interface's development was that the controllers' vibrotactile capacities were less than predicted. Using another haptic system would be an interesting addition.

One participant in section 5.3.3 gave interesting feedback on interacting with the interface. Instead of moving around and grabbing the graphs, the participant suggested making the graphs come to the user requiring less movement and possibly making the user less sick after a long time in virtual reality.

Another interesting possibility to be explored is sound Spatialization, which could be used as another dimension to transmit information.

These were the more relevant functionalities that could lead to interesting results using the interface. The multisensory interfaces in data analyses are vast and full of potential for creating a more interactive, captivating, and interesting way of analyzing data.

Appendix A

Data collected

This appendix contains the data collected in the experiment. All the responses of the participants are in the final pages of this appendix.

Age	Gender	Education	Experience with Virtual Reality	Hearing Problems	Vision problems
20-30	M	Bachelor’s degre	2 - I have experienced virtual reality	No	Myopia
20-30	M	Master's degree	0 - I have no prior experience.	No	Myopia
10-20	M	Decimo segundo	1 - Já experienciei realidade virtual u	Não	
10-20	M	Decimo segundo	1 - Já experienciei realidade virtual u	Não	Miopia
20-30	M	Licenciado	1 - Já experienciei realidade virtual u	Não	Miopia
20-30	F	Licenciado	1 - Já experienciei realidade virtual u	Não	Miopia
20-30	M	Mestrado	1 - Já experienciei realidade virtual u	Não	
20-30	M	Mestrado	1 - Já experienciei realidade virtual u	Não	Miopia
20-30	F	Licenciado	0 - Nunca tive experiência com reali	Não	Miopia
10-20	M	Decimo segundo	1 - Já experienciei realidade virtual u	Não	Miopia
10-20	F	Decimo segundo	0 - Nunca tive experiência com reali	Não	
10-20	M	Decimo segundo	0 - Nunca tive experiência com reali	Não	Daltonismo
10-20	M	Decimo segundo	1 - Já experienciei realidade virtual u	Não	
10-20	M	Decimo segundo	0 - Nunca tive experiência com reali	Não	Hipermetropia
20-30	F	Licenciado	1 - Já experienciei realidade virtual u	Sim	Miopia
20-30	M	Licenciado	0 - Nunca tive experiência com reali	Não	
20-30	M	Licenciado	2 - Já experienciei realidade virtual r	Não	
20-30	M	Decimo segundo	0 - Nunca tive experiência com reali	Não	Miopia
20-30	M	Decimo segundo	1 - Já experienciei realidade virtual u	Não	
10-20	F	Decimo segundo	0 - Nunca tive experiência com reali	Não	Astigmatismo
20-30	F	Licenciado	1 - Já experienciei realidade virtual u	Não	Miopia
20-30	F	Mestrado	0 - Nunca tive experiência com reali	Não	
20-30	M	Licenciado	0 - Nunca tive experiência com reali	Não	Astigmatismo

Scene	I like the interface used.	The interface was engaging.	The interface was usefull.	The interfaced help in the data analysis.	The data presented was interesting.	The data presented was hard to analyze.	I understand the data presented and its relations.
Multisensorial	3	4	4	2	4	3	3
Multisensorial	5	4	5	5	5	2	5
Multisensorial	5	5	5	5	4	5	4
Multisensorial	5	4	4	4	2	3	4
Multisensorial	4	4	2	3	4	4	4
Multisensorial	5	5	5	5	5	4	4
Multisensorial	5	4	4	5	5	4	3
Multisensorial	3	4	5	2	5	2	5
Multisensorial	5	5	5	5	5	4	3
Multisensorial	5	5	5	4	4	1	5
Multisensorial	5	5	5	5	5	1	5
Multisensorial	5	5	5	5	5	2	5
Exclusivamente v	5	5	5	5	5	1	5
Exclusivamente v	5	5	4	5	3	2	4
Exclusivamente v	4	5	4	4	5	2	3
Exclusivamente v	4	5	3	5	4	3	4
Exclusivamente v	4	5	4	4	3	3	4
Exclusivamente v	5	5	5	5	4	4	4
Exclusivamente v	5	4	5	4	3	2	3
Exclusivamente v	4	5	5	4	5	3	4
Exclusivamente v	5	5	5	4	5	1	4
Exclusivamente v	5	5	5	5	5	2	4
Exclusivamente v	4	5	5	5	4	3	3

Scene	I like the interface used.	The interface was engaging.	The interface was usefull.	The interfaced help in the data analysis.	The data presented was interesting.	The data presented was hard to analyze.	I understand the data presented and its relations.
Exclusivamente v	4	4	4	4	4	3	4
Exclusivamente v	3	2	3	4	3	1	4
Exclusivamente v	5	5	5	5	4	5	4
Exclusivamente v	4	3	4	3	2	2	4
Exclusivamente v	5	5	5	5	5	4	4
Exclusivamente v	3	3	4	4	4	3	4
Exclusivamente v	5	2	4	4	5	3	5
Exclusivamente v	4	4	4	2	5	2	5
Exclusivamente v	5	3	4	5	5	1	5
Exclusivamente v	4	4	4	4	5	2	5
Exclusivamente v	4	4	5	5	5	1	5
Exclusivamente v	5	5	5	5	5	2	5
Multisensorial	5	5	5	5	5	1	5
Multisensorial	4	5	5	5	3	1	5
Multisensorial	4	5	4	4	5	2	4
Multisensorial	4	4	3	3	4	4	3
Multisensorial	4	5	4	4	3	3	4
Multisensorial	5	5	5	5	4	4	4
Multisensorial	5	5	4	4	3	3	2
Multisensorial	5	5	5	5	5	4	4
Multisensorial	5	5	5	5	4	1	4
Multisensorial	5	5	2	2	4	3	4
Multisensorial	4	5	4	5	4	3	4

Was there an advantage to using the multisensory interface? What was it?	What type of graph worked best with the multisensory interface	Ways to improve the multisensory interface (feedback)
Not much, when data is centered around a specific subset I would agree it is useful. But when seing multiple groups represented on the same graph not much.	Timeseries data to "feel" the evolution, the change of pitch was really useful.	Move graphs without teleport, have a way of stretching or compressing the "lazer" hit point to bring stuff closer without moving from the place.
more engaging and interactive. the none-multisensory could be very usefull however the multi-sensory one could bring huge applications and make things more interactive and interesting.	the one that you can see the data points while pointing on them	
Mais envolvência e mais didático	Pinguins e incêndios	Acrescentar a unidade utilizada nos gráficos (por exemplo, Cº ou anos). No tutorial mostrar uma legenda de um comando com todas as suas finalidades.
Sim. As interações com os gráficos ajudam na sua leitura e interpretação.	Acredito que os datasets que possuem menos informação retiram melhor proveito da interface.	Nos datasets com mais informação os pontos sobrepunham-se de diferentes maneiras dependendo da perspetiva o que dificulta a leitura do gráfico.
é engraçado mas não diria que o som e o tato adicionam valor à análise dos dados	-	
envolvimento; melhor perceção da posição dos dados	sloths	começar com a visual e depois multissensorial, pois esta última é mais interessante. Acrescentar um gráfico de barras seria interessante.
o som tinha algumas variaveis que a parte visual nao tinha	o das petalas porque os dados era bastante distintos e conseguia ver a diferença, no entanto nao consegui explorar todos os dados por isso podia ter havido um melhor	ser mais facil carregar nos botoes
É possivel identificar certos padrões, nomeadamente quando estamos a falar em escalas temporais (time series) que possivelmente não reparava apenas visualmente. No entanto para o resto dos cenarios uma visualização em papel é mais util. VR faz dificil ler as legendas dos graficos e em maior parte dos casos o audio não garante grande vantagem e até dificulta a quantidade de tempo necessaria para analisar um grafico	Os datasets com funçoes de tempo. Por exemplo tempo do porto... ou Co2 plot	O tutorial estava bom, no entando parecia uma sobrecarga de texto em certas ocasioes, uma explicaçao mais breve benificiaria o utilizador, mas é importante notar que era possivel entender tudo sem grandes problemas. As vezes é dificil ler o plot porque requer o constante movimento da pessoa no mundo virtual , combinando isto com as letras desfocadas pelas lentes faz a interpertaçao visual dos graficos um pouco dificil. Acho que graficos a multi dimensoes (3D) benificiariam mais deste tipo de analise do que 2D plots já que trazia uma vantagem unica que VR traz que nao é possivel em papel.
Obter uma melhor compreensões dos gráficos, e sentir-me mais interassado pelo assunto que ali estava a ser demonstrado	Pinguins	letras dos gráficos deveriam ser maiores, e utilizar cores com um maior contraste para ser possível visualizar mais facilmente
Perceber melhor a evolução de uma variável ao longo do tempo, ter feedback de cada valor inserido o que ajuda nos gráficos que são mais preenchidos.	Principalmente nos gráficos que representavam a evolução de uma variável ao longo do tempo (tempratura ou pressão)	
sim, torna mais facil e intuitiva a leitura dos dados.	todos	
Torna a experiência mais interativa e dessa forma, mais divertida	Penso que foi o dataset da emissão de dióxido de carbono. Na minha opinião foi de certa forma engraçado já que foi dos mais fáceis de analisar.	Ter mais botões interativos
Sim. Acho que torna a análise de dados mais fácil e interessante.	Todos os datasets.	Talvez diminuir a quantidade de dados num só gráfico pois fica longo a parte do som mesmo em velocidade 2.
Facilidade em interpretar as informações	O dataset que incluia as informaçoes no controle da mao direita, pois facilitava a visualizaçao da sua evolução	A analise dos graficos (questao sonora) ter uma ordem mais especifica, ou seja, seguir a evoluçao por um dos eixos ao inves de ser tao aleatoria
Sim! O facto de ser multissensorial ajuda a que os vários estímulos recebam mais atenção, por conseguirmos interagir com eles, sendo também cativados por o som e coordenação estímulo-som.	O do reino animal, mas por motivos pessoais - por ser algo que me cativa.	Tive algumas dificuldades a focar a minha visão em alguns valores, mas creio que poderá ser devido à miopia.
Não, o visual foi suficiente, o som adicionou caos	Time series - Valor por tempo	Agrupar pontos por espécies, verificar que notas/sons usados são "bons de ouvir"
O som permite a análise de declives em intervalos pequenos melhor	Os das temperaturas, em que os dados seguem curvas suaves.	A parte háptica não é muito indicativa, especialmente como só têm indicações binárias. Se tiver maneira de mudar a intensidade se calhar é mais indicativo.
Conseguirmos obter de forma mais interativa e imersiva a analise dos dados	Forest Fires, conseguimos obter de forma mais detalhada as os dados	
Não, uma vez que retiro a maior parte dos dados da interação visual com os comandos e gráficos.	Pinguins e o weather.	
Sim, com esta interface consegue-se compreender melhor os gráficos e os dados respetivos ao mesmo.	O dataset dos pinguins porque como continham mais dados eram mais difíceis de analisar e compreender sem a interface multissensorial.	
a musica ajuda a analisar os gráficos com mais facilidade	todos	
quando era musica para os dois eixos era mais fácil de perceber a data	os que tinham as musicas para os dois eixos	pouco tempo para a analise completa de todos os dados
Sim, maior dimensionalidade na analise e torna mais facil analisar datasets complexos	Iris	Melhor seleçao de cores e separaçao de ferramentas diferentes por cores

The number of people between 10-20	8
The number of people between 20-30	15
The number of people that are Male	16
The number of people are Female	7
The number of people has High Scholl or equivalent	10
The number of people has Bachelor’s degree	9
The number of people has Master's degree	4
The number of people that had no experience with virtual reality	10
The number of people that used virtual reality once or twice before	11
The number of people that used virtual reality before but have not used it regularly.	2
Hearing Problems	
No	22
Yes	1
Vision problems	
No	8
Yes	15
First Scene	
Vison only	11
Multisensory	12

Results of the scene	Vision only		
	When it was the first scene	When it was the last scene	TOTAL
Q1 - I like the interface used.			
5	6	5	11
4	5	5	10
3	0	2	2
2	0	0	0
1	0	0	0
Q2 - The interface was engaging.			
5	10	3	13
4	1	4	5
3	0	3	3
2	0	2	2
1	0	0	0
Q3 - The interface was usefull.			
5	7	4	11
4	3	7	10
3	1	1	2
2	0	0	0
1	0	0	0
Q4 - The interfaced help in the data analysis.			
5	6	5	11
4	5	5	10
3	0	1	1
2	0	1	1
1	0	0	0
Q5 - The data presented was interesting.			
5	5	7	12
4	3	3	6
3	3	1	4
2	0	1	1
1	0	0	0
Q6 - The data presented was hard to analyze.			
5	0	1	1
4	1	1	2
3	4	3	7
2	4	4	8
1	2	3	5
Q7 - I understand the data presented and its relations.			
5	1	6	7
4	7	6	13
3	3	0	3
2	0	0	0
1	0	0	0

Results of the scene	Multisensory		
	When it was the first scene	When it was the last scene	
			TOTAL
Q1 - I like the interface used.			
5	9	6	15
4	1	5	6
3	2	0	2
2	0	0	0
1	0	0	0
Q2 - The interface was engaging.			
5	6	10	16
4	6	1	7
3	0	0	0
2	0	0	0
1	0	0	0
Q3 - The interface was usefull.			
5	8	5	13
4	3	4	7
3	0	1	1
2	1	1	2
1	0	0	0
Q4 - The interfaced help in the data analysis.			
5	7	6	13
4	2	3	5
3	1	1	2
2	2	1	3
1	0	0	0
Q5 - The data presented was interesting.			
5	7	3	10
4	4	5	9
3	0	3	3
2	1	0	1
1	0	0	0
Q6 - The data presented was hard to analyze.			
5	1	0	1
4	4	3	7
3	2	4	6
2	3	1	4
1	2	3	5
Q7 - I understand the data presented and its relations.			
5	5	2	7
4	4	7	11
3	3	1	4
2	0	1	1
1	0	0	0

Was there an advantage to using the multisensory interface? What was it?	Type	Type 2
Not much, when data is centered around a specific subset I would agree it is useful. But when seing multiple groups represented on the same graph not much.	2	3
more engaging and interactive. the none-multisensory could be very usefull however the multi-sensory one could bring huge applications and make things more interactive and interesting.	1	
Mais envolvência e mais didático	1	
Sim. As interações com os gráficos ajudam na sua leitura e interpretação.	2	
é engraçado mas não diria que o som e o tato adicionam valor à análise dos dados	1	3
envolvimento; melhor perceção da posição dos dados	1	2
o som tinha algumas variaveis que a parte visual nao tinha		
É possivel identificar certos padrões, nomeadamente quando estamos a falar em escalas temporais (time series) que possivelmente não reparava apenas visualmente. No entanto para o resto dos cenarios uma visualização em papel é mais util. VR faz dificil ler as legendas dos graficos e em maior parte dos casos o audio não garante grande vantagem e até dificulta a quantidade de tempo necessaria para analisar um grafico	4	5
Obter uma melhor compreensões dos gráficos, e sentir-me mais interassado pelo assunto que ali estava a ser demonstrado	1	2
Perceber melhor a evolução de uma variável ao longo do tempo, ter feedback de cada valor inserido o que ajuda nos gráficos que são mais preenchidos.	5	
sim, torna mais facil e intuitiva a leitura dos dados.	2	
Torna a experiência mais interativa e dessa forma, mais divertida	1	
Sim. Acho que torna a análise de dados mais fácil e interessante.	1	2
Facilidade em interpretar as informações	2	
Sim! O facto de ser multissensorial ajuda a que os vários estímulos recebam mais atenção, por conseguirmos interagir com eles, sendo também cativados por o som e coordenação estímulo-som.	2	
Não, o visual foi suficiente, o som adicionou caos	4	
O som permite a análise de declives em intervalos pequenos melhor	5	
Conseguirmos obter de forma mais interativa e imersiva a analise dos dados	1	
Não, uma vez que retiro a maior parte dos dados da interação visual com os comandos e gráficos.	3	
Sim, com esta interface consegue-se compreender melhor os gráficos e os dados respetivos ao mesmo.	2	
a musica ajuda a analisar os gráficos com mais facilidade	2	
quando era musica para os dois eixos era mais fácil de perceber a data	2	
Sim, maior dimensionalidade na analise e torna mais facil analisar datasets complexos	2	
Type		
1 - The interface turns the analysis more immersive/fun.	8	
2 - The interface turns the analysis easier.	12	
3 - The interface does not help the analysis.	3	
4- The interface disturbs the analysis.	2	
5- The interface helps find patterns in the data	3	

What type of graph worked best with the multisensory interface	Type	Type 2
Timeseries data to "feel" the evolution, the change of pitch was really useful.	1	
the one that you can see the data points while pointing on them	2	
Pinguins e incêndios	2	4
Acredito que os datasets que possuem menos informação retiram melhor proveito da interface.	5	
-	3	
sloths	6	
o das petalas porque os dados era bastante distintos e conseguia ver a diferença, no entanto nao consegui explorar todos os dados por isso podia ter havido um melhor	7	
Os datasets com funçoes de tempo. Por exemplo tempo do porto... ou Co2 plot	1	
Pinguins	2	
Principalmente nos gráficos que representavam a evolução de uma variável ao longo do tempo (temperatura ou pressão)	1	
todos	3	
Penso que foi o dataset da emissão de dióxido de carbono. Na minha opinião foi de certa forma engraçado já que foi dos mais fáceis de analisar.	8	
Todos os datasets.	3	
O dataset que incluia as informaçoes no controle da mao direita, pois facilitava a visualizaçao da sua evolução	2	
O do reino animal, mas por motivos pessoais - por ser algo que me cativa.	9	
Time series - Valor por tempo	1	
Os das temperaturas, em que os dados seguem curvas suaves.	1	
Forest Fires, conseguimos obter de forma mais detalhada as os dados	4	
Pinguins e o weather.	1	2
O dataset dos pinguins porque como continham mais dados eram mais difíceis de analisar e compreender sem a interface multissensorial.	2	
todos	3	
os que tinham as musicas para os dois eixos	3	
Iris	7	
Type		
1 - Time series	6	
2 - Penguins	6	
3 - All	5	
4 - Forest Fires	2	
5 - Small datasets	1	
6 - Sloths	1	
7 - Iris	2	
8 - CO2 emmissions	1	
9 - Animals datasets	1	

Ways to improve the multisensory interface (feedback)	Type	Type 2
Move graphs without teleport, have a way of stretching or compressing the "lazer" hit point to bring stuff closer without moving from the place.	1	
Acrescentar a unidade utilizada nos gráficos (por exemplo, Cº ou anos). No tutorial mostrar uma legenda de um comando com todas as suas finalidades.	2	3
Nos datasets com mais informação os pontos sobrepunham-se de diferentes maneiras dependendo da perspetiva o que dificulta a leitura do gráfico.	1	2
começar com a visual e depois multissensorial, pois esta última é mais interessante. Acrescentar um gráfico de barras seria interessante.	1	4
ser mais facil carregar nos botoes	1	
O tutorial estava bom, no entando parecia uma sobrecarga de texto em certas ocasioes, uma explicaçao mais breve benificiaria o utilizador, mas é importante notar que era possivel entender tudo sem grandes problemas. As vezes é dificil ler o plot porque requer o constante movimento da pessoa no mundo virtual , combinando isto com as letras desfocadas pelas lentes faz a interpertaçao visual dos graficos um pouco dificil. Acho que graficos a multi dimensoes (3D) benificiariam mais deste tipo de analise do que 2D plots já que trazia uma vantagem unica que VR traz que nao é possivel em papel.	2	3
letras dos gráficos deveriam ser maiores, e utilizar cores com um maior contraste para ser possível visualizar mais facilmente	2	
Ter mais botões interativos		
Talvez diminuir a quantidade de dados num só gráfico pois fica longo a parte do som mesmo em velocidade 2.	1	
A analise dos graficos (questao sonora) ter uma ordem mais especifica, ou seja, seguir a evoluçao por um dos eixos ao inves de ser tao aleatoria	2	
Tive algumas dificuldades a focar a minha visão em alguns valores, mas creio que poderá ser devido à miopia.	1	
Agrupar pontos por espécies, verificar que notas/sons usados são "bons de ouvir"	1	
A parte háptica não é muito indicativa, especialmente como só têm indicações binárias. Se tiver maneira de mudar a intensidade se calhar é mais indicativo.	1	
pouco tempo para a analise completa de todos os dados	4	
Melhor seleçao de cores e separaçao de ferramentas diferentes por cores	1	
Type		
1 - Feedback about the interface	9	
2 - Feedback about the scene	5	
3 - Feedback about the tutorial	2	
4 - Feedback about the experiments.	2	

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