

EVALUATING 5D DATA VISUALIZATION ACROSS LOW- AND HIGH- IMMERSIVE ENVIRONMENTS

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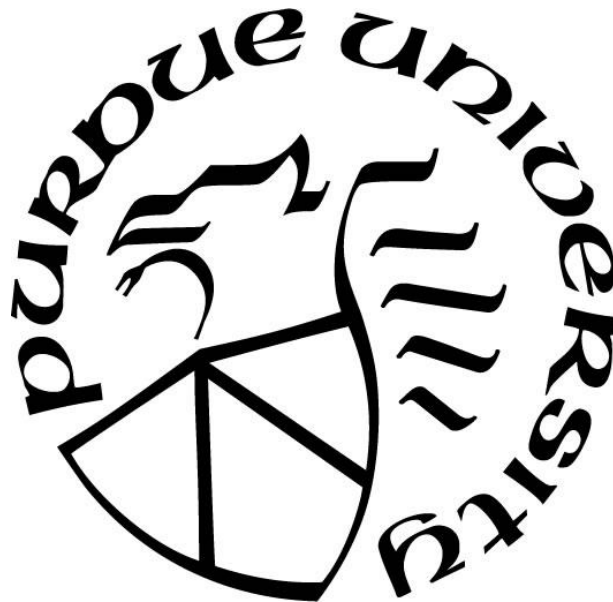
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ABSTRACT

The amount of data in our world is increasing quickly. As data keep increasing, so does its number of dimensions and there is currently no official standard tool that can visually represent all dimensions of a multi-dimensional data without dimensionality reduction or just as a set of matrices in a 2D plane. It will become necessary for multi-dimensional data to be represented in an environment where all of its dimensions can be fully defined in order to be interpreted correctly, specifically by audiences with no background in data analysis. Therefore, immersive visualizations through Virtual Reality (VR) provide a great opportunity to its users as they have the advantage of including higher dimensions of data and providing a perspective from different angles which is not always possible in the traditional 2D interpretations. However, the problem is that there is minimal to no guidelines about using higher dimensions of data in a 3D environment through visual mediums. The purpose of this study is to understand how different applications (VR and Desktop) affect the interpretation of multi-dimensional data across various levels of dimensions. This comparison will lead to a better understanding of the development and use of proper visual techniques in Immersive Analytics.

CHAPTER 1. INTRODUCTION

Data Visualization has become critical with the fast-increasing volume of Big Data. The term Big Data refers to the management and the analysis of large amounts of information and it is found in every field from sciences and technology to economics and social studies (Olshannikova et al., 2014). Social networks like Twitter or Facebook, for example, store millions of bytes of data that are developed every day. Medical records are updated regularly as well, with the patients' information from their medical history to their personal information. According to International Data Corporation (IDC) data volumes are growing exponentially (Olshannikova et al., 2015). Finding efficient methods to visually present huge amounts of data in a meaningful manner will be very important for the coming decade in data analysis. So far, 98% of the companies working with Big Data are displaying results of their data analysis by using Information Visualization tools and techniques (Olshannikova et al., 2015). These companies use well known Desktop tools like Tableau and Statistical Analysis System (SAS), as well as useful libraries like JavaScript library D3 and Python library Plotly. All these options work perfectly within 2D settings; however, Big Data means that there will be a large number of variables which will translate to a large number of data dimensions. Without the proper tools to represent this complexity, the interpretation of the data can be incorrect and full of bias. It is a challenge; however, to properly represent multi-dimensional data in 2D visualizations as “depth” cannot be correctly represented in 2D and more complex data can get lost in the process. “Depth” representation in 2D is inefficient and it is highly recommended to never use 3D charts in 2D environments as it will skew the perception of the visualization. Therefore, a high complexity or a multi-dimensional data set represents a critical obstacle in Data Visualization and data analysis (Donalek et al., 2014). Eventually, other solutions need to be considered to properly visualize multi-dimensional data as the only way to archive progress in Data Visualization is to use new and innovative procedures fitting to the times (Cleveland & McGill, 1984).

Problem

Immersive Analytics (IA), which includes both Virtual Reality (VR) and Augmented Reality (AR), is regarded as the future for visualizing complex data sets using different

visualization components or modalities. The use of “depth” and immersive interaction in IA might be better suited for the representation of complicated Data Visualization techniques (Whitlock et al., 2020). Since multi-dimensional data keep increasing, more variables are included which creates higher dimensions of data. By adding “depth”, there is another dimension of the data to be represented. Since this process offers the opportunity of a 3D simulation, a user can move around the environment and interact with the visualizations as well. This causes the user to become more immersed in the experience and immersion has shown to be advantageous in data exploration by increasing attention and focus on observation, hence the name Immersive Analytics (Hoppenstedt et al., 2019; Raja et al., 2004). There has been research focusing on presenting multi-dimensional data using different graph components in IA and how that differs from 2D visualization (Donalek et al., 2014; Whitlock et al., 2020). There has also been research focusing on using different applications in IA (Bach et al., 2018; Millais et al., 2018; Kraus et al., 2020; Zhao et al., 2020). Most of the geometrical visualization techniques they use are simple graphs like scatter plots, as they are well known devices for many audiences that have a basic understanding of statistics (Millais et al., 2018). However, the data sets for these scatter plots usually will not go higher than 4D and the interaction between the levels of dimension and applications has not been investigated deeply. The problem that is addressed by this research is that there are minimal to no guidelines on how to properly present data in IA in different levels of dimensions for particular sets of multi-dimensional data.

Significance of Problem

In the study by Whitlock et al. (2020), the researchers attempted to create a preliminary guideline on how effective visualization techniques can be developed by exploring how people understand data on different displays and graph modalities by using Graphical Perception (GP) experiments in 3D environments. GP is the visual decoding of categorical and quantitative information from a graph, and it is necessary in the development of IA (Cleveland & McGill, 1984). The researchers used a basic scatter plot and bar plot for their experiment using synthesized data. Most of their graphs were represented in a 3D environment, with only a few trials utilizing a 4D data set for the scatter plots. Each 3D scatter plot used a different modality to represent its last dimension, like color, size, depth, height, and orientation, while the 4D plots only used color, size, and orientation. The participants were assigned various tasks to complete in each scatter plot and

their time of completing each task was recorded, as well as their positional and rotational movement. Several findings were reported significant like: (1) there were interaction effects between applications and modalities used; (2) Desktop displays induced more error than VR and AR applications; (3) participants were significantly more accurate with color than with other modalities; (4) participants were significantly slower at evaluating depth and height on the Desktop than on immersive applications; and (5) estimating size in 4D was significantly more difficult on Desktop than on VR or AR (Whitlock et al., 2020). In the end, the researchers recommended future studies to extend their tasks and use different types of data, as well as select effective visualization colors by using techniques for colorblind accessibility to ensure more successful color palettes and utilize different color spaces (Whitlock et al., 2020).

In another study, Millais et al. (2018), the researchers also utilized a 3D scatter plot and “Parallel Planes” graph, a graphical tool showing the relationships between variables using lines, to perform their study. The scatter plot used a 3D data set, and their data were real world data. Each plot also had a version in 2D displays that it could be compared with. The data collected were mostly qualitative, as the participants were encouraged to report any insight they had gained from the data while exploring the plot (Millais et al., 2018). They also completed a NASA Task Load Index (NTLX) Questionnaire after their trial. The researchers recorded that the participants found data exploration to be more satisfying in VR. They also observed that while participants reported the same number of insights and hypotheses in both VR and 2D displays, the participants reported fewer inaccurate insights when using the VR visualizations (Millais et al., 2018). According to this study, VR has a huge of potential for the future, but more investigation is required.

In the study by Bach et al. (2018), the participants used a 3D Desktop application, a tablet AR application, and AR through a Microsoft HoloLens application to solve assigned tasks in a point cloud (a visualization that includes 3D scatterplots and time cubes). Their results showed that each application had its advantages, however unlike the other discussed studies, Desktop was generally the fastest, most precise, and easiest to use (Bach et al., 2018). The researchers also noticed that performance for AR increased with training and could be an area for future investigations.

Overall, visualization in higher dimensions is still a new topic and only the basic guidelines have been explored so far. However, data are increasing rapidly. Soon it will become necessary for multi-dimensional data to be represented in an environment where all its dimensions can be fully defined in order to be interpreted correctly. A concrete example of these type of data would involve integrated climate-economy models that deal with socio economic analysis and environmental risk management during climate change. These types of models produce multi-dimensional data that need to be interpreted correctly by decision makers who are not necessarily experts (Simpson et al., 2016). In the study by Simpson et al. (2016), the researchers were trying to develop an IA application for the visualization of different climate scenarios that can offer important insight on the future of economic and biophysical models. The results showed that traditional 2D data reduction models often make unrealistic assumptions about stakeholder preferences by combining everything into a single function and erase other preferences that can weigh on decision making (Simpson et al., 2016). Therefore, experts need a tool that can be multi-dimensional in order to capture reality. Another example is multi-dimensional medical data sets. The VR application, VRvisu, was developed to represent medical data in an engaging 3D environment in order to create efficient data analysis techniques (Reddivari et al., 2017). In another study, the researchers proposed a VR data-based tool for urban planners, architects, and researchers to 3D visualize an urban quarter that could capture all of its complexities (Al Bondakji et al., 2018).

Spatiotemporal data is also important to visualize and utilizes both location and time. It serves as the foundation of most location-based applications and geospatial databases (Jitkajornwanich et al., 2020). For example, many popular applications and systems, like the global positioning system (GPS), environmental monitoring, and transportation schedule, utilize a large spatiotemporal database to store and query their data (Jitkajornwanich et al., 2020). The global geospatial data analytics market is set for considerable growth, increasing from a projected \$69.9 billion in 2018 to \$88.3 billion in 2020.¹ That is why multi-dimensional data cause a major obstacle, as for many experts the challenge will be evaluating how they can leverage large volumes of data from many different sources and thinking of creative ways they may be able to store and present

¹ How GIS and Big Data are Creating Big Change for the World, retrieved from <https://gis.usc.edu/blog/how-gis-is-taking-advantage-of-big-data/>, last accessed: October, 2020

this data.¹ Immersive Analytics could be one solution. Although IA tools are still in their development phase, as data become more complex, a guideline would be advantageous for the future.

Purpose & Research Questions

Data dimensions refer to a variable of consideration like X or Y variables. By considering more variables of interest, the data will have more dimensions which will result in a larger amount of information that needs to be represented visually. Modalities, in this specific study, will refer to the different characteristics of a graph that can be used to represent a dimension like the axes, color, or size. For example, in a scatter plot graph, the axes can represent the X and Y variables, while the color of the points can represent the Z variables. The visualization becomes more complex as more dimensions are added which can be represented by other modalities as size and depth. Techniques where users are assigned specific tasks like guessing where the outlier is located for a specific category or figuring out the maximum and minimum values in a data set by only looking at the visualization could be helpful to utilize as they determine whether the user can correctly interpret said visualization. When real world data are included in the process, they give the data a story that a user can use to gain further insight from the visualization and become more immersed with the project.

The purpose of this study is to understand how introducing more complex data sets of real-world scenarios utilizing different modalities will affect the interpretation of the data in various 3D environments throughout different levels of dimensionality. The research questions that are being addressed include the following:

- RQ1.** When presented with different levels of the data dimensions, how will this affect the user's decoding of the data in IA?
- RQ2.** How will each 3D setting affect the user's observation of a particular multi-dimensional data?

Significance of Study

It is important to understand how data can be represented on different levels of dimensions. As it was mentioned before, Donalek et al. (2014), and Whitlock et al. (2020) used different modalities like color, size, and orientation to represent higher levels of dimensions of the data as well. This type of experimentation was mostly used for 3D data when utilizing a scatter plot; however, it was not explored much further than 4D (Millais et al., 2018; Kraus et al., 2020; Whitlock et al., 2020). Currently, complex data sets with higher levels of dimensions are being simplified into lower dimensions by using dimensionality reductions techniques which try to preserve as much information as possible from the original (Sedlmair et al., 2013). Although this is a popular short-term solution, it also tends to lead to critical data loss. For example, Principal Component Analysis (PCA), the most used dimension reduction tool, is very sensitive to outliers and can miss variables of interest (Koren & Carmel, 2014). For many large data sets there are too many variables to display as a scatter plot matrix (SPLOM) form (Wilkinson, et al., 2006). A method where one could see the whole data would be beneficial in order to get the full scope of the data and the most promising way to do so is through IA.

The data has also been synthetically generated for some of the research studies (Bach et al., 2018; Hoppenstedt et al., 2019; Kraus et al., 2020; Millais et al., 2018). The goal of this analysis; however, is to generate knowledge from the real world (Kraus et al., 2019). Synthetic Data Visualizations can be useful, but they often include little context information about the real world. Therefore, there is no story that the subject can understand or will have to assess through the visualization. This creates a gap between the data world and the real world, as well as the subject's relationship with the understanding of the data. In the real world, every data set has a story, and the story extends context to the visualization. Visual Analytics is an explanatory process that requires context, and this should be included in research as well (Perer & Shneiderman, 2009).

Although this is a new field, there is no doubt that the amount of data will continue to increase and so will the dimension levels of the data. There will be a point where representing 2D environments will not be enough to get a valid interpretation of all the data has to offer. There is also the issue of presenting this type of data to an audience that does not have experience with data analysis and might encounter challenges in interpreting the overwhelming amount of information in a multi-dimensional data set (Bravo, 2020). Therefore, figuring out efficient

techniques to effectively portray this data fully will be key in the development of Data Visualization in the future. VR tools like VRvisu and IATK (Cordeil et al., 2019; Reddivari et al., 2017) are currently being developed in order to account for the increasing dimensions of the data; however, a guideline for multi-dimensional Data Visualization would be another step in the right direction.

Assumptions

There were various assumptions made in this study. First, it was assumed that during this study, the participants' gender was not going to significantly affect their performance as well as they would answer the questionnaire provided honestly and to the best of their abilities. Another assumption was that the participants might be somewhat familiar with VR technology. They would be familiar with the computer desktop and would have probably used a type of Data Visualization tool like SAS or Microsoft Excel, which are tools Purdue uses in its statistics courses. They would have probably worked with a scatter plot as well. They would be proficient in English to fill the questionnaires included in the experiments as every Purdue student needs to be proficient in English. Participants who could have a vision problem and needed to wear assigned prescription glasses, would be able to wear them during the IA simulations since the VR headsets are big enough, so a good vision was another assumption made in this project. A major assumption about this study was that the current pandemic situation would have improved until the time of experimentation, so the study would be able to continue normally in a lab setting. However, if this was not the case, an alternative procedure was considered in Limitations. Fortunately, the study was able to be completed in lab successfully.

Delimitations

The most important delimitations included the number of dimensions represented, type of graphical tools utilized, and the choice of sample. For this study, the focus was in introducing data sets with 5 dimensions. The focus was VR versus 3D Desktop applications. 2D applications were not included in order to save time on experimentation and development; however, it is a comparison that could be considered and expanded upon in later studies. AR applications were not used either as it further extended the experimental trials and did not fit with the scope of the study

design. Any other applications or levels of dimensions that could have been included would become redundant and this range laid the base for a good guideline. It also cut down on time of experimentation and sample size.

This study utilized a scatter plot for the experimentations, as a scatter plot is one of the most popular tools used in Data Visualization, and it can also provide a lot of information. By using a scatter plot, the participants did not need to spend a long time to get familiar with the application, and the graphical properties of a scatter plot can be easily modified. The tasks they were assigned were derived from observations of the collected data set and it included a questionnaire within the application. These were basic questions that any participant with a basic proficiency in mathematics and statistics can understand and identify. In both applications a 3D scatterplot was included with the X, Y, Z axis as well as a 2D grid on the ground so the participants could determine the coordinates of the points and not get too overwhelmed inside the plot.

Another delimitation included the types of modalities that this study focused on. The modalities were the color of the points, Y-axis (vertical), and the size of the points of the scatter plot. These were some of the main graphical properties among the modalities and according to Whitlock et al. (2020) offered overall the least error rate. Including more than this would have led to more treatments and a lengthier session, which this study could not afford (Sarkar, 2018). These modalities were also included as color, size and height are generally intuitive and widely used (Smart & Szafir, 2019). It was important to choose modalities the participants would recognize and understand. Hence there was a color scale and size scale provided in the application so participants could constantly use them as a reference. Various modalities were used to gain a better understanding of the users' decoding of the data in different dimension levels, and how these dimensions can even affect each-other.

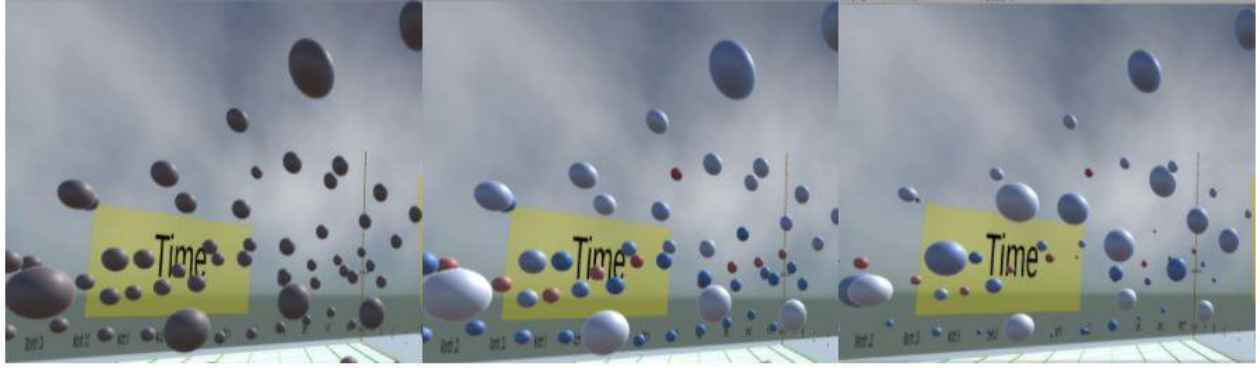


Figure 1. 3D, 4D and 5D

Note. Above each Dimension level is represented. 3D has same size points, and all are colored in a dark gray; 4D uses the same sized points with the blue-white-red color interpolation; 5D includes both the color and size interpolation for its points.

The size and color were interpolated as the data they represented was continuous data. Usually, these modalities can be used for categorical data as well; however, if there are many categorical groups, the multiple groupings of size and colors would overwhelm the participants (Kashyap, 2020). The data values were also normalized to ensure there was a common scale. The color interpolation went from blue, being the lowest value, to white being the center value, and red being the highest value. These are colors that are usually intuitive in such visualizations as well as very well used. These colors were also picked as they present the ideal palette to work with for colorblind participants² (Cravit, 2019; Rost, 2020). This color scale was achieved by using the script *LABColor.cs*³ which is used to approximate human vision.

In the VR application, height was a limitation unlike the Desktop application as the user could not fly around the environment. That could have caused discomfort and nausea, especially for users who were not very familiar with VR (Caddy, 2016; Porcino et al., 2017). The users were still able to rotate around all directions similar to the Desktop application with the keyboard. The speed of the motion was also not adjustable for both applications as it was constant. The participants also could not re-pick points, as once they pressed enter or the trigger

² *COLORBREWER 2.0.*, retrieved from <https://colorbrewer2.org/#type=diverging&scheme=RdBu&n=5>, last accessed: October, 2020

³ UnifyCommunity, retrieved from <http://wiki.unity3d.com/index.php/LABColor>, last accessed: December, 2020

button in VR for their choice, this was their final choice, in order to get their initial response and save time for the participants.

The data used was collected from the research paper “Air pollution knowledge assessments (APnA) for 20 Indian cities” (Guttikunda et al., 2019). The data set contained the emissions of three different air pollutants in 12 different Indian cities for each month of the year 2012. The air pollutants included Particulate Matter (PM-10) emissions in $\mu\text{g}/\text{m}^3$, Sulfur Dioxide emissions in $\mu\text{g}/\text{m}^3$, and Nitrogen Dioxide emissions in $\mu\text{g}/\text{m}^3$. The air pollutants were represented by the Y-axis (vertical), color interpolation and size interpolation respectively for all applications. In the future, it would be useful to create a comparison where modalities have their own groups or levels and each dimension can be compared throughout all of them, or different groups can use different modalities; however, that would have added more trials for the participants and lengthen the experimentation. In order to reduce time and sample size, the modalities were analyzed once on their specified level; future studies with more resources should consider such a study and include more possible modalities.

As for the sample, the participants had to come from a proficient mathematical background (ex. taken a statistics course) or understand basic concepts (ex. outliers, minima, being able to read a graph) in order to make sure that they understand the tasks that they are being asked to complete and the results are not skewed. For this reason, an online questionnaire to test their abilities was provided before the trials and it was multiple choice with no open-ended questions. The test is provided in Appendix A. If the participants answered all of these questions wrong, they were considered an outlier and their response was removed. In the demographic questionnaire, there is also a question checking if the participants were color blind and exactly what type of colorblindness it is as color was a main component in the experiment, so such participants needed to be considered in the statistical model in order to reduce bias. All the participants were Purdue students, both undergraduate and graduate, from the campus in West Lafayette, Indiana.

The outputs that were collected were the tasks they had to complete for each level and for each application as well as the time it took the participants to complete each task. The tasks were completed within the application and a text file was created with the answers selected as well as recorded time for each participant in each level. A NTLX Questionnaire and USE Questionnaire was also completed after each trial to obtain qualitative data for the usability and workload of the applications in each level and to check if there was a difference between the levels in the overall

answers (Hart, 1986; Lund, 2001). Both questionnaires are featured in Appendix B and C respectively. The participants also left comments in the end of the USE questionnaire about the positives and negatives of their experiences.

Limitations

An important limitation in this case, was the time provided to the participants. The participants had to go through several trials in the same session. This took about 30-45 minutes per participant; therefore, the experimentation had to continue for a substantial number of weeks. Scheduling was also another issue as some participants were not be available for the lengthy session of trials. An external incentive like \$10 Amazon gift card was provided to motivate the students. In total, there were 64 participants. The size of the sample depended on the two different scenarios considering the limitations that the pandemic had created. If the lab was still not opened for example, the trials would have to continue online. Fortunately, as it was mentioned before, the lab was opened and the headsets were deemed safe to use, so all the participants were able to complete their trials in person.

As it was mentioned on the last subsection, height was a limitation for VR, however the participants were positioned inside the graph and were able to move around and use their own height as a reference.

Definitions

- **Big Data:** The management and the analysis of large amounts of information (Olshannikova et al., 2014).
- **Data Analysis:** The process of collecting, changing, modeling and visualizing data in order to discover information that will aid in decision-making tasks.
- **Graphical Perception (GP):** The visual decoding of categorical and quantitative information from a graph (Cleveland & McGill, 1984).
- **Immersion:** The user's engagement with the simulated experience.
- **Immersive Analytics (IA):** New research field that aims to support data analysis and decision making by utilizing immersion.

- **Modality:** Different visual components of a graph that can be used to represent a dimension of the data. In this specific study it includes color, size, and Y-axis (vertical).
- **Multi-dimensional data:** Data that is not confined to 2 dimensions only.
- **High-dimensional data:** Refers to multi-dimensional data with a higher number of dimensions than 3 for this specific study.
- **Depth Perception:** Ability to perceive the distance between objects in a 3D setting.
- **Embodied Data Exploration:** An environment where a user can utilize other tools like touch, sound, and tangible interaction in order to engage with the data (Dwyer et al., 2018).
- **Spatial Immersion:** An environment where the users can utilize the space around them as a 3D workspace (Dwyer et al., 2018).
- **Visual Analytics:** Includes various methods for interactive visualization simulations as well as data analysis processes to support the analytical reasoning for decision-making tasks.

CHAPTER 2. METHODOLOGY OF REVIEW

The two main databases used were the ACM Digital Library and the IEEE Xplore database. These databases contained most of the type of research needed for this literature review. ACM provided useful papers on the topics of Virtual Reality and multi-dimensional data (Butscher et al., 2018; Cordeil et al., 2017; Millais et al., 2018; Reddivari et al., 2017; Simpson et al., 2016). IEEE, on the other hand, offered many various papers on the topics of Immersive Analytics and Data Visualization (Bach et al., 2018; Batch et al., 2020; Cordeil et al., 2019; Donalek et al., 2014; Hoppenstedt et al., 2019; Kraus et al., 2020; Olshannikova et al., 2014; Reddivari et al., 2017; Simpson et al., 2017; Wagner et al., 2018; Zollmann et al., 2012). Both databases included a lot of useful research on the field. OpenThesis was also utilized as a Thesis and Dissertations database; however, it does not provide as many resources as the first two databases.

For most of the papers and projects, many of the references were pulled from different revered Conferences and Symposiums in the last five years like IEEE Xplore, eCAADe, and CHI conferences (Al Bondakji et al., 2018; Butscher et al., 2018; Cordeil et al., 2019; Millais et al., 2018; Porcino et al., 2017; Reddivari et al., 2017; Simpson et al., 2017; Smart & Szafir, 2019; Zhao et al., 2019; Wagner et al., 2018). Some projects were focused on developing a 3D Visualization tool like VRvisu and ImAxes (Cordeil et al., 2017; Reddivari et al., 2017), while many of the other references were focused on the new emerging field of Immersive Analytics and its advantages over traditional methods of Data Visualization (Dwyer et al., 2018; Olshannikova et al., 2014, 2015; Raja et al., 2004). Some of the references also concentrated on multi-dimensional data and how it can be analyzed visually and through other methods in both 2D and 3D (Millais et al., 2018; Sedlmair et al., 2013; Wilkinson et al., 2006; Zollmann et al., 2012). Online articles and software were considered as well (Brewer et al., 2009; Bravo, 2020; Kashyap, 2020) as they provided another perspective regarding IA and color perception.

Findings Pertaining to Immersive Analytics and its Significance

There were papers and projects about developing a specialized tool that could be useful in certain fields. Some of these tools were being developed for medical models like VRvisu

(Reddivari, et al., 2017), or urban data (Al Bondakji et al., 2018). VRvisu was developed as a way to not rely on 2D visualization tools as data gets more complex in the healthcare industry and research. Currently, VR is utilized in the medical domain to solve real world problems like surgical training, exposure therapy, and as a training simulation for new medical students (Reddivari, et al., 2017). However, this research argues that there is no deep investigation when it comes to using VR for Data Visualization. Al Bondakji et al. (2018) focuses on integrating both 3D and 2D simulations to create a hybrid that could overcome the limited number of variables and relationships 2D simulations show into something the users can recognize. There are also more general tools like ART, which is a potential collaborative analysis tool for multi-dimensional data in Augmented Reality (Butscher et al., 2018). ImAxes and IATK, as well, are 3D interactive multi-dimensional visualization tools that let the user interact with the application and built their own visualizations in order to analyze different variables and relationships inspired by traditional 2D tools (Cordeil et al., 2017, 2019). The researchers' goal was to create a standard to visualize multi-dimensional data and lead to the emergence of new visualizations that can be specifically used for IA, like ImAxes did with 3D SPLOM (Cordeil et al., 2017). However, they admit that further research can improve and provide a better standard for these models in order to create a more effective design for IA tools. Many of these tools are still in their development phase, but they demonstrate the urge many data analysts or non-experts have in the development of standard immersive 3D visualization tools. There are also already developed visualization tools that can be used by scientists like ParaView4, which is a tool that can work through multi-platforms analyzing large data sets using 3D visualizations, and Virtualitics5 which provides more efficient data analytics (Wanick et al., 2019).

Many of the other papers supporting the development and utilization of Immersive Analytics for Big Data Visualization (Donalek et al., 2014; Olshannikova et al., 2015; Wanick et al., 2019) emphasize the challenges the ever-increasing amount of Big Data will prompt to current 2D Data Visualization tools like SAS and Tableau as well as the difficulties of analyzing a huge amount of data through human perception. As Olshannikova et al. (2015) mentions, many government, scientific and technical laboratories have released data not only for review, but also for public use, which means that Big Data analysis is becoming more widely utilized in industry and research. Many companies that use Big Data Visualization are interested in the invention of tools that allow someone to: (1) produce quick and effective outputs working with large amounts

of data; and (2) assess the visualized data from all angles in scalable ways (Olshannikova et al., 2015). Therefore, Immersive Analytics is seen as the next step for Data Visualization as it can visualize more dimensions of data as well as provide more engaging interactions, collaboration between participants, and an embodied data exploration as shown in Figure 2.

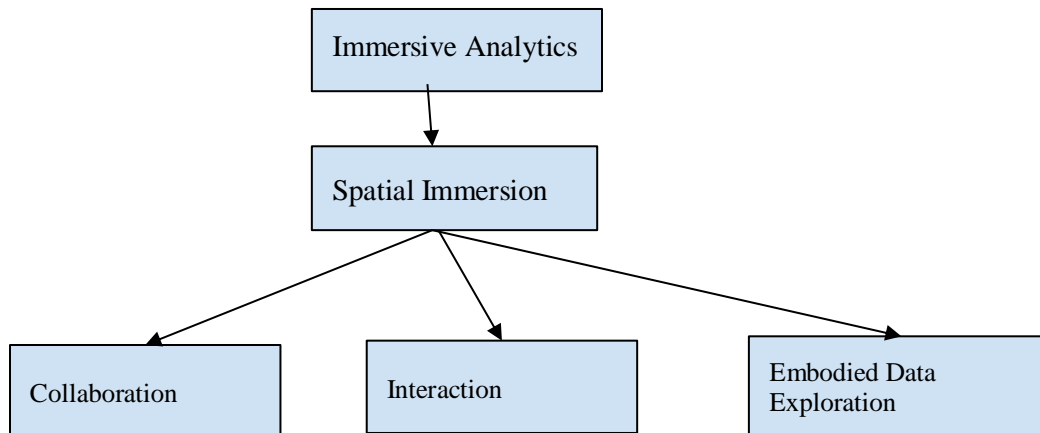


Figure 2. Concept Map for Characteristics of Immersive Analytics

Note. Immersive Analytics needs to include Spatial Immersion, which in turn gives the users the opportunity for collaboration with each-other, interaction with the data set, and exploration of the data from different perspectives by being physically in the environment.

However, as Wanick et al. (2019) mentions this creates another challenge as there are more questions than answers when it comes to proper IA visualization and interaction practices. Donalek et al. (2014) also emphasizes that visualization is an integral part of the data analysis process, as it represents the bridge between quantitative content and human intuition. However, although humans possess remarkable pattern recognition systems, those systems are optimized for a 3D world, which makes higher dimensional data a critical challenge for effective visualization in the modern world (Donalek et al., 2014). Currently many research papers are focused on providing some type of guideline like (Bach et al. 2018; Hoppenstedt et al., 2019; Kraus et al., 2020; Millais et al., 2018; Simpson, et al., 2016) and more research is expected in the future concerning this topic for different applications, modalities, interactions, and types of data in IA. For example, Bach et al. (2018) focuses on interpreting data in various tangible AR devices like Tablet AR and Microsoft HoloLens, while Kraus et al. (2020) focuses on cluster detection in 3D scatter plot visualizations across various applications. Scatter plots are heavily utilized as visualization tools

as they are the simplest and at the same time most familiar tools that can be interpreted by general audiences (Tufte, 1983).

Some research was also found about color perception and size. As it was mentioned before Whitlock et al. (2020), these modalities tended to produce the overall least amount of error rate. However, there has not been any consideration for color blindness. Utilizing different resources (Cravit, 2019; Rost, 2020; Zhao et al., 2019) as well as the application ColorBrewer 2.0⁴, a color palette was picked. Accounting for all conditions of colorblindness, red, blue, and white with varying brightness would be the best option for a visualization (Cravit, 2019; Zhao et al., 2019).

Intuitively, visual representation is more likely to be understood by a person in comparison with large amounts of textual information and that is why the challenges of multi-dimensional data have been urging many scientific and innovative projects in Data Visualization as well as promoted the emerging field of IA (Olshannikova et al., 2015). In Cleveland & McGill (1984) a more scientific approach on how to represent the data in graphs and charts effectively by utilizing GP was laid. Their findings aided in laying a groundwork on how to properly visualize data in 2D. Currently a similar process is happening with IA and multi-dimensional data. According to IDC, by 2025 worldwide data will grow 61% to 175 zettabytes (Patrizio, 2018). This large amount of data, may cause difficulty in managing the data, visualizing it, and gaining knowledge from it. As Donalek et al. (2014) mentions “...it is about discovery and understanding of meaningful patterns hidden in the data”. Without the proper tools to visualize these types of huge data sets, there will be no pattern recognized and no knowledge gained.

⁴ *COLORBREWER 2.0.*, retrieved from <https://colorbrewer2.org/#type=diverging&scheme=RdBu&n=5>, last accessed: October, 2020

CHAPTER 3. PARTICIPANTS

The population the sample was derived from was Purdue students, both graduate and undergraduate, many coming from the Engineering and Computer Graphics Technology departments. The participants were selected through random sampling. The sample of students was randomly separated into two different groups: Desktop group and VR group. The size for the sample of this study was determined through power analysis to be about 40, however 64 participants were collected in order to account for any outliers.

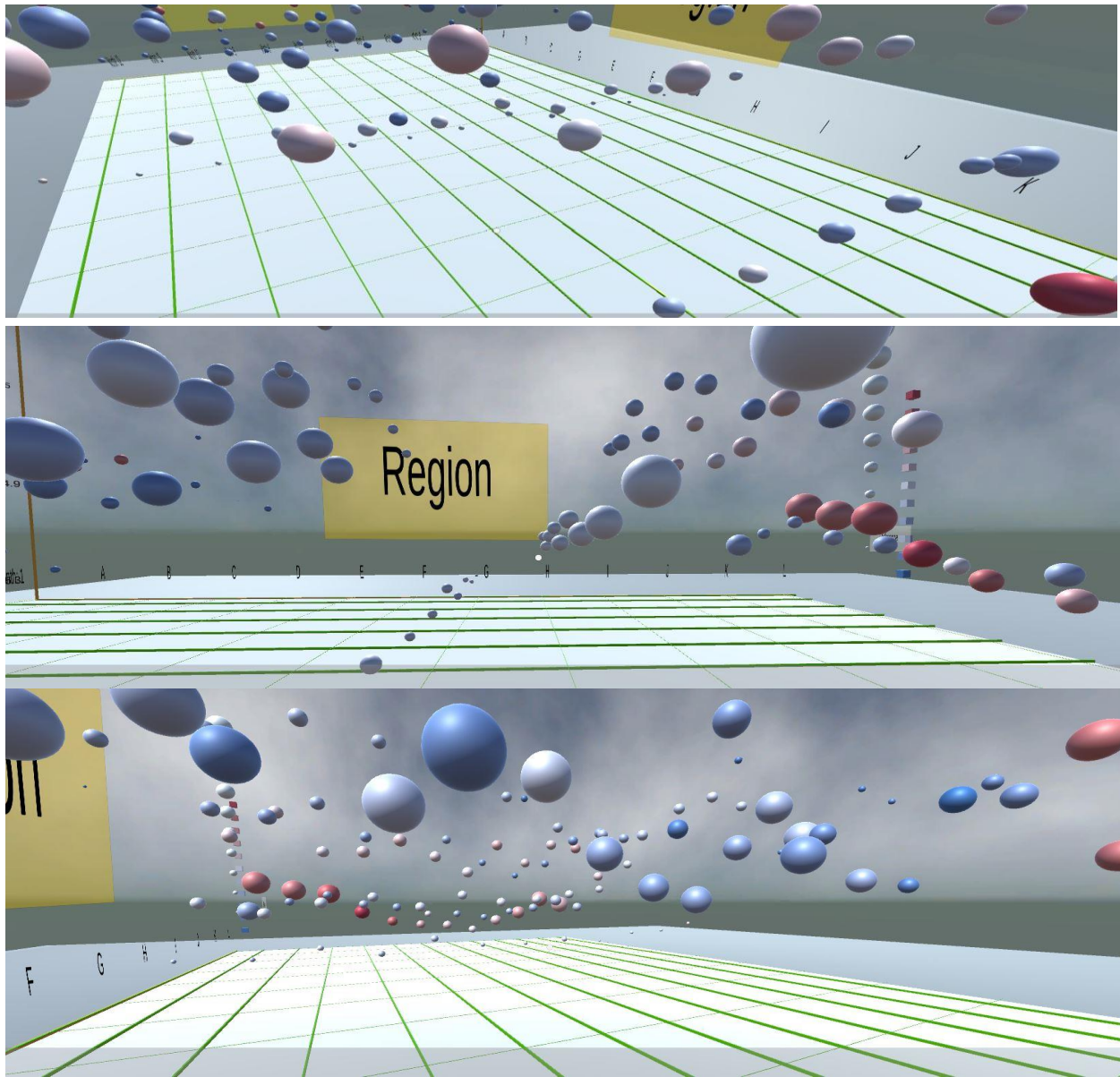


Figure 3. Application Scatter Plot

Note. This is a view of the 3D scatter plot from the Desktop application for the 5D data set from different perspectives.

Research Model

This was an experimental research with quantitative and qualitative data. It was a basic research as it dealt with theory development and refinement by aiding in laying a general guideline on how to develop visual tools in IA for multi-dimensional data.

Experimental Conditions

Before the trials started, an online questionnaire to test the participants' abilities was provided and it was multiple choice with no open-ended questions. The purpose of the questionnaire was to affirm that the participants in the study understood the statistical terminology that the tasks used. There were about 3 questions covering basic statistical concepts like determining outliers, minima, and correlation for a sample data provided by Python library seaborn. Figure 4 provides an image of the scatter plot and box plot used to understand the level of statistical knowledge. The participants were randomly assigned to either use a Desktop application or VR application for the session based on Latin Squares. Then they started a short training process with a 3D graph in their assigned application in order to get used to the tools they were going to be using for the rest of the session. The participants were interpreting the data either through a Unity developed Desktop application or through Virtual Reality by using an Oculus Quest device which Purdue provided. The experimental design was based on the experiments conducted by Bach et al. (2018), Donalek et al. (2014), Raja et al. (2004), and Whitlock et al. (2020).

Each experiment consisted of three different trials representing the three different levels of dimension. There was a 3D data set, a 4D data set, and a 5D data set, and their sequence of appearance was randomized using Latin Squares to reduce bias and lower the number of participants needed. Each dimension included a different added modality that they had to interpret: The Y-axis (vertical) for the 3D data set, the color interpolation for the 4D data set, and the size interpolation for the 5D data set. The dimensions were added on top of the same application. For each participant, for whichever application they were using, there were about 9 different tasks to complete. Figures 5 provides a better understanding of the treatment methods.

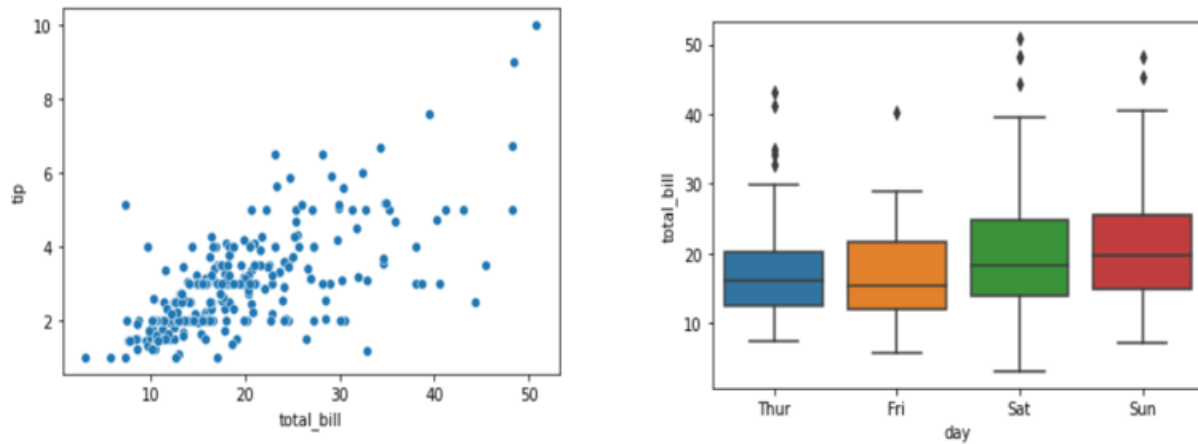


Figure 4. Questionnaire Scatter plot and Box Plot

Note. These are two simple graphs used for the statistics test. They were built using the Python library seaborn for the data set “tips”⁵.

Measurements

The study included benchmarks tasks, which means the participants needed to complete certain tasks in each trial. Participants were given three different tasks per each level of dimension in order to understand their interpretation of the data. The questions were given context by the story provided by the data set by Guttikunda et al. (2019). Qualitative data were also collected after each trial from the NTLX Questionnaire and USE Questionnaire, as well as before the trials in the pre-experimental questions.

For each level, the dependent variables were the time of completion of the trials as well as the participants’ answers for the task assignments. The independent variables in this case were the applications and the levels of dimensions. The timer started when they pressed a button in the Desktop version, or a trigger button through their hand controller in the VR, and it ended when they selected their answer. The study then was able to collect the data that the participants had provided in the form of estimations to the assigned tasks, more specifically their relative error, and time it had taken them to complete these tasks. The questions referred to the Y-axis (vertical)

⁵ *Seaborn_tips_dataset*, retrieved from <https://www.kaggle.com/ranjeetjain3/seaborn-tips-dataset>, last accessed: October 2020.

variable in the 3D data set, the color interpolation variable in the 4D data set, and the size interpolation in the 5D data set. The 3 questions/tasks were similar in nature in each to trial for similar topics. The questions included:

3D Data Set Level

- 1. What is the outlier of the city of H?*
- 2. What is the lowest emission of PM-10 for the month of August (Month: 8)?*
- 3. Which of the cities has the largest emission of PM-10 for which month?*

4D Data Set Level

- 1. What is the outlier for the city of G?*
- 2. What is the lowest emission of Sulfur Dioxide for the month of September (Month: 9)?*
- 3. Which of the cities has the largest emission of Sulfur Dioxide for which month?*

5D Data Set Level

- 1. What is the outlier for the city of A?*
- 2. What is the lowest emission of Nitrogen Dioxide for the month of May (Month: 5)?*
- 3. Which of the cities has the largest emission of Nitrogen Dioxide for which month?*

The data set provided by Guttikunda et al. (2019) was already analyzed using Python, and the answer sheet had been created in order to calculate the error rate of the students. These outputs were then compared by using Inferential Statistics, to understand the two researched questions proposed earlier.

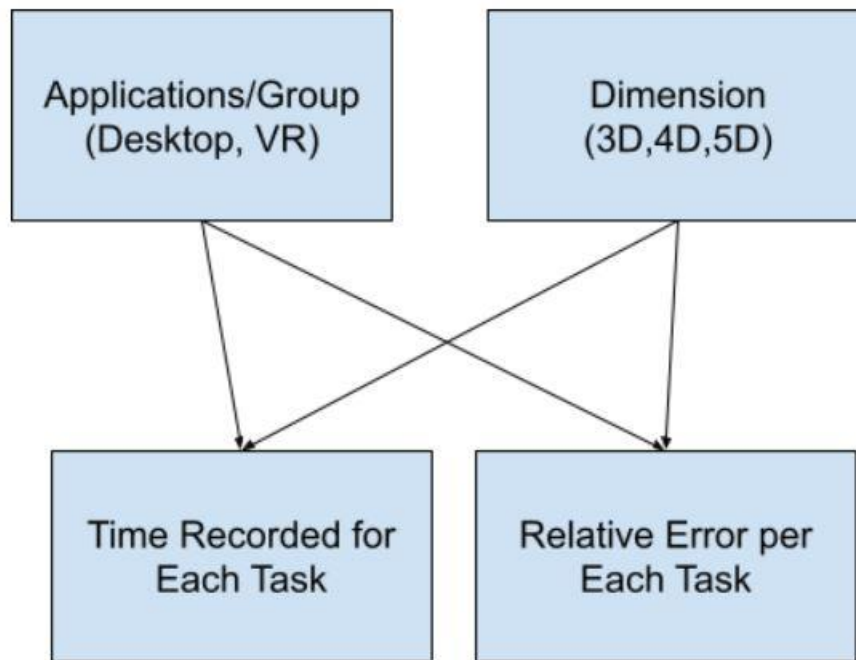


Figure 5. Diagram for Generalized Linear Mixed Effects Model

Note. This model shows the variables involved. The relative error rates and the measured time-to-completion are the dependent variables, while the dimension levels and type of application are the independent variables.

Procedure

The first step all participants completed was to read the consent form approved by IRB and sign it before starting any of the trials. When the participants were ready, they started the study. In the beginning, they had to complete a pre-experimentation questionnaire for general demographics information survey as well as a short statistics survey to understand their abilities. Then, they completed a short training session in order to get used to the environment. Once, they were ready, they were assigned into one of the groups: either VR or Desktop. There were 3 different trials they had to complete per each dimension. Once they were done with one trial, they would complete a NTLX and USE questionnaire. This would happen for all 3 trials. They were also encouraged to leave comments about some positive and negative aspects for the application in each dimension.

Unity version 2019.4.14f1 was used for all applications. The scatter plot also had similar features and interactions for all applications. The online questionnaires were created through Purdue's provided web-based survey Qualtrics including the pre-experimentation questionnaire.

The lab used was KNOY 366, which is a green room located on the third floor of Knoy at Purdue campus.

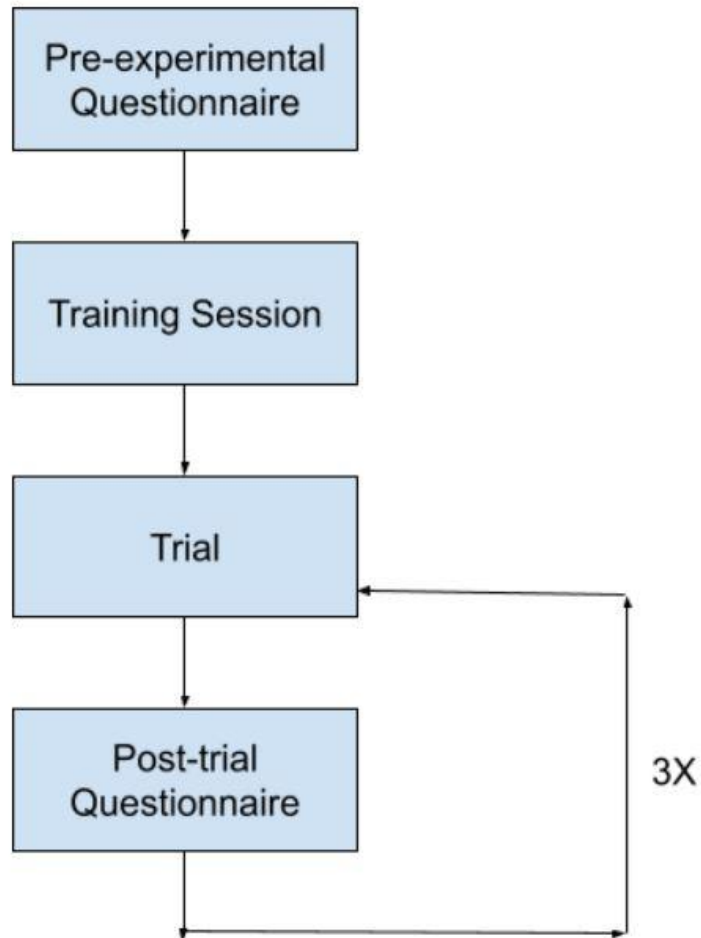


Figure 6. Diagram for the Procedure of the Study

Note. This diagram shows the steps of the study.

Developed Applications

All applications featured a 3D scatter plot with the X, Y, and Z axes showing in all levels. In all versions, the 4D graph was represented by using the X, Y, and Z axes for its first three dimensions, and color interpolation for the fourth dimension. The 5D data set also utilized the X, Y, Z axes for the first three dimensions, color interpolation for the fourth dimension, and size interpolation for the fifth dimension.

In both applications, the participants could turn 90 degrees clockwise by pressing the right mouse on the Desktop keyboard or the right thumb stick on the VR controller, or just by moving around in both applications. In Desktop for example, they could move around use the W, A, S, D keys and the mouse. They could also hoover on the coordinates of a point by click on the point. In VR, they could move around by walking, or with the right thumb stick. To hoover on the coordinates of a point, they would pick using ray tracing. For both applications, once the users picked their answers, they would be taken to the next task, their chosen point will be recorded as would their recorded time, and the timer would restart for the next task. This was all explained in the training sessions before the participants started the trials.

By introducing different levels of dimensions of data in each trial and comparing the data collected from the VR and Desktop application, the study could answer the first proposed research question and offer an understanding on how different levels of multi-dimensional data will affect the user's decoding of the data in IA. By comparing the applications, there was a much better comprehension of the last research questions on how the application can affect the judgment of the participants for each level of dimension.



Figure 7. Photos of Different Participants during the Trials

Note. The photos show a few of the participants experiencing the VR trials in the lab.

Data Collection and Analysis

Data were collected from Qualtrics for both pre-experimentation questions as well as the qualitative data from NTLX questionnaire and USE questionnaire. The quantitative data collected from within the application was analyzed using a Generalized Linear Mixed Effects Model. This model was utilized with application groups and levels of dimensions treated as fixed factors, while the participant remained a random variable. That means that there was between groups relations with the two applications (VR, Desktop) while the levels of dimensions (3D, 4D, 5D) were within groups and were considered repeated measures. By using this method, there can be drawn conclusions for each level of dimension as well as each application. The interaction between applications and levels can also be accounted for in this model. For the purpose of accuracy and the usage of a correct statistical model with the least amount of bias and error, the Purdue Statistical Consulting Services aided in this project and offered their assistance for the data analysis portion.

The anonymity of the participants was protected, and all participants were required to complete all the trials and the assigned tasks, as well as follow COVID-19 safety regulations. Afterwards, there was no follow-up procedures with the participant.

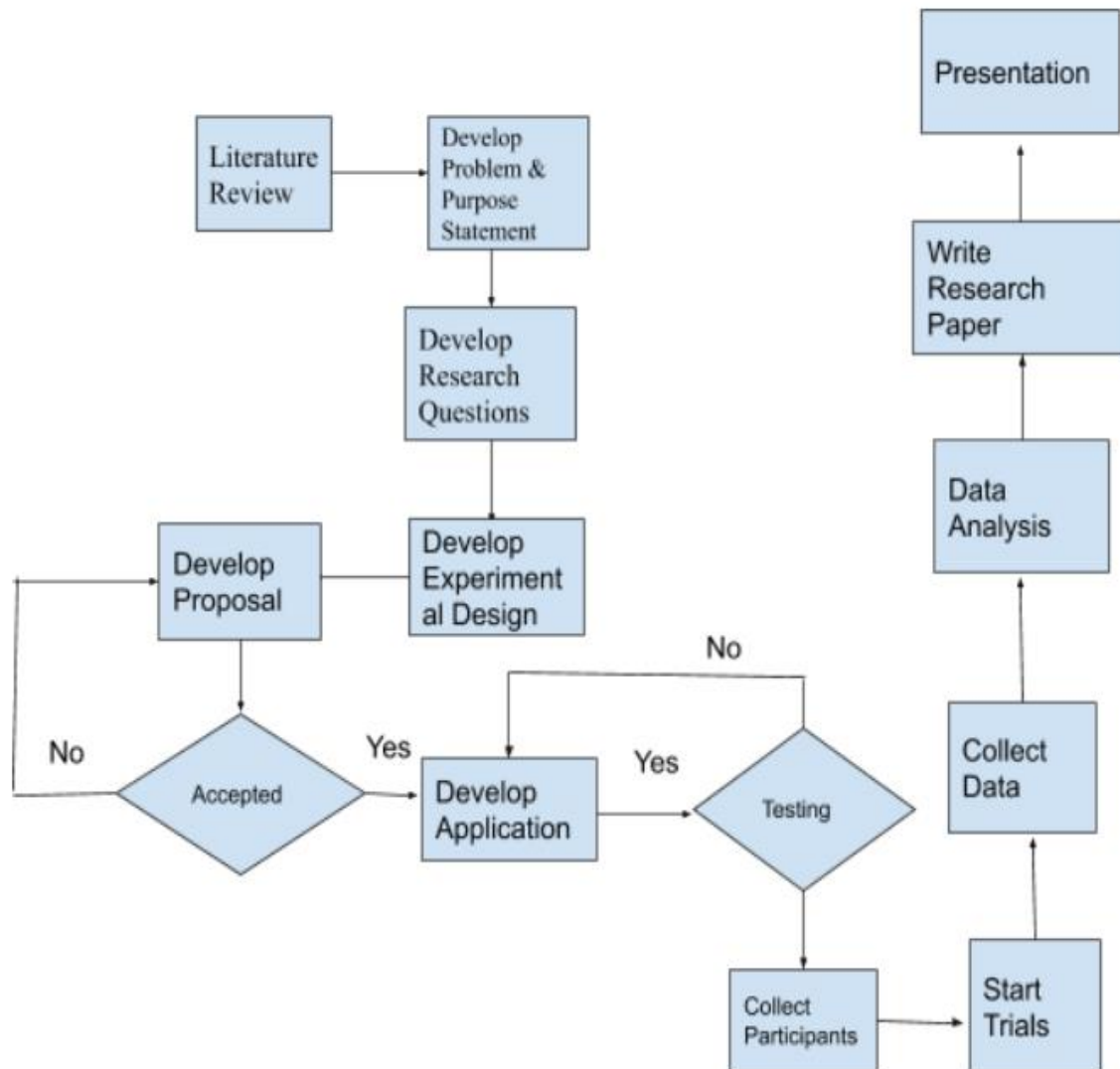


Figure 8. Flowchart

Note. This model demonstrates the flowchart representing the plan of work for this study.

CHAPTER 4. DATA RECORDING

For this study, the Generalized Linear Mixed Effects Model (GLMM) was utilized in order to analyze the quantitative data and parts of the qualitative data using different distributions. The data were first separated into the qualitative and quantitative data. The quantitative data included the responses from the tasks, the calculated relative error from those tasks and the averages per each dimension. It also included the recorded time it took each participant to complete each task as well as the average recorded time for each dimension. R and Tableau were used to visualize and test the data. A multiple comparison was completed with Tukey HSD for general post-hoc comparisons.

There were three tasks that needed to be completed in each dimension as mentioned before, but because of outliers found in task 2 and later discussed in this chapter, only task 1 and task 3 were used to calculate averages. The averages for time and relative error for each participant were named Average Time and Average Error, respectively. The independent variables and fixed effects in this case were the Dimension levels (3D, 4D, 5D) and Group types separated into VR and Desktop applications. The participants were treated as a random effect (1| ID), while the relationship between Dimension and Group was included as well (Dimension*Group). There were other effects that were considered as well, some of them incorporated from the qualitative data, that were used for a further look into the data discussed later in this chapter.

The qualitative data included the pre-experimentation questionnaire which each participant completed in the beginning of the trials, as well as the NTLX questionnaire and USE questionnaire that each participant completed after each trial. The data collected from the start of the experiment included general demographic information and a short 3 question test to take a look at the statistical capabilities of each participant which will be referred to as the Statistics Test and included in Appendix A. The USE questionnaire was broken into subsections where averages were collected for Usefulness, Ease of Use, Ease of Learning, and Satisfaction. Since each trial included 30 USE questions, as seen in Appendix C, and there were 3 trials, it was best decided to look at the averages for each subsection. Cronbach's alpha was calculated as a measure of reliability for the USE questionnaire and to confirm that cumulative scores can be used for the data analysis portion.

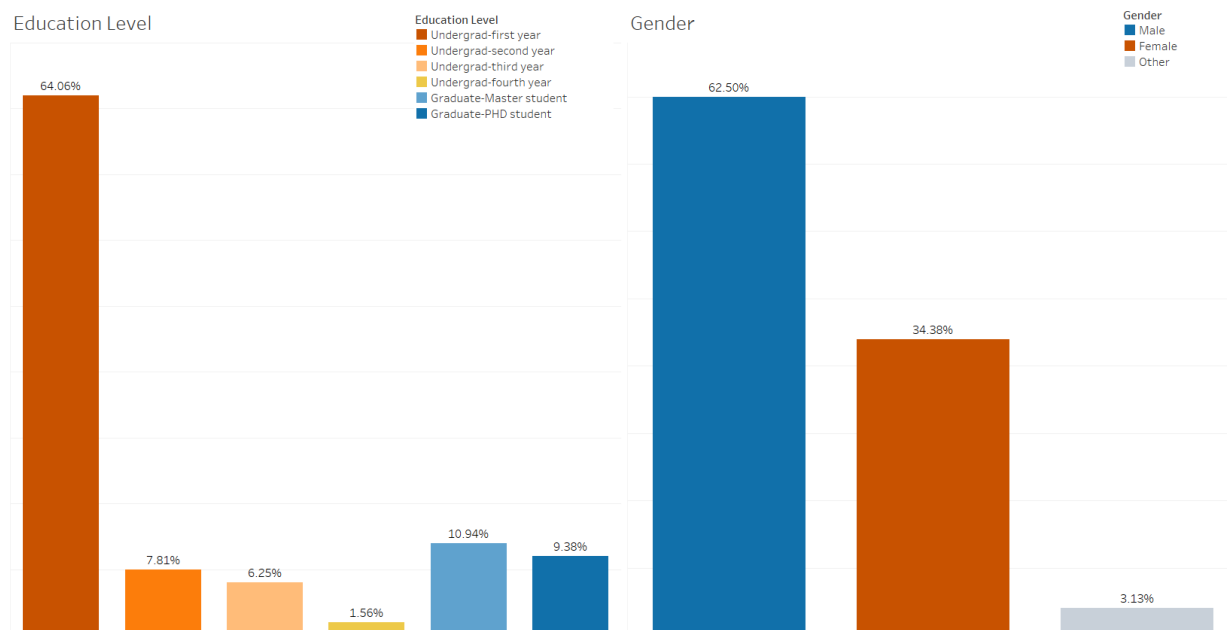


Figure 9. General Statistics for the Participants

Note. The two bar plots show the Education Level and Gender of the participants.

General Statistics

There were a total of 64 participants, all students from Purdue (Age: $M = 20.2$, $SD = 3.01$) ages ranging from 17-30 years old. As it was mentioned in the previous chapter, the participants included about 64% first year undergraduate students, about 20% graduate students, and the rest were a mix of undergraduate students from other years. As for the gender of the participants, there were about 63% male participants, 34% female participants, and the rest nonbinary or did not want to answer. Most of the participants had little to no experience with VR applications, about 75% in total, and 69% in the VR group as seen in Figure 10. About 70% of participants had either taken a statistics course at Purdue or outside of it, while the rest had not taken a statistics course before. Still from the error recorded from their answers in the Statistics Test, 61% of the participants were able to pass the survey with no errors, 36% only had one error, and 3% only had one answer right. There was no participant that received a 100% error rate for this test.

VR Experince

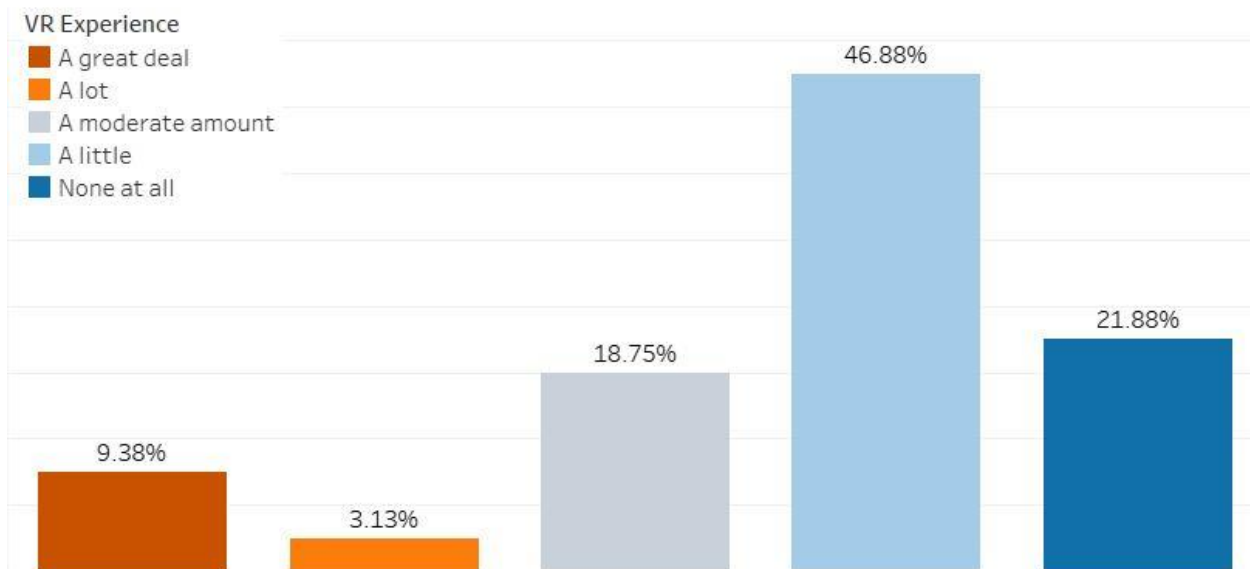


Figure 10. VR Experience for the Participants

Note. The bar plot shows the VR Experience for participants in Group VR.

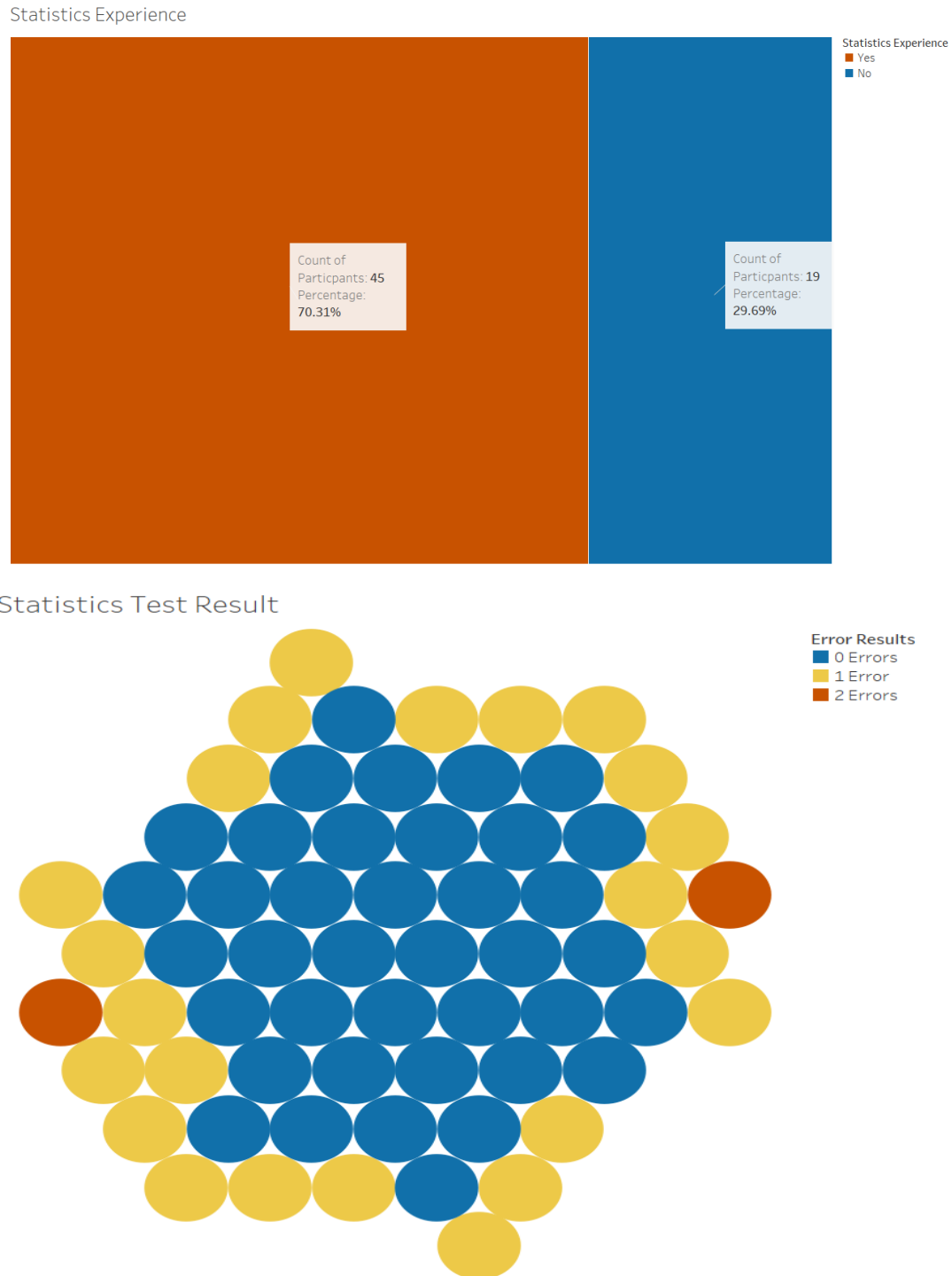


Figure 11. Statistics Experience and Test Results for the Participants

Note. The two plots show the Statistics experience participants have reported as well as their error rate in the Statistics Test.

Outliers

For the Average Time and Average Error only task 1 and task 3 were considered as task 2 had participants make some unexplainable choices, especially for the 4D trial where the participants were focusing on color. Figure 12 shows the point that 31% of participants picked vs the right answer to the question. This answer was what the majority of Desktop Group (34%) and as well as a good portion of the VR Group (28%) picked, and it had a high relative error (2.63). Although the question referred to picking the lowest value of “Month 9”, which would be the darkest shade of blue for this month, a considerable percentage of participants picked Figure 12a as their answer, although it is clearly not a close shade of blue, or close to the correct value.

This could have been a simple case of forgetting the color scale, however, the participants picked either correctly or closer shades for the other tasks (much lower relative errors), showing that they were paying attention to what they were doing. In task 3, for example they were still paying attention to color and choosing close shades of the color they are looking for. About 84% picked points that were either the correct choice or very close approximations to the correct choice with relative errors in a range of 0 to 0.1, including 70% of the participants that chose the point in Figure 12a. Actually, 100% of these participants picked the correct choice for task 1, showing that they were paying attention to what they were doing. Even when asked after the trial, the participants were usually confident with their answers.

It is curious to note that although Figure 12a is clearly not the lowest value for this Dimension, it is the lowest value for the 3D trial as it has the lowest height for that month. Still this trend, as will be discussed in the next chapter, works in a different way in the other tasks or trials. There were also smaller percentages of participants that picked points with a relative error higher than 1, about 42% in 4D, about 5% in 3D, and about 2% in 5D. These high values of relative errors only occurred for task 2. Having these results did skew the answers, and because there is not really a proper explanation that can be given, it was decided to remove task 2 completely from the comparisons.

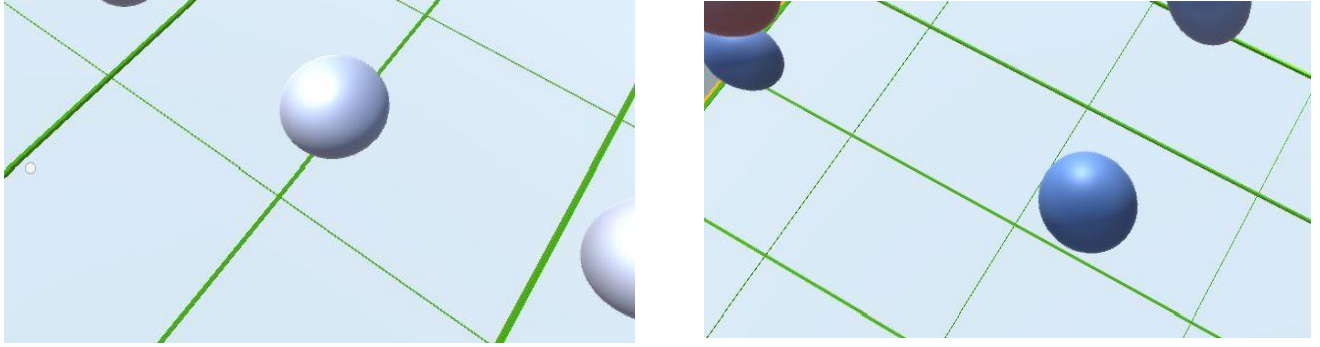


Figure 12. 4D Trial Task 2 Choices⁶

Note. The point on the left(12a) represents the wrong choice, while the point on the right(12b) represents the right choice.

Data Analysis

Average Error

When using Average Error as a response variable, significant effect was found for Dimension ($\chi^2(2, N=64) = 26.893, p < .001$) as well as the interaction between Group and Dimension ($\chi^2(2, N=64) = 12.410, p = .002$). However, there was not found a significant effect for Group ($\chi^2(1, N=64) = 2.192, p = .139$), although the overall Average Error for VR ($M=7.19, SD=12.15$) was slightly lower than that of the Desktop group ($M=7.24, SD=12.30$) agreeing with previous experiments (Millais et al., 2018; Whitlock et al., 2020). The interaction plot below, shows that there is an interaction between the different levels of Dimension and types of Groups as well.

⁶ A lot of participants picked the left point as their answer, although it was not closely related to the actual answer that is the point to the right.

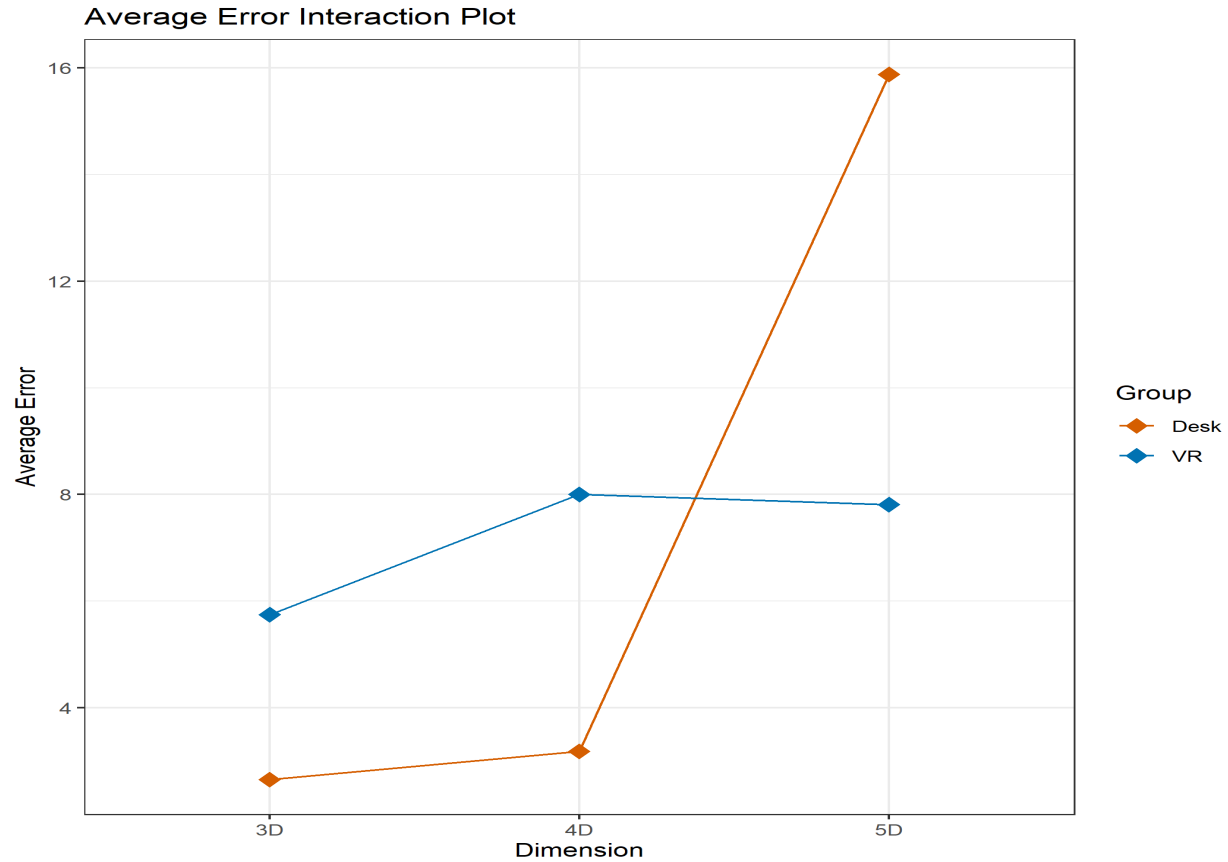


Figure 13. Average Error Interaction Plot

Note. The interaction plot shows that there is an interaction between Group type and Dimension levels. In Desktop, as the Dimension levels increase, the Average Error increases as well, however, in VR this does not seem to be the case entirely.

Although, the Desktop group follows an expected pattern that as Dimension levels increase so does the Average Error, the VR group does not seem to follow this pattern entirely as it can be seen in Table 1. The relative errors for this analysis were multiplied by 100 to calculate the averages.

Table 1. Descriptive Statistics for Average Error

Group-Dimension	Average	Standard Deviation	Maximum	Minimum
VR-3D	5.75	12.05	57	0
VR-4D	8.00	12.86	46	0
VR-5D	7.81	11.78	45	0
Desktop-3D	2.66	7.18	32	0
Desktop-4D	3.19	8.87	46	0
Desktop-5D	15.88	14.76	45	0

According to Tukey HSD for general post hoc comparison, there was a significant change between the Dimension levels in Desktop (Desk 3D - Desk 5D: $p = .002$; Desk 4D - Desk 5D: $p = .003$). There was also a significant change between the different Dimension levels (3D - 5D: $p = .002$; 4D - 5D: $p = .012$). Overall, the VR group had a lower Average Error in 5D than in 4D. For both groups however, 3D had the lowest Average Error, although the Desktop group performed much better than VR. However, the VR group appeared to have done much better than the Desktop group in 5D leading to some interesting insights in the next chapter.

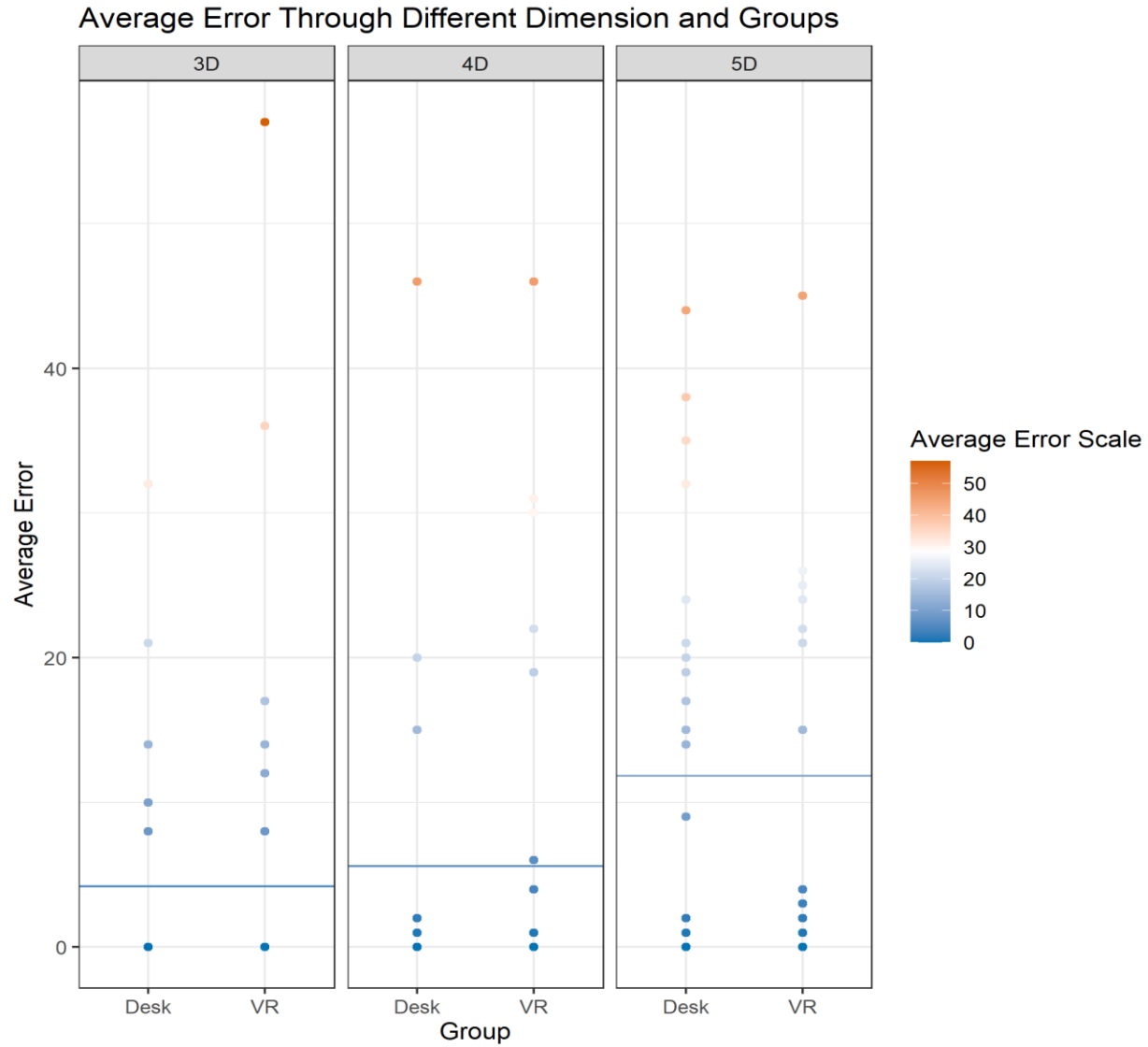


Figure 14. Average Error Distribution Graph

Note. The horizontal reference line shows the average for each Dimension. Considering only Dimensions, it keeps increasing after each level.

Dimension Order was also treated as another effect that could have affected the response variables. Dimension Order refers to the order that a specific Dimension level was presented to the participant. For example, the 3D trial for some subjects was their first trial and for others, it was their second trial or third trial. However, it seems to have had no significance ($\chi^2(2, N=64) = 2.929$, $p = .231$) on Average Error. There was also no significant difference with error in the Statistics Test that the students answered in the beginning of the experiment ($\chi^2(2, N=64) = 0.269$, $p = .874$), or their experience in statistics ($\chi^2(1, N=64) = 1.572$, $p = .210$), which is why participants with low

experience were not removed from the data set. VR experience also did not seem to be significant ($\chi^2(4, N=32) = 5.005, p=.287$).

Average Time

When using Average Time as a response variable, significant effect was found for Dimension ($\chi^2(2, N=64) = 19.913, p < .001$), however this was not the case for the Group and Dimension interaction ($\chi^2(2, N=64) = 0.968, p = .616$), as well as Group only ($\chi^2(1, N=64) = 2.3593, p = .125$). Overall, the VR application took more time ($M = 45.78, SD = 31.89$) than the Desktop application ($M = 36.38, SD = 20.52$).

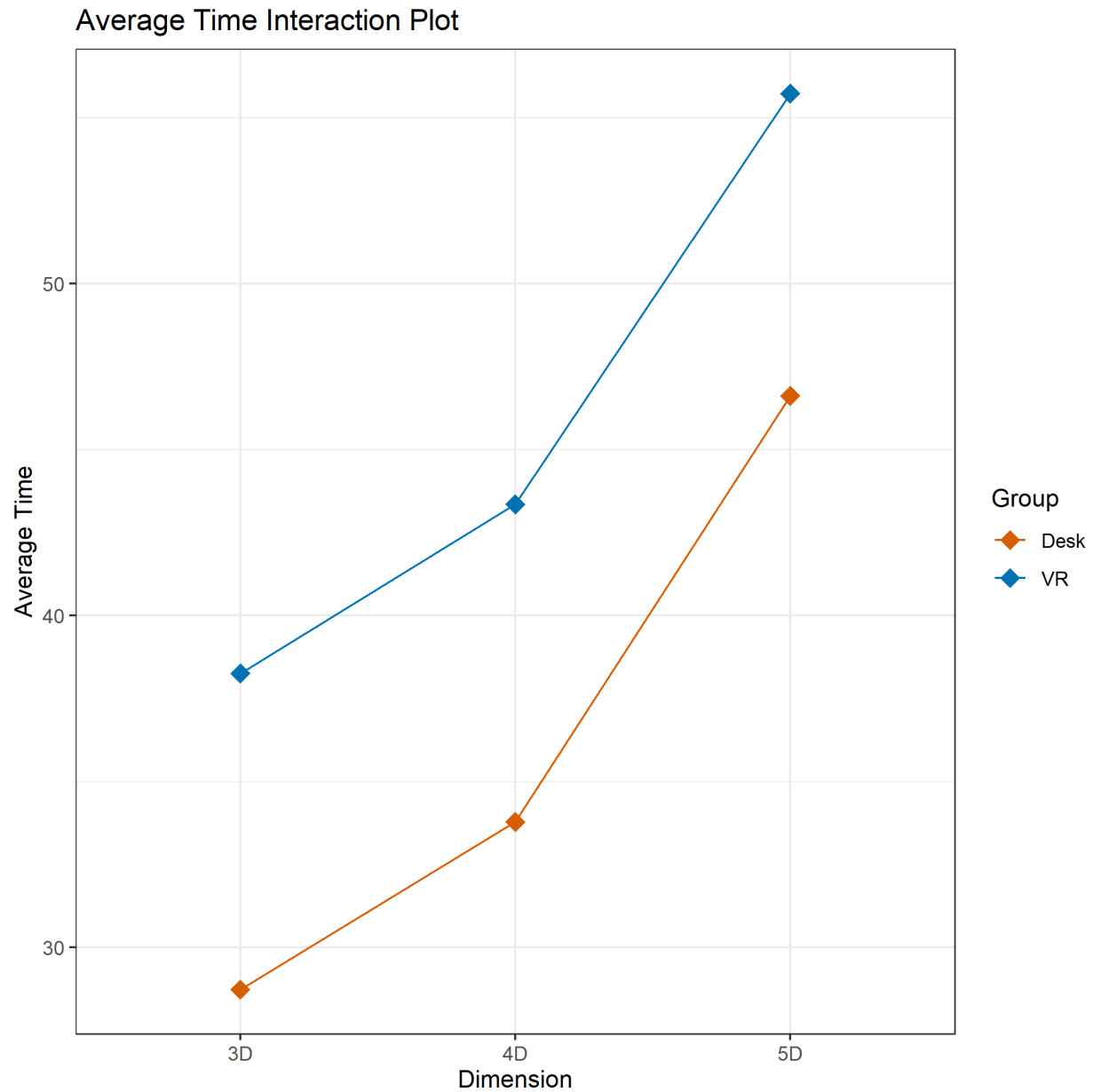


Figure 15. Average Time Interaction Plot

Note. The interaction plot does not show any interaction between Group and Dimension as they both follow similar patterns.

The Average Time also tended to increase as Dimension levels increased for both Desktop and VR application as it can be seen below in Table 2. The time is calculated in seconds.

Table 2. Descriptive Statistics for Average Time

Group-Dimension	Average	Standard Deviation	Maximum	Minimum
VR-3D	38.26	24.64	138.5	9.84
VR-4D	43.35	19.00	87.41	13.12
VR-5D	55.73	44.52	263.49	14.12
Desktop-3D	28.73	19.58	109.76	12.54
Desktop-4D	33.78	16.47	86.46	12.58
Desktop-5D	46.62	21.45	95.17	16.6

This was also expected as each Dimension would increase the number of variables the participants would have to focus on, introducing more distractions in the plot. Although, it took more time for participants of each Group to complete their tasks in 5D, the VR Group still had a lower Average Error than the Desktop Group. Using Tukey HSD for general post-hoc comparison, there were significant comparisons between the different Dimension levels and Group types as it can be seen in Table 3. There were also significant changes between the Dimensions (3D - 5D: $p < .001$; 4D - 5D: $p < .001$). In both groups, there was a significant increase in time for the 5D trial.

Table 3. Significant Comparisons Results from Tukey HSD on Average Time

Group-Dimension 1	Group-Dimension 2	<i>p</i> -value
Desktop-3D	Desktop-5D	.001
Desktop-3D	VR-5D	<0.001
Desktop-4D	Desktop-5D	.033
Desktop-4D	VR-5D	.012
VR-4D	VR-5D	<.001
VR-3D	VR-5D	<.001

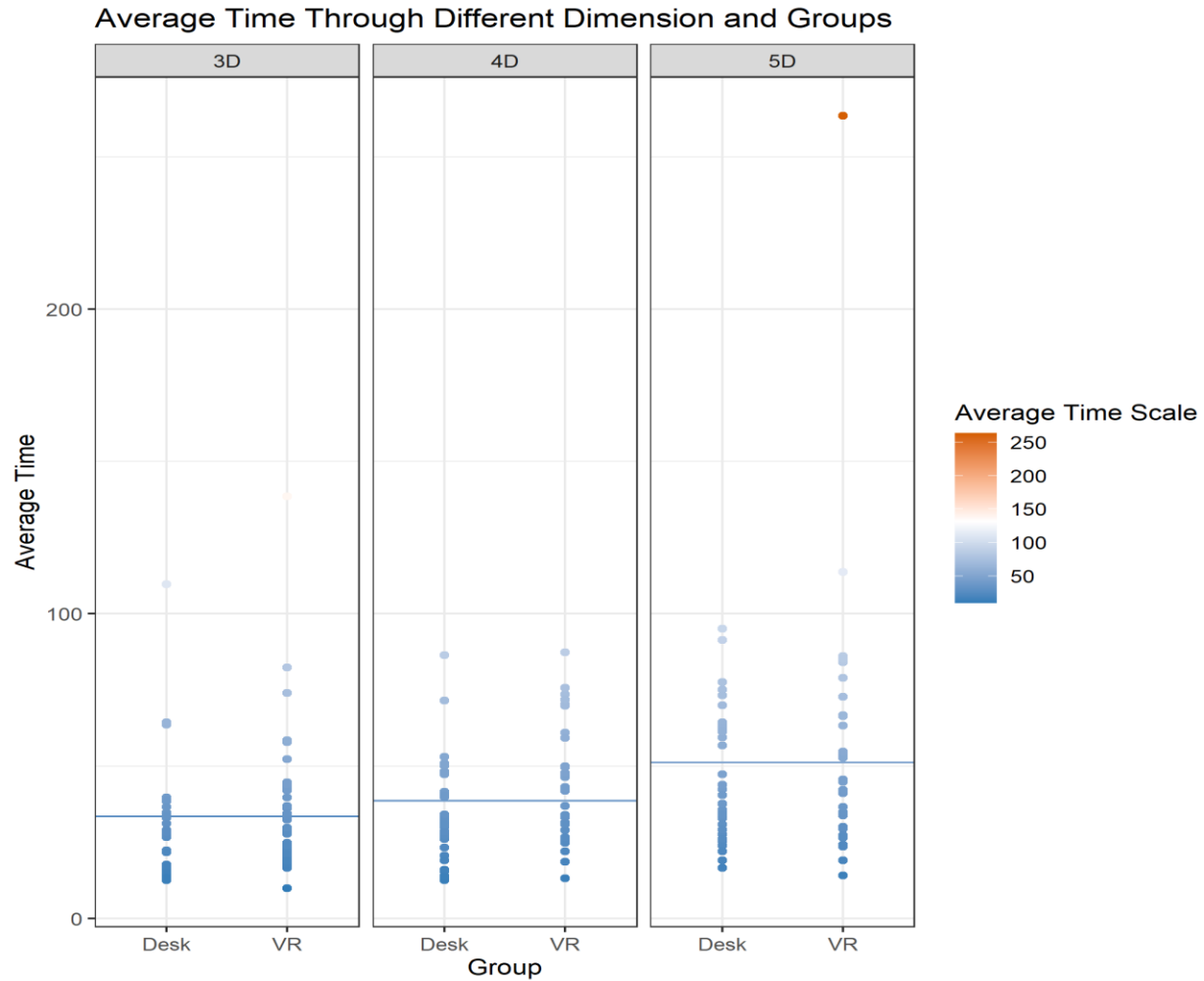


Figure 16. Average Time Distribution Graph

Note. The horizontal reference line shows the average for each Dimension.

Unlike, in the previous subsection, Dimension Order appeared to have a significant effect on Average Time ($\chi^2(2, N=64) = 27.659, p < .001$). As seen in Figure 17, the first trial usually took the longest time in each Group as the participants were still getting used to the application. Except for the 5D trial, if the level were presented first, it would take the most time and if it were presented last, it would take the least time. This is also supported by Tukey HSD that shows significant change between the first and last trial ($p = .002$) as well as the first and second trial ($p < .001$). Like Average Error though, there was also no significant difference with error in the Statistics Test that ($\chi^2(2, N=64) = 3.534, p = .171$) and their experience in statistics ($\chi^2(1, N=64) = 0.879, p = .348$). Surprisingly, VR experience also did not seem to be significant for Average Time ($\chi^2(4, N=32) = 4.747, p = .314$). However, a large number of participants (65%) did have no to little experience in

VR and Dimension Order had a significant effect on time, so it is not a factor that should be completely excluded from the discussion. Figure 17 shows that as participants complete each trial and are more exposed with the applications, they generally spent less time for both applications, including VR. Exposure to the application could have considerable effect on their time and it is something it should be looked further into (Bach et al., 2018).

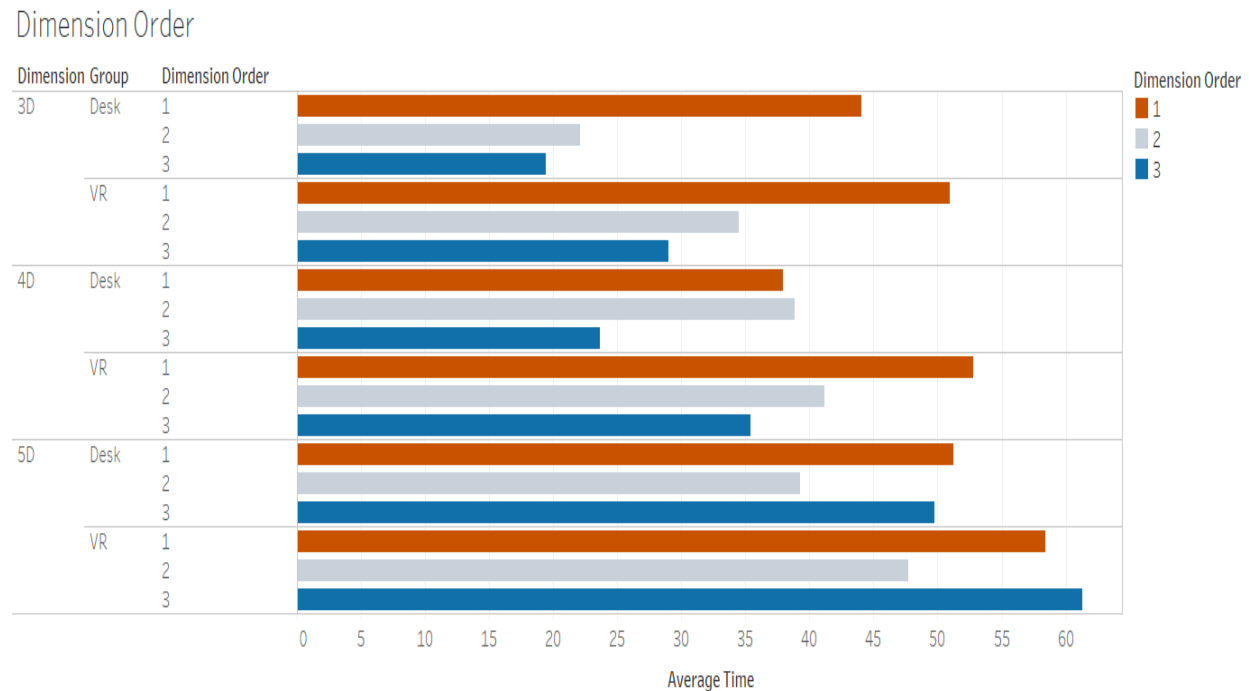


Figure 17. Dimension Order Bar Chart

Note. The bar chart shows the order each Dimension level was presented in the x-axis.

NASA Task Load Index Questionnaire

The NTLX Questionnaire includes 6 different statements which the participants rated after each trial. (Hart, 1986). It provides an overall workload score based on (1) Mental Demand, (2) Physical Demand, (3) Temporal Demand, (4) the Subjects' Performance, (5) their Effort as well as (6) Frustration or major stress. The scale used was calculated between 1-7, each number representing "Strongly Disagree", "Disagree", "Somewhat Disagree", "Neither Agree or Disagree", "Somewhat Agree", "Agree", and "Strongly Agree" respectively. In the last chapter it was mentioned that the participants took the NTLX survey after each trial or Dimension level and

those levels were randomly ordered per participant and were referred to as Dimension Order as before. A one-way repeated measures ANOVA test was applied for each question to check if the order of the Dimension levels had any effect or difference in the responses of this questionnaire, however only Mental Demand showed significance ($F(2,63) = 7.443, p < .001$). Looking at Figure 18, it appears that the first trial took more mental effort, however after that, the tasks might have seemed much easier to complete for the participants. This could have to do with the participants “getting used” to the application or the environment. Although the participants might have started to believe they were doing better as the nature of the tasks was similar per each trial/Dimension, it really had no effect on their performance as observed in Average Error.

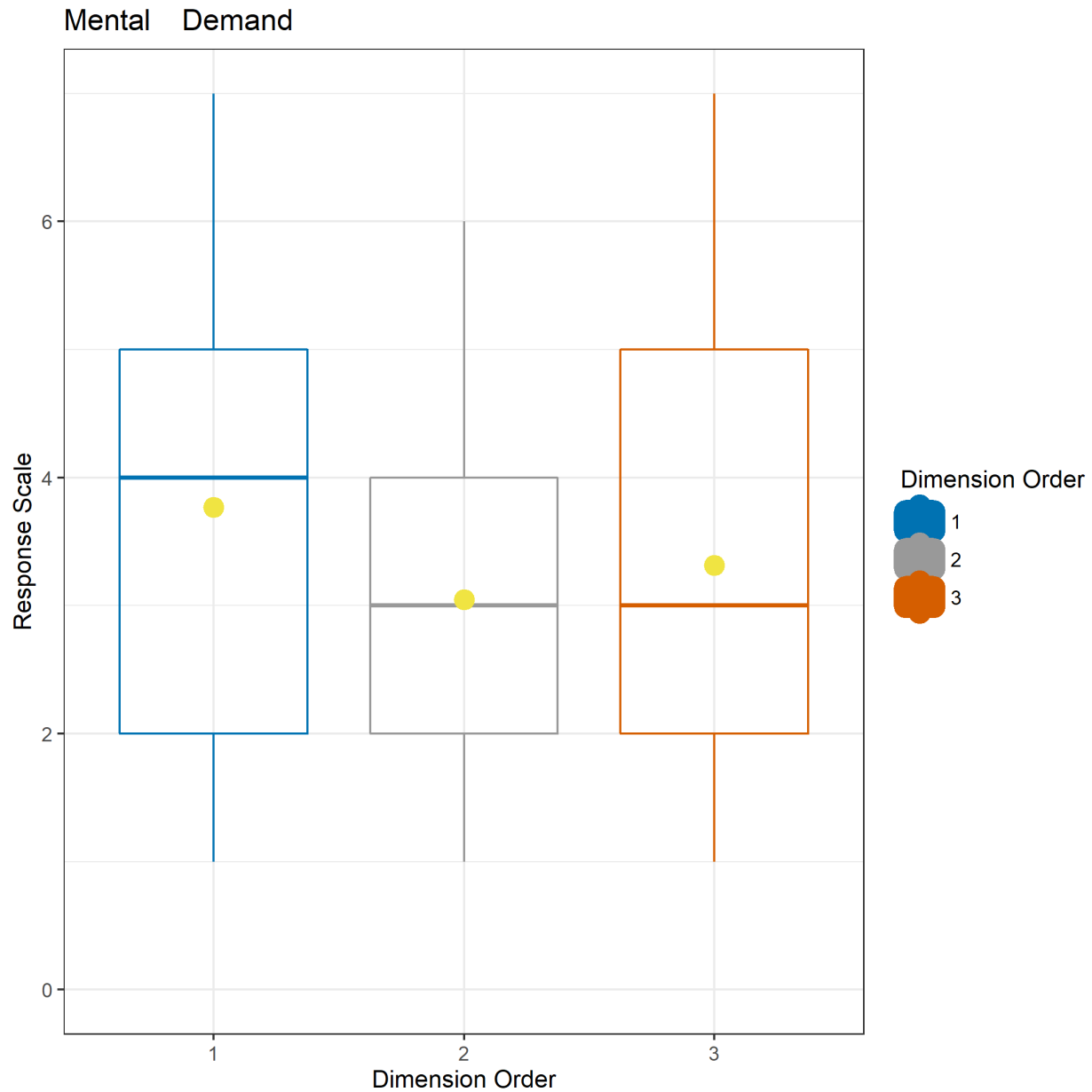


Figure 18. NTLX Mental Demand Boxplot

Note. The first trial, not matter what Dimension, offered the participants more mental demand. The yellow points represent the average for that Dimension Order.

There was no significant effect when Average Error or Average Time were used as response variables for either question or statement. There was also no significant comparison for type of Group and Dimension level using a two-way MANOVA test or any interaction between them.

For the first statement responding to Mental Demand, about 43% of the responses disagreed or somewhat disagreed with it, with only 24% somewhat agreeing at most. With question 2, 44% of the responses strongly disagreed and another 44% were either disagreeing or somewhat disagreeing. Yet the overwhelming majority did not agree that there was any kind of Physical Demand for both Desktop and VR, although more physical movement was needed in VR. Question 3, representing Temporal Demand, also followed a similar pattern with 78% of the responses disagreeing or strongly disagreeing. This is surprising as there were significant changes in Average Time according to different Dimension levels, with the 5D trial taking a lot of time for both Groups as it was discussed in the last subsection. However, the participants did not seem to have realized this. This is especially true for the VR Group that had a high rate of disagreement for the 5D trial, although it took more time in average than the other Dimension levels.

The participants' performance, question 4, is where there were found more positive responses. About 61% of the responses either agree or strongly agree that they were confident in their performance. Question 5 had more of a neutral leaning as 17% of the participants neither agreed or disagreed, yet there were far more disagreements than agreements with 22% somewhat disagreeing for spending effort and 20% somewhat agreeing for spending effort. The last question referring to the participants encountering any type of frustration or stress received many disagreements. About 68% of the responses either strongly disagreed or disagreed with this statement. This did not always agree with the comments, many of the comments mentioned the height or the size of points being difficult to distinguish without moving around a lot. However even with these complaints, there were not any major frustrations or demands expressed in the NTLX responses. It is interesting to note though, that the Desktop group had a higher rate of frustrations and a lower rate of subject performance with the 5D trial compared to its other Dimension levels or even the VR Group as it can be seen in the heatmap below.

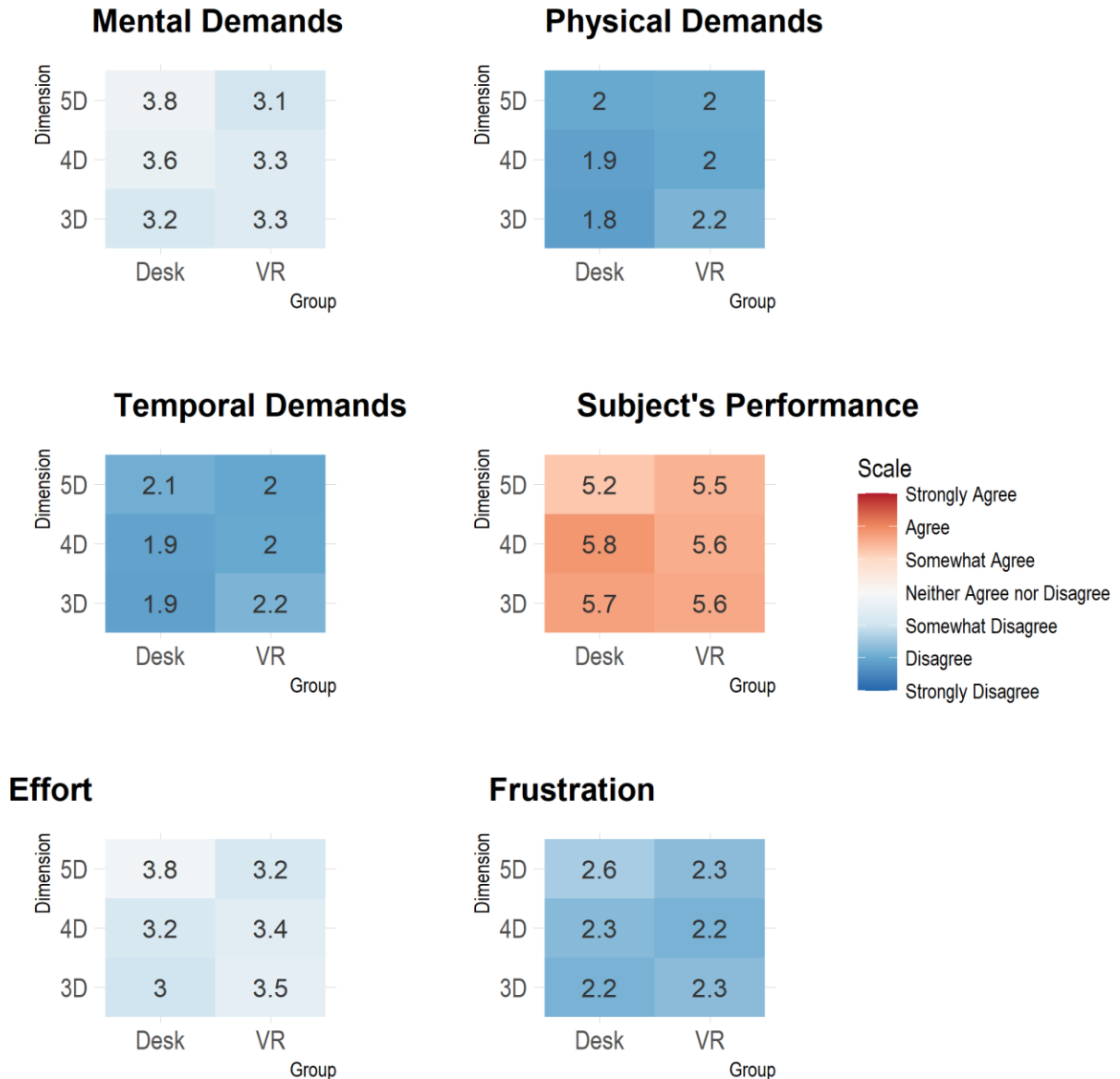


Figure 19. NTLX Heatmap

Note. The heatmap show the average response for each statement. The numbers represent the averages of ratings per each Group and Dimension.

For both applications, there did not seem to be any significant physical, temporal, or any major frustrations. Although, VR took much more time for the participants to complete, this sentiment was not really shared in the responses as there was no significant comparison between the two Groups. The VR participants might have not thought that VR took a lot of time to accomplish as seen by their ratings in Figure 19 as well as Figure 20. Mental Demand ratings

appeared to decrease after each trial, but it still had no significant effect on their performance. There does seem to be a trend that as the Dimension levels increase the ratings for the workload increase in Desktop which can also be seen in Figure 20, while the opposite is happening in VR except for Frustration. However, there are not any significant comparisons between the Groups and Dimension levels, and it requires a deeper investigation. Majority of the participants appeared to not have spent high effort and they were somewhat satisfied with what they picked as seen from the high ratings in Subject Performance.

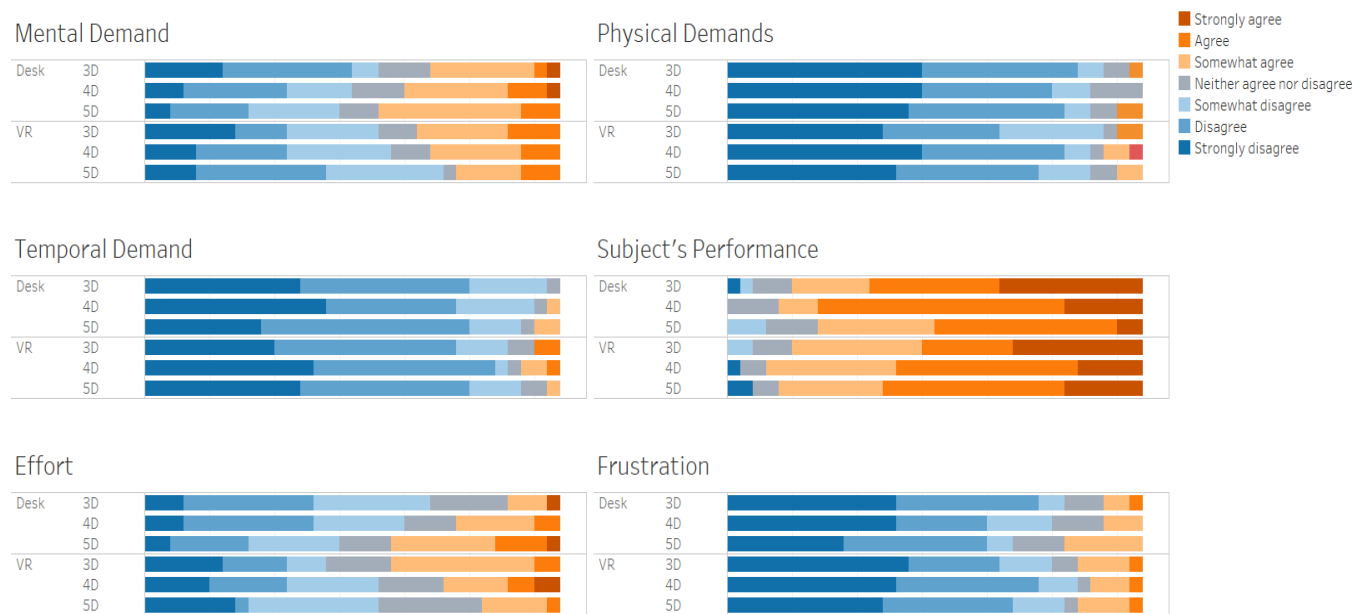


Figure 20. NTLX Bar Plot

Note. The heatmap shows all the response for each statement, each Group, and each Dimension level.

USE Questionnaire

The USE questionnaire focuses on the usability of the application, in this case containing different questions under 4 subsections: Usefulness, Ease of Use, Ease of Learning, and Satisfaction. Like before, the scale used was 1-7, however this time it was referring to “Extremely Useless”, “Moderately Useless”, “Slightly Useless”, “Neither Useful nor Useless”, “Slightly Useful”, “Moderately Useful”, and “Extremely Useful”. Cronbach’s alpha was also calculated for the survey subsections showing a reliable test and supporting that a cumulative score can be used for each subsection as seen in Table 4.

Table 4. Alpha Values for USE Questionnaire Subsections

Sections	Alpha Value
Usefulness	0.84
Ease of Use	0.89
Ease of Learning	0.81
Satisfaction	0.90

For the data analysis portion, GLMM was utilized for each subsection in order to look at the effect of Group types and Dimension levels. The order of the trials or Dimension levels was also utilized here as Dimension Order, and unlike the NTLX data, there was some significance in the order in which the dimensions were presented, as well as Group types and Dimension levels for the USE responses. First the Usefulness subsection showed significance for Dimension Order ($\chi^2(2, N=64) = 10.421, p = .005$), Group ($\chi^2(1, N=64) = 4.233, p = .040$), Dimension ($\chi^2(2, N=64) = 8.036, p = .018$), and even the interaction between Group and Dimension ($\chi^2(2, N=64) = 6.335, p = .042$). As for Ease of Learning subsection there did not seem to be any significance, although it has many positive ratings. Ease of Use only showed significance for Dimension Order ($\chi^2(2, N=64) = 18.257, p < .001$) and Satisfaction only showed significance for the interaction between Group and Dimension interaction ($\chi^2(2, N=64) = 6.761, p = 0.034$). There was also another analysis completed where the subsections were used as effects for the Average Error and Average Time, and like the NTLX analysis, the participants' rating of the application did not really seem to affect their performance either. There was no significance between their rating and their error rate or time spent in the application. Although just like NTLX, the participants felt more confident about their results after each trial.

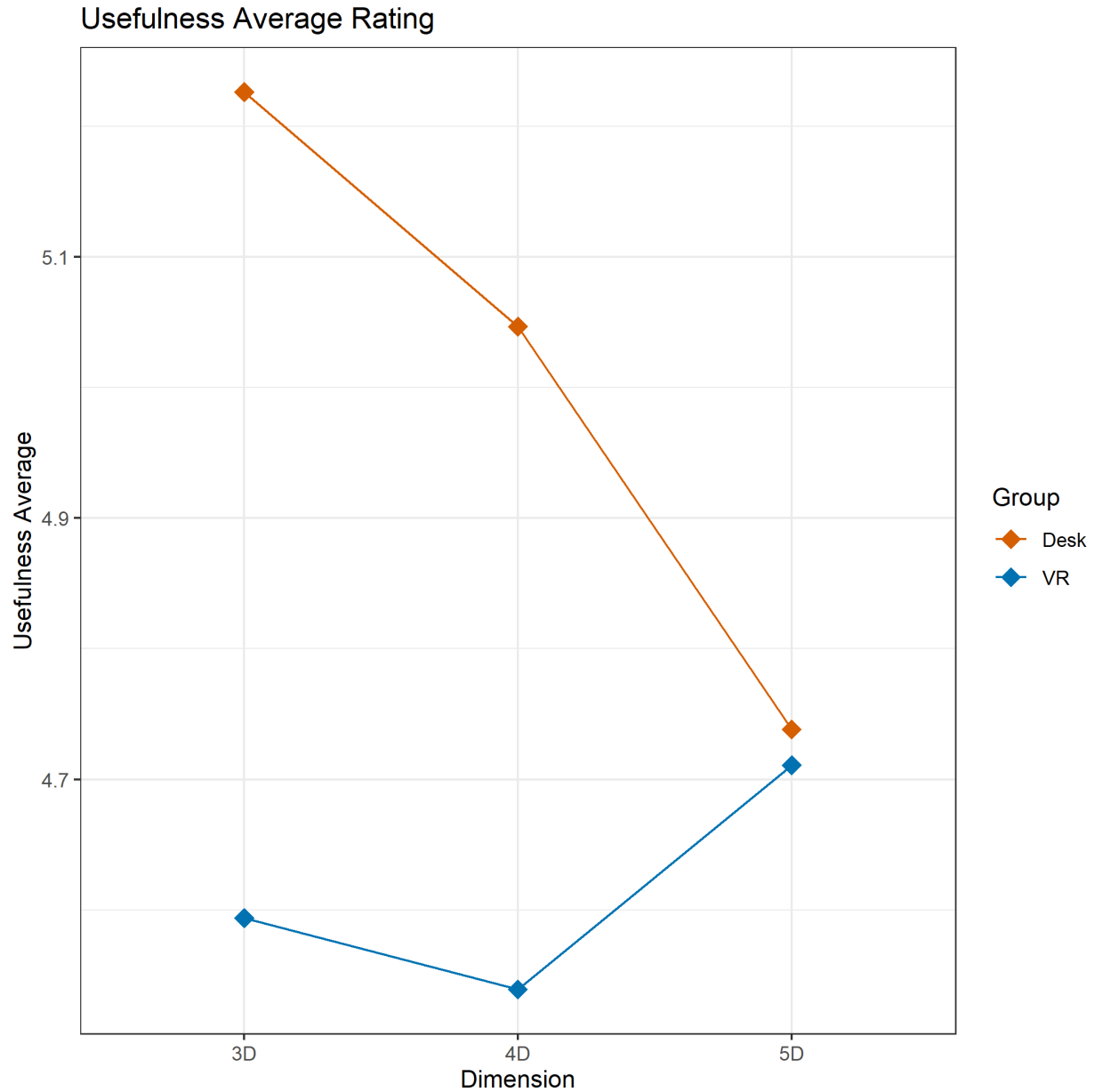


Figure 21. Usefulness Average Rating Interaction Plot

Note. The interaction plot shows the average rating for Usefulness.

Tukey HSD was also used for general post-hoc comparisons. For Usefulness, there was a significant comparison between the first and last trial (1 – 3: $p = .005$) as well as the Dimension Order and Group interaction (1 Desk - 3 Desk: $p = .011$; 1 VR - 3 VR: $p = .011$). Looking at the boxplot for Usefulness as well as the data analysis, the participants would rate higher in Usefulness after each trial for both Groups. As they spent more exposed to the application, on average they

would rate it higher in Usefulness. Overall, the VR application had higher ratings of Usefulness from 3D to 5D while the opposite occurred in the Desktop application as seen in the interaction plot above as well as Table 5.

Table 5. Descriptive Statistics for Usefulness Ratings

Group-Dimension	Average	Standard Deviation	Maximum	Minimum
VR-3D	4.59	1.43	6.63	1
VR-4D	4.54	1.27	6.5	2.13
VR-5D	4.71	1.29	6.75	1.5
Desktop-3D	5.23	1.26	7	1
Desktop-4D	5.05	0.99	6.38	2.25
Desktop-5D	4.74	1.12	7	2.25

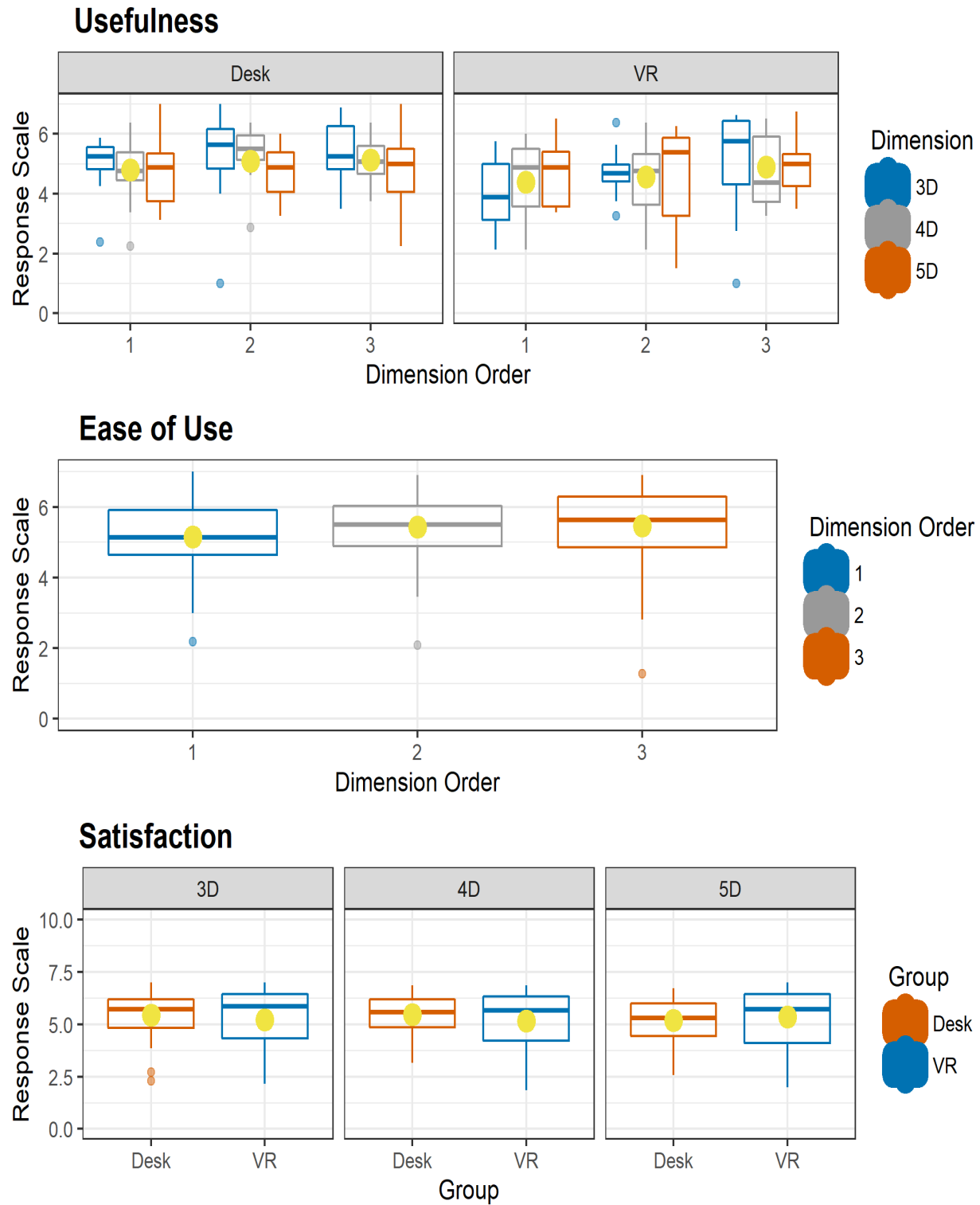


Figure 22. Usefulness, Ease of Use, Satisfaction Boxplots

Note. The Boxplots for the Usefulness, Ease of Use and Satisfaction subsections. The yellow points represent the averages.

For Ease of Use, like the mental demand in NTLX, the trials would become easier for the participants after more exposure no matter Group type or Dimension level. Like mental demand there was also significance between the first and last trial (1 – 3: $p < .001$) and first and second trial (1 – 2: $p = .002$).

Table 6. Descriptive Statistics for Satisfaction Ratings

Group-Dimension	Average	Standard Deviation	Maximum	Minimum
VR-3D	5.21	1.41	7	2.14
VR-4D	5.17	1.39	6.86	1.86
VR-5D	5.34	1.34	7	2
Desktop-3D	5.42	1.13	7	2.29
Desktop-4D	5.45	0.94	6.86	3.14
Desktop-5D	5.18	1.07	6.71	2.57

For Satisfaction, there was also an inverse relationship between the ratings of VR and Desktop applications. Although 3D and 4D in Desktop were satisfactory, the rating for Desktop in 5D fell, while the opposite happened for VR application.

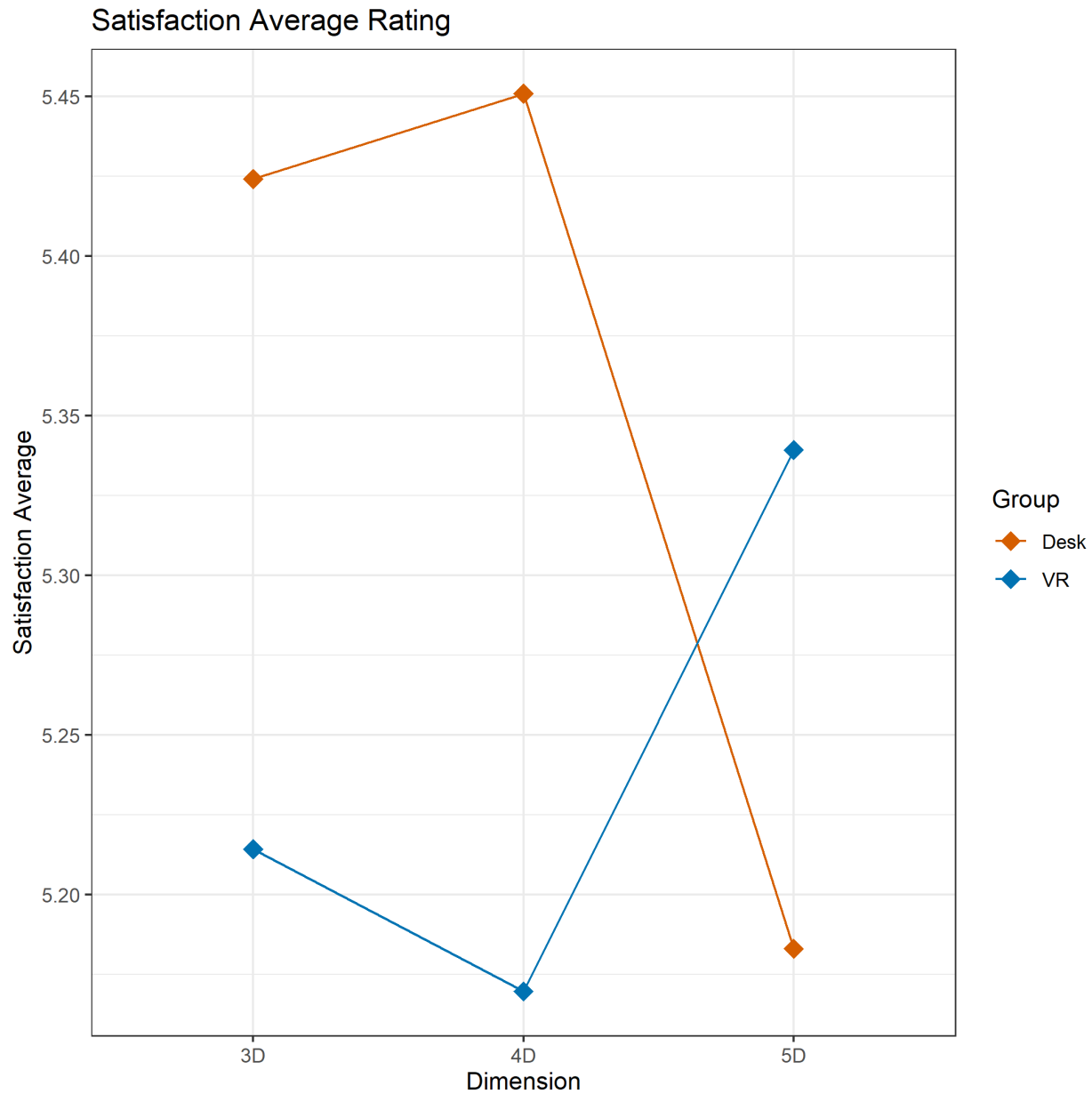


Figure 23. Satisfaction Average Rating Interaction Plot

Note. The interaction plot shows the average rating for Satisfaction.

Overall, the responses for this survey were positive, especially for the Ease of Learning subsection where 46% found it “Extremely Useful”. As for Usefulness, about 60% of responses found the applications either “Slightly Useful” or “Moderately Useful”. In other subsections like Ease of Use, 47% responses found the applications “Moderately Useful”, and “Extremely Useful”, while for Satisfaction 54% noted the applications as “Moderately Useful”, and “Extremely Useful”.

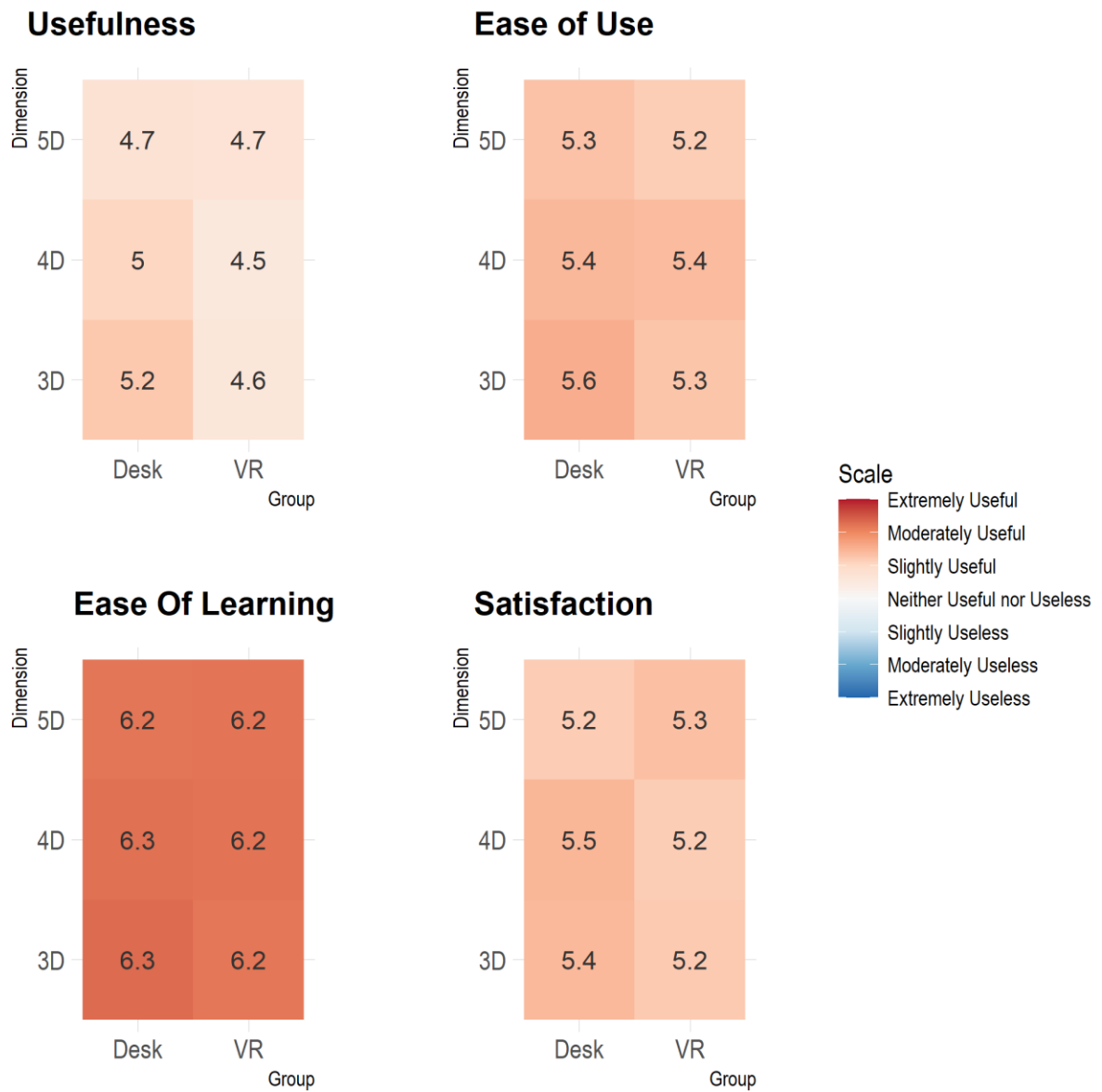


Figure 24. USE Heatmap

Note. The heatmap show the average response for each question. The numbers represent the averages of ratings per each Group and Dimension.

CHAPTER 5. OVERVIEW

Overall, there were some significant differences between the applications and Dimension levels looking at the qualitative data, however, there did seem to be some interesting patterns, looking at the quantitative data, specifically their Average Error. From the data, it seems that what type of Dimension level and Group type is used, it has some type of effect on the user's judgement of the data. Some of these results may contradict with some studies, specifically Average Time, and others are supported like the qualitative data and the overall Average Error.

During the study, there were also some limitations or recommendation for future studies that were observed more closely, and this paper wants to explore. There are a lot of different opportunities that can be explored moving on from this research.

Desktop VS VR in Different Dimensions

Although Desktop did outperform VR in the 3D and 4D levels, the VR Group did much better on the 5D level, while the Desktop Group had a lot more errors. The qualitative data did reflect this with the participants' ratings of NASA and USE questionnaires as well as their comments. Participants reported to not have difficulty with learning though in both Groups and as seen by the NTLX and USE questionnaires, feeling more confident by each trial: *"Easy to learn and use, I could eventually answer with confidence"*(3D Desktop) and *"The application itself is easy to navigate and easy to learn... I did not feel too stressed out like the first trial which is a benefit"*(4D VR). This was also reported on Simpson et al. (2017) where the participants had no apparent difficulty learning the VR system.

3D Trial

The Desktop application appeared to do much better than the VR in this trial. The 3D trial also took the least amount of time for the Desktop and VR Group. According to some comments from both Desktop and VR group though, they felt they had to move more since they were using height and needed to look around the 3D environment: *"It required the most movement inside the simulation"* (3D Desktop). Although qualitative data like NTLX does not show any major differences between these two, there was an interesting comment from VR Group: *"The only*

negative for this specific program I was in was you could complete it more quickly and accurately on a desktop” (3D VR).

About 91% of the participants of Desktop Group picked the right answer for task 1 and 94% picked the right answer for task 3 compared to the VR Group that included 94% of the participants pick the right answer for task 1 but only about 66% pick the right answer for task 3. Height also had some effect in this choice as it was a limitation in VR. A couple of participants wanted to be able to observe the graph by moving vertically as well. However, Desktop also presented some difficulties as a participant mentioned: *“It was a bit difficult to determine the height when not being able to see the spheres from a completely horizontal aspect” (3D Desktop).* It is also important to note that participants did find the 3D trial easy, interesting, and fun to participate in. As a participant mentioned, height in this case was intuitive and they were glad that they only had to deal with one modality: *“This time however, since I only needed to focus on the height and not the color or size, I felt I could do it much faster” (3D Desktop)* and *“Only having to pay attention to location and not being concerned with size or color was a positive” (3D VR).* It is not very surprising that 3D had the lowest Average Error and Average Time for both applications. As it can be seen in Figure 25, 3D overall had high percentages of participants picking the correct choice. It must also be noted, however, that there were no significant comparisons between the VR and Desktop Groups for the 3D level specifically. Instead, there seem to be more significant comparisons between the two Groups as Dimension levels are increased. As another participant mentioned in Desktop Group: *“This was much better than the 5D graph. I feel that this software is much suited for 3D than 5D” (3D Desktop).*

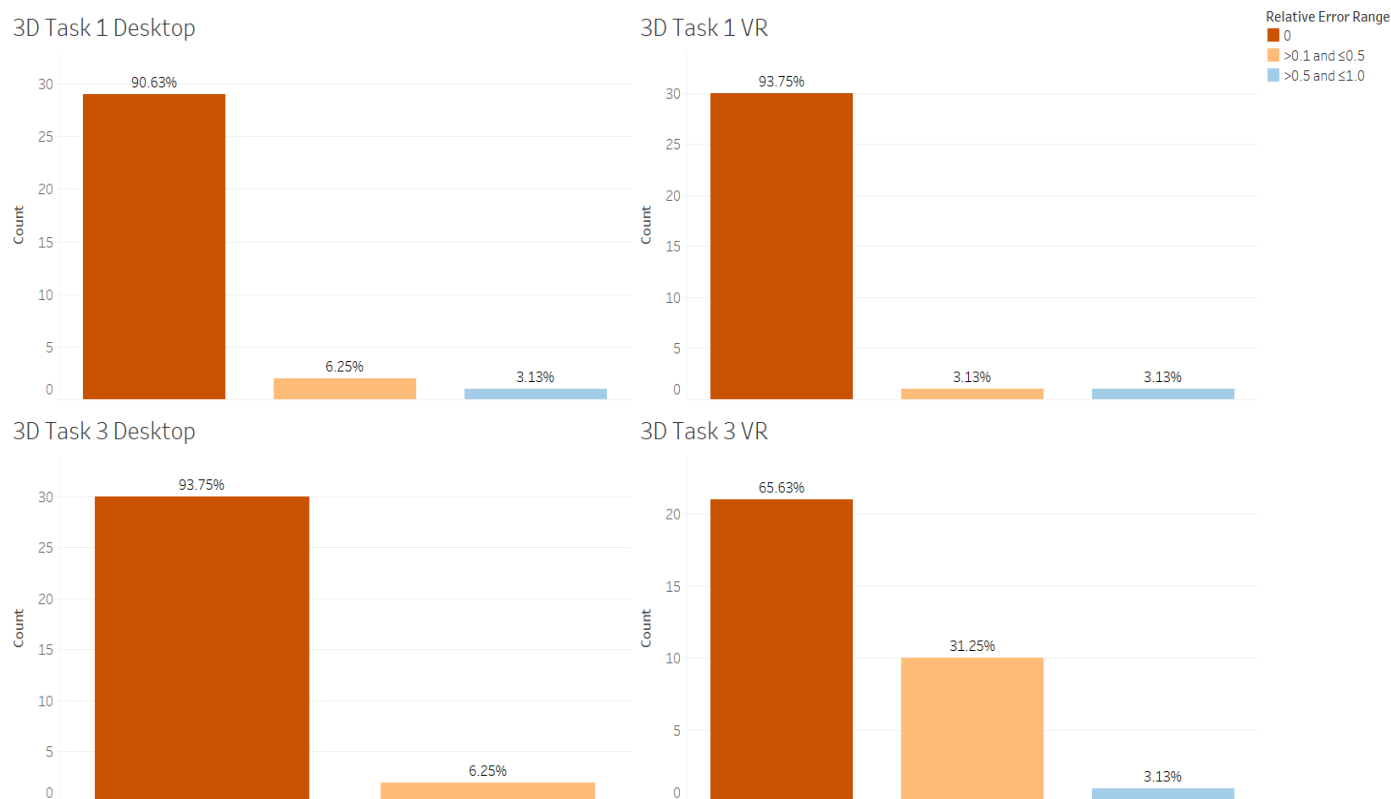


Figure 25. 3D Relative Errors Range

Note. The bar plots show the relative errors from the participants answers of the tasks and categorize them in different ranges, depending how far it is from the correct choice. There was no answer with relative ranges between 0 and 0.1 for this level.

4D Trial

This trial had interesting results for both Groups. For example, point “B5” was picked by many as an answer for task 3 in both groups although it was not the right answer. It is important to note that even though this point was not the largest value, or darkest shade of red, it was a very close value (relative error of 0.16) as well as it was the highest point in the graph leading about 53% of the participant of the VR group to pick this choice, as well as 63% of the Desktop group. Still, overall, the Desktop Group did much better in this trial, while the VR Group struggled. As it can be seen in Figure 27, Desktop had a higher percentage of participants picking the right answer for task 3, although in task 1 the results were the same for both groups.

When Whitlock et al. (2020) used color for their 4D data, it was one of the most accurate modalities for this level of Dimension. The VR application performed slightly better than Desktop. This is not reflected in this study as Desktop 4D performed much better than VR 4D although. 4D

also seemed to have much higher Satisfaction rates in Desktop than in VR. This could be a case of the color space used, as Whitlock et al. (2020) used *HSL* while this study used *LABColor*. The VR setting could have affected color in the study as well as VR tends to have issue with showing color variations and incorrect reflection effects (Billger et al., 2004). There should be more studies that solely focus on different color spaces for color visualization in VR. Other very important considerations are the light and height set, as they could have affected the perception of color. This was also mentioned by a participant in VR: *“It said to use the color values, but the varying height had some effect of my decision to choose the answers”* (4D VR). Desktop might have also been facing the same issue as another participant also mentioned a similar comment: *“The colors seemed difficult to differentiate because of some of the lighting in the graph”* (4D Desktop). These factors are further discussed on Design Consideration and Recommendation.

A lot of participants liked how the visualization looked and color was deemed *“fun”* and *“user friendly”*. Participants were positive about their experience in all levels, even those unfamiliar with VR (Batch et al., 2020; Millais et al., 2018): *“The application itself is easy to navigate and easy to learn”* (4D VR).

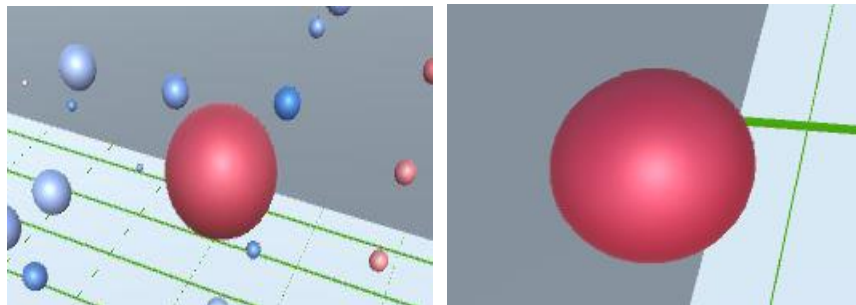


Figure 26. Task 3 Choices

Note. The point on the right was “5B”, while the correct choice is on the left.

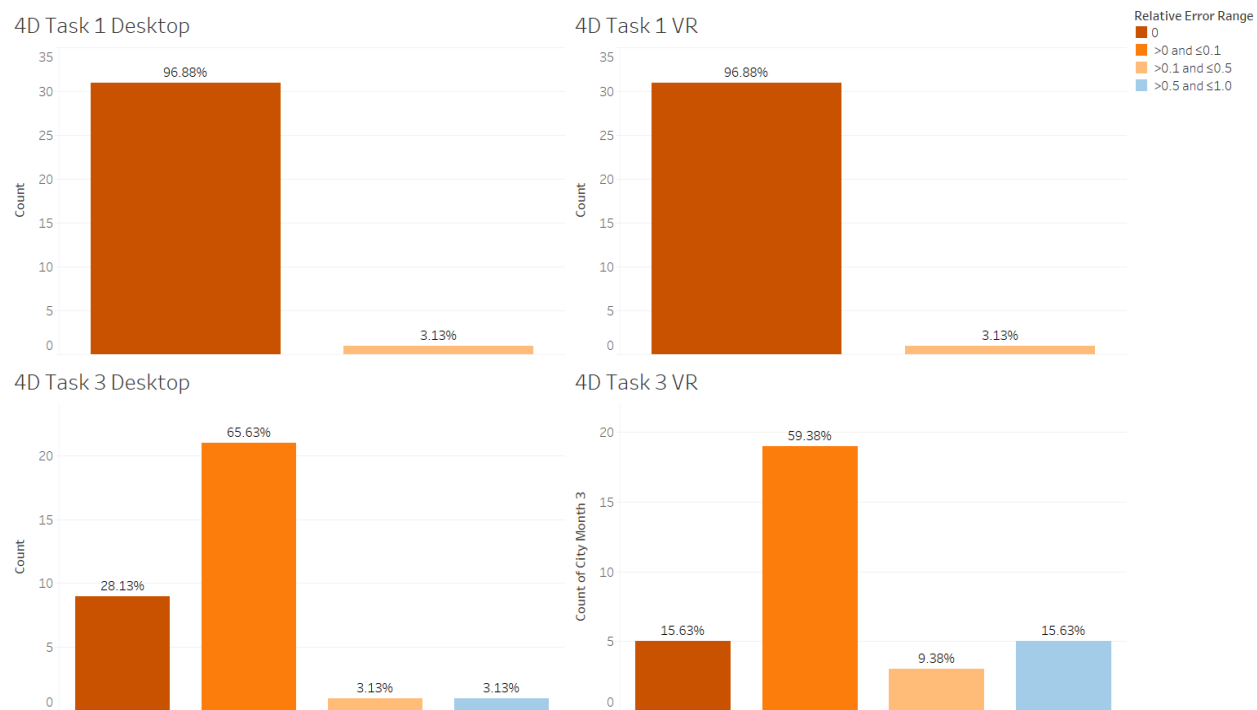


Figure 27. 4D Relative Errors Range

Note. The bar plots show the relative errors from the participants answers of the tasks and categorize them in different ranges, depending how far it is from the correct choice.

5D Trial

Desktop Group did take less time than VR and there was not a huge jump in time as it was on Average Error from 4D to 5D. There also did not appear to be any huge frustrations or mental demands as expressed from the NTLX survey, although there did seem to be less of a disagreement for 5D than the other levels as looking at the heatmaps in Figure 19 when it comes to the Desktop Group. According to some of the comments for this group for the 5D trial, there were admittance of participants getting confused with whether they should consider height or color at all, or just confused with the modalities, especially in Desktop. As a participant mentions: “*I was a little confused on whether or not to take in consideration the height of the balls*” (5D Desktop).

The points Desktop Group picked also showed that they were unsure sometimes and were relaying on other modalities like in 4D. For example, there were about 25% of the participants that still picked point “B5” as an answer for task 3 in the Desktop Group although it was not the right choice for the 5D trial, but it was the highest point. This did not happen as much with the

VR Group though as only about 6.2% made this choice. As a participant in the Desktop Group mentioned: *“After doing all the three trials, I realized the more the parameters (size, color, position), more difficult it is for me to work around the space”* (3D Desktop). Looking at the figure below, VR Group did much better in task 1 than Desktop. In task 3, although VR did have a higher percentage of higher relative errors, it also had a higher percentage of correct answers than Desktop.

There was no experiment found where size was used in a 5D data set or compared to other Dimension levels in IA, however, in Whitlock et al. (2020) when using a 3D data set there was no significant comparison between Desktop and VR, while in 4D dataset the Desktop error rate had increased significantly more. Increasing the Dimension levels in this study as well, appears to further widen this gap. In this study, Desktop seemed better suited for lower dimensions, while VR did better in representing a multitude of levels. As the levels increased there was more of a significant comparison between the two applications. The first statement is supported by the Usefulness and Satisfaction results from the USE questionnaire, where participants felt more comfortable with 5D in VR, while the opposite was occurring in Desktop. Further exploring higher Dimension levels, not just 5D, could reveal more interesting insight about this relationship between higher levels of Dimensions and increased immersion.

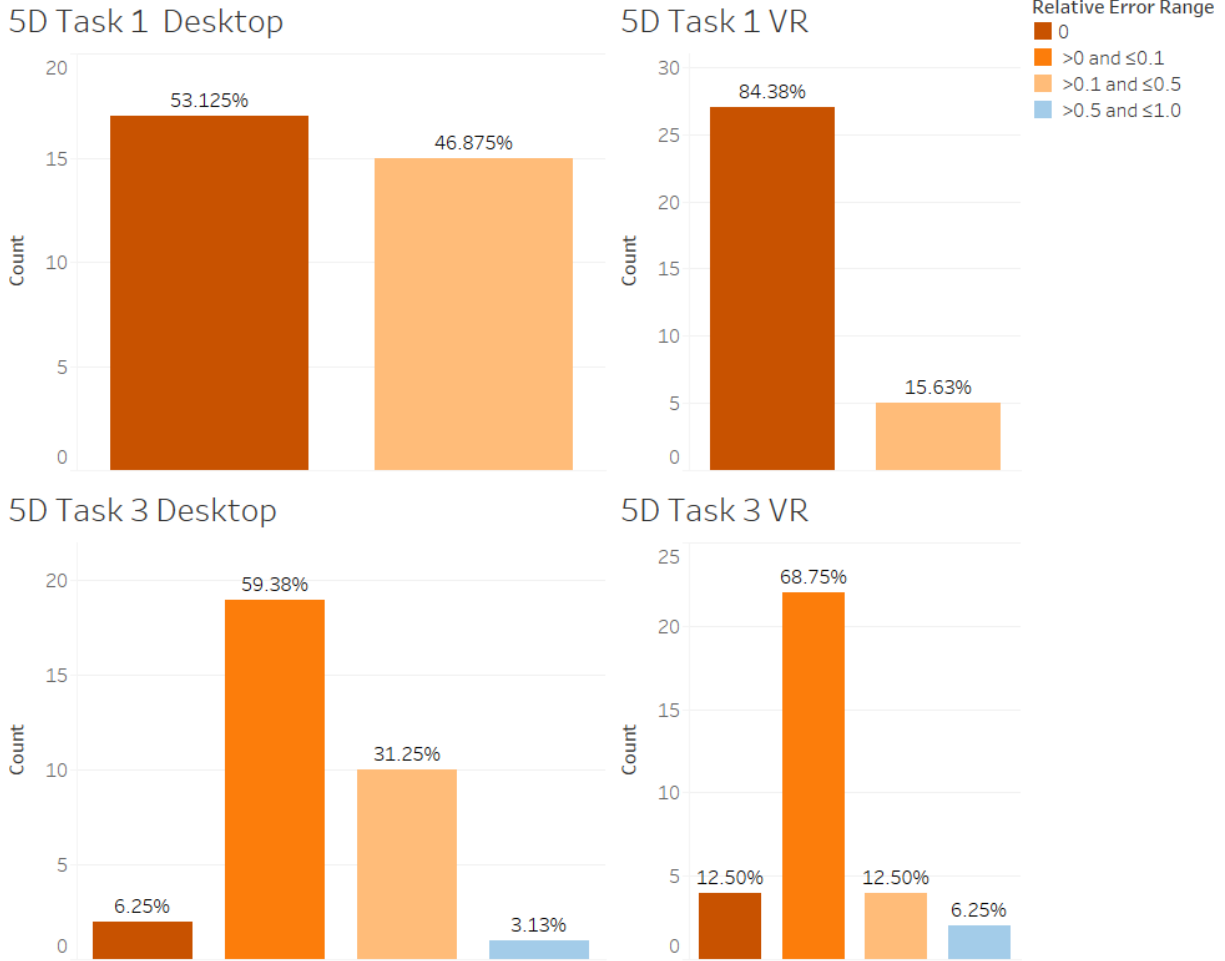


Figure 28. 5D Relative Errors Range

Note. The bar plots show the relative errors from the participants answers of the tasks and categorize them in different ranges, depending how far it is from the correct choice.

Overall Discussion

In this study, there were two main questions that needed to be answered. Through the use of benchmark tasks and various questionnaires, various outputs were produced to offer more insight for these questions.

RQ1: When presented with different levels of the data dimensions, how will this affect the user's decoding of the data in IA? Overall, it appeared that as the Dimension levels were increasing, the Average Error and Average Time would increase as well as seen in Figures 9 and 14. A reason for this, as supported by some of the comments the participants left, when there were more modalities/variables included, they would become more confused, and it was difficult to tell the

modalities/variables apart. There were not any major differences from the NTLX questionnaire as seen in the heatmap in Figure 19. There were other significant variables like interaction with Group types that had effects on their performance, specifically for Average Error and Usefulness and Satisfaction ratings, as well as Dimension Order which would usually favor higher ratings for Dimension levels appearing in later trials although their performance did not reflect this. This could have led to some participants being too “comfortable” and leaving more favorable ratings in the USE questionnaire. As it was mentioned in the beginning of this paper, there were not many research topics specifically focused on the differences between Dimensions in IA. Millais et al. (2018) conducted a study between a 2D and a 3D VR visualization where they also utilized the NTLX questionnaire. This study also had no significant difference in overall workload, although there were some slight variations. However, many of the current studies are more focused in the comparisons between various devices and 3D applications.

RQ2. How will each 3D setting affect the user’s observation of a particular multi-dimensional data? In terms of Average Error, the VR Group did better than the Desktop Group, which aligns with other research studies (Millais et al., 2018; Kraus et al., 2020; Whitlock et al., 2020). Unlike Whitlock et al. (2020), the VR Group took much more time to complete their tasks than the Desktop Group. This could be as 69% of the participants had no to very little experience with VR so it might have taken more time for them to get used to the controllers and the 3D environment. As seen in Figure 17, with each trial they spent less time once they were used to the application. Especially for the VR Group, the first trial took much more time than the Desktop Group. Motion could have also been a limitation as it was mentioned in Chapter 3, certain movements were limited in VR. However, in the study by Bach et al. (2018), where a Desktop application, tablet application and an AR Microsoft HoloLens application were compared, Desktop did perform significantly much faster than the other 3D applications, while the AR headset performed the slowest. A similar thing happened in Kraus et al. (2020) where the 3D Desktop application performed faster than the 3D VR application in cluster identification. There can be several reasons for why the VR application could have taken more time to complete the tasks, like most of the users having little to no experience with VR causing a few of the users to be uncomfortable with the headset and controllers, the speed used for the simulations being too slow especially for some of the more experienced users as well as the huge size of the plot and the users being too overwhelmed with all the points. However, as mentioned by Bach et al. (2018),

Desktop has the advantage of that it requires minimal effort to interact, and participants are already familiar with the mouse and keyboard. A longer training session and more exposure to the applications could lead to different results, as Average Time was significantly affected by the Dimension Order.

Still, in terms of Average Error, although the Dimension levels have significant influence, the amount of time taken, did not specifically improve or worsen the error rate. Although Average Times does increase for each level of Dimension for both applications, the Average Error reflects a change in higher dimensions, where the VR Group performed better in 5D, than in 4D, and considerably much better than Desktop group. Desktop Group on the other hand, performed much better in 3D and 4D. This is also reflected by the Usefulness and Satisfaction ratings in USE questionnaire. As the Dimension levels increase, there are more significant comparisons between the Groups. Although Desktop did overall better in 3D and 4D, VR was preferred more and did much better in 5D. The next step would be to experiment with higher levels of dimensions to observe if this trend would continue.

Other Limitations

Speed was constant and unchangeable; however, it could have been too slow specifically for some of the more experienced VR users. Since the pool that the participants were picked from, generally had very low experience with VR, the speed for transportation was chosen to not be too fast in order to avoid any major discomforts as continuous travel in VR for long periods of time can cause serious simulation sickness (Porcino et al., 2017; Zhao et al., 2020). There were discomforts and dizziness reported. The lab the participants were working in, also did not have enough space for physical movement, so they had to rely on the controllers, that they were not particularly familiar with, to move long distances within the simulation. Although there was a training session for them to get use to the controllers, they were not generally preferred for usage. There were comments about the users desiring to have the option to change the speed of the motion and including more options for turning. In the future, there should be included various methods of transportation around or inside a 3D plot like teleportation for example like Zhao et al. (2020). Using more familiar controllers or including hand sensors instead could also offer more insight.

There were also participants that mentioned that they generally did not like to turn using the 90 degrees option on VR. As a participant mentioned: *“I wish I could rotate with more flexibility*

instead of fixed angle using controller” (3D VR). This can also be used as another feature that can be modified and investigate more deeply for proper motion in a plot in VR. It also might be better to just have the participants work with one controller, instead of two as some of them would be confused. It also seemed that the text might have been placed too left for the participants, and overall, the text being placed on top was not always preferred by the participants. Desktop movement was also not preferred being considered “slow” and “rudimentary,” however the purpose was to keep the movement as simple as possible. There might have also been some lag in both applications, however this is because of the power of the computers.

Font size could have been a limitation for VR, as there were a few reports of participants having a difficulty to read all text. However, there was still no issues of participants misunderstanding the questions. This could have been an issue of the headset not fitting right for some of the participants that did not have experience and were not sure how to wear it properly. As these participants mentioned: *“The headset may have become slightly looser from multiple trials but at the same time it was hard to read the task at times”* (3D VR) and *“The headset is a bit heavy which makes it uncomfortable to use for longer periods of time”* (5D VR). In the study by Batch et al. (2020), where the participants used a VR headset for professional economic analysis, there were also reports of participants disliking wearing the headset.

Design Considerations and Recommendations

There were certain design models that should be considered for future studies. In this study, the participants were positioned inside the graph for the VR portion, however, this caused some disadvantages when it came to height and size, as the participants would have to move around all the plot to try to compare the heights and sizes of the points. This caused difficulties when the participant was trying to compare two points that could be in opposite sides of the graph. Size perception of a point is affected by the distance of the subject to that point, so this can be something that should be considered for future studies (Willett et al., 2017). This difficulty was also found in the Desktop group as well. A recommendation for future studies would be to try using a smaller scale plot in VR that the user can rotate and move around with either the controllers or using hand tracking. There could also be more focus on allowing different forms of motions and transportation in a plot in VR. According to Elmqvist et al. (2008) moving through 3D environments is a high cognitive load task.

Another recommendation would be to use a flat lighting set up for the scene as the light and height in this case, could affect color perception. Performing some sort of study where the focus is in exploring the types of different light and set up that can be used in such an environment could be advantageous for future studies. Further exploring the amount of exposure that a participant gains in these types of 3D settings can also lead to some interesting results as it was seen by the rating given in the Usefulness subsection through the consecutive trials, as well as the time spent in the applications.

There was one type of color space that was used for this study, however experimenting with various types of color spaces could be beneficial for many researchers as it was as it was mentioned in the previous subsection. Experimenting with different type of color scales could be helpful as well as the only colors used in this study were blue, white, and red interpolation. Including more colors, could lead to a better interpretation of the values, especially for interpolation.

As it was mentioned in Chapter 3, the only modalities that could be used were height, color and size as including more than that would have not been affordable by this study in terms of size of the study and number of participants. There have been a few studies for the effects of these modalities in human perception and these effects could have also been involved in this study mostly by Whitlock et al. (2020). That is why a future study that involves various types of modalities and focuses on the relationship between modalities and Dimension levels could also be of equal interest and provide more insight.

Conclusion

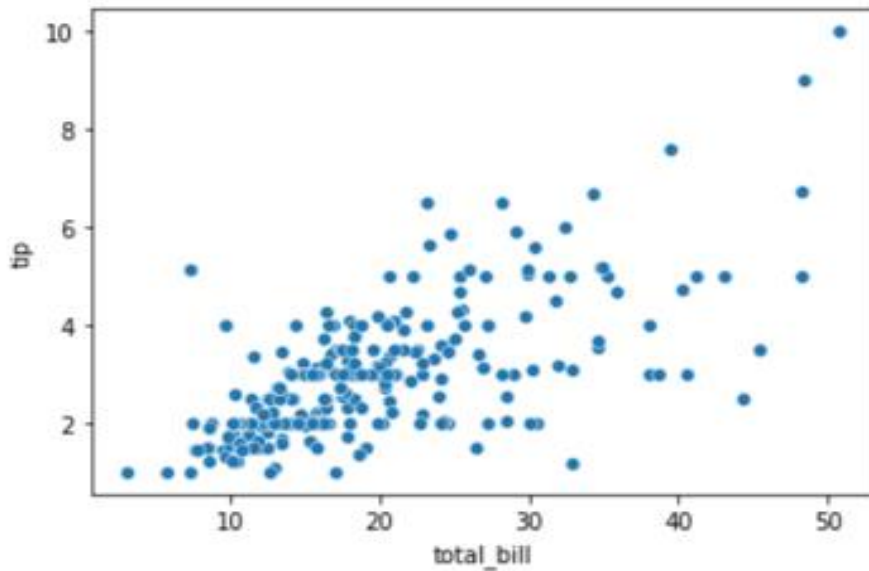
Big Data will become an obstacle in Data Visualization and data analysis if other tools and techniques are not explored. As Big Data keeps increasing, so does the number of dimensions. IA offers a great opportunity for the visualization of multi-dimensional data as it offers a 3D environment the user can walk around and interact with. However, the problem is that there is minimal to no guidelines about using higher dimensions of data in a 3D environment through visual means. Providing a guideline for multi-dimensional data in 3D would create a useful tool for many data analysts or other non-experienced audiences. In this study, the focus was to understand if there is a connection between different types of 3D applications and dimension levels and how this would affect the subject's judgement. By comparing the participants' performance

in a VR and Desktop setting, there will be a better understanding on the advantages of visual tools in IA.

The study found that there might be a connection between different levels of Dimensions and various 3D applications, as participants did much better and found more satisfaction in using higher levels of Dimensions like 5D in a VR application, while lower levels were better suited in Desktop. Overall performance and ratings from the NTLX and USE questionnaires favored VR in 5D, while Desktop did much better in 3D and 4D. It would be advantageous to conduct more studies where more levels of Dimensions and various applications can be compared as there are not many studies that have closely looked into this relationship. Understanding more about this relationship, will aid in developing more efficient IA tools.

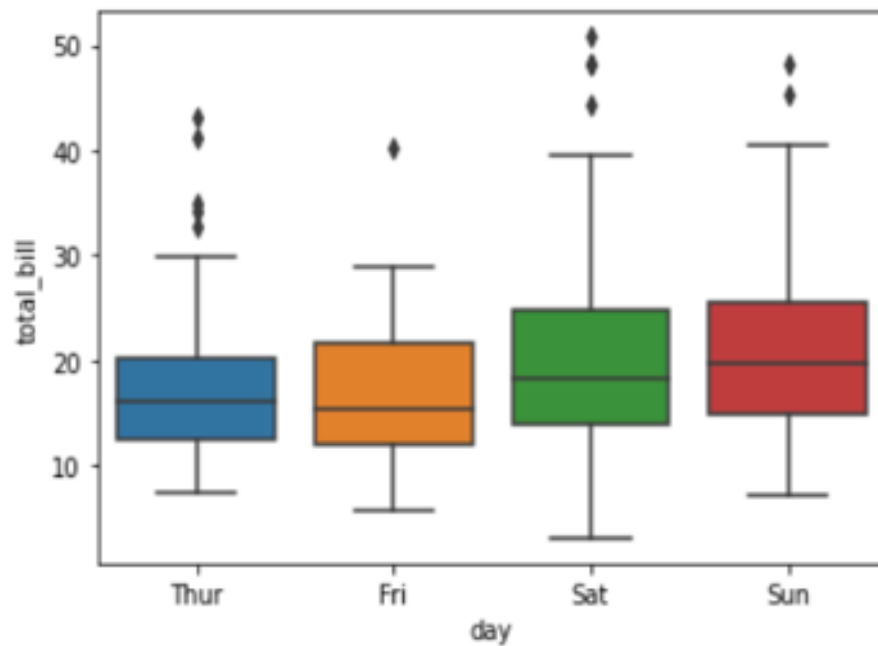
APPENDIX A. STATISTICS TEST

Look at the provided images and answer the questions to the best of your abilities.



1. Look at the scatter plot provided above. What is the correlation between tips and total bills?

- ☐ Strong positive correlation.
- ☐ Strong negative correlation.
- ☐ Weak negative correlation.
- ☐ There is no correlation.



2. Which day has the lowest value for the total_bill?

- ☐ Thursday
- ☐ Friday
- ☐ Saturday
- ☐ Sunday

3. How many outliers does Sunday have on the boxplot?

- ☐ 0
- ☐ 1
- ☐ 2
- ☐ 3

APPENDIX B. NASA TASK LOAD INDEX QUESTIONNAIRE

The questions will be concerning the application you used.

1. The tasks were mentally demanding.

- ☐ Strongly Agree
- ☐ Agree
- ☐ Somewhat Agree
- ☐ Neither Agree nor Disagree
- ☐ Somewhat Disagree
- ☐ Disagree
- ☐ Strongly Disagree

2. The tasks were physically demanding.

- ☐ Strongly Agree
- ☐ Agree
- ☐ Somewhat Agree
- ☐ Neither Agree nor Disagree
- ☐ Somewhat Disagree
- ☐ Disagree
- ☐ Strongly Disagree

3. The pace of the tasks were hurried/rushed.

- ☐ Strongly Agree
- ☐ Agree
- ☐ Somewhat Agree
- ☐ Neither Agree nor Disagree
- ☐ Somewhat Disagree
- ☐ Disagree
- ☐ Strongly Disagree

4. I was successful in accomplishing what was asked.

- ☐ Strongly Agree
- ☐ Agree
- ☐ Somewhat Agree
- ☐ Neither Agree nor Disagree
- ☐ Somewhat Disagree
- ☐ Disagree
- ☐ Strongly Disagree

5. I had to work hard to accomplish my tasks.

- ☐ Strongly Agree
- ☐ Agree
- ☐ Somewhat Agree
- ☐ Neither Agree nor Disagree
- ☐ Somewhat Disagree
- ☐ Disagree
- ☐ Strongly Disagree

6. I felt insecure/discouraged/ irritated/stressed.

- ☐ Strongly Agree
- ☐ Agree
- ☐ Somewhat Agree
- ☐ Neither Agree nor Disagree
- ☐ Somewhat Disagree
- ☐ Disagree
- ☐ Strongly Disagree

APPENDIX C. USE QUESTIONNAIRE

The questions will be concerning the application you used.

Usefulness

1.It helps me be more effective.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

2.It helps me be more productive.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

3.It is useful.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

4.It gives me more control over the activities in my life.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

5.It makes the things I want to accomplish easier to get done.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

6.It saves me time when I use it.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

7.It meets my needs.

- ☐ Extremely Useful
- ☐ Moderately Useful

- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

8.It does everything I would expect it to do.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

Ease of Use

9.It is easy to use.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

10.It is simple to use.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless

- ☐ Moderately Useless
- ☐ Extremely Useless

11.It is user friendly.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

12.It requires the fewest steps possible to accomplish what I want to do with it.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

13.It is flexible.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

14.Using it is effortless.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

15.I can use it without written instructions.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

16.I don't notice any inconsistencies as I use it.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

17.Both occasional and regular users would like it.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless

- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

18. I can recover from mistakes quickly and easily.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

19. I can use it successfully every time.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

Ease of Learning

20. I learned to use it quickly.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

21. I easily remember how to use it.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

22. It is easy to learn to use it.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

23. I quickly became skillful with it.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

Satisfaction

24. I am satisfied with it.

- ☐ Extremely Useful

- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

25. I would recommend it to a friend.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

26. It is fun to use.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

27. It works the way I want it to work.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless

- ☐ Moderately Useless
- ☐ Extremely Useless

28. It is wonderful.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

29. I feel I need to have it.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

30. It is pleasant to use.

- ☐ Extremely Useful
- ☐ Moderately Useful
- ☐ Slightly Useful
- ☐ Neither Useful nor Useless
- ☐ Slightly Useless
- ☐ Moderately Useless
- ☐ Extremely Useless

APPENDIX D. COMMENTS

The participants had to mention the negatives and positives of their applications per each dimension level.

3D VR

Negatives

[1] *"So many balls! Hard to tell which ones are with which month from far away, I had to get very close in order to see which row of balls were for a certain month. The brown color made is difficult to distinguish between the different months. It took a long time to find the answers."*

[2] *"the data points actually make me feel a little uneasy"*

[3] *"The turning controls being locked to intervals instead of smooth movement led me to rarely use them, and I rarely felt my depth perception was enough to make judgements on points' positions when comparing them. Spending lots of time looking up to compare points was also beginning to feel uncomfortable."*

[4] *"The way to rotate and move was somewhat hard to adapt to because all of a sudden you move the joystick and boom you are at a different angle, and that messes with your mind a little."*

[5] *"tough to navigate the view points, it would be easier if the joystick would move continuously"*

[6] *"It's harder to turn due to the fact it switches frames, its not a smooth transition"*

[7] *"The test box was a little bit out of alignment so it was hard to read at times, some of the dots appeared to be at the same height which was a bit troublesome."*

[8] *"i got stuck a couple times on the grid."*

[9] *"hard to read instructions"*

[10] *"The only negative was for this specific program I was in, you could complete it more quickly and accurately on a desktop."*

[11] *"Even though controlling it is easy, it takes some getting use to."*

[12] *"Again, the turning is a problem."*

[13] *"Just like the color one, it's not easy to look at visually."*

[14] *"It can be hard to see everything around you, large scale"*

[15] *"The head gear fitting can be uncomfortable"*

- [16] *"There were no negative aspects except the bulky and uncomfortable nature of the headset."*
- [17] *"The text box is difficult to see sometimes. It's a little difficult to look at the whole plot at the same time."*
- [18] *"I wish I could rotate with more flexibility instead of fixed angle (using the left controller)"*
- [19] *"I had to move around a lot to find the correct spheres"*
- [20] *"Not being able to move up or down makes it harder to gauge height."*
- [21] *"It's harder to compare the height of each point when the differences aren't drastic"*
- [22] *"Inconsistency in between controls; requires effort to get used to and operate"*
- [23] *"Hard to compare the height of each ball from the ground"*
- [24] *"Again the distance of each point makes it difficult to analyze the height."*
- [25] *"Not being able to get the perfect perspective"*
- [26] *"It takes time to move around, you cannot go up and down in the y axis and that could be helpful for determining some things."*
- [27] *"difficult to view the entire plot from the user's POV"*
- [28] *"The only negative about this part was if the objects were far above the perspective of the user and so judging their height became difficult. If I was able to move vertically in addition to horizontally I feel as though I would have been more confident in identifying the greatest values."*
- [29] *"N/a"*
- [30] *"Without having a unit on each orb it is difficult to tell the height of the orbs in relation to others"*
- [31] *"Determining color was the most difficult way to go through the data. In this trial, analyzing the data with height was slightly easier."*
- [32] *"The most negative aspect in this trial was where the text was positioned. The headset may have become slightly looser from multiple trials but at the same time it was hard to read the task at times. Furthermore, the height was harder to judge without being able to go in an z direction and look directly horizontal."*

Positives

- [1] *"Perhaps if I could have seen it from very far away, it would have been a cool way to look at all the data. But I was too close/within it, for it to be useful. However I like the idea of an*

immersive data visualization. It may have uses concerning engagement with data, but it currently takes too long to interpret the data in this way"

[2] "it's cool to submerge into the graphs and data points"

[3] "I was able to use my body as psuedo-measurement for point placement, though I almost made one or two hasty incorrect guesses, from what I can tell. I could also hold my head in place and clip the instruction window through higher points as a way to measure height more consistently. I felt a bit nauseous at first, but overall, I felt physically well using the simulation."

[4] "You can see 2D things in 3D, which can be very useful for certain things."

[5] "Good graphics and visuals"

[6] "Overall very easy to use and user friendly"

[7] "The laser was helpful, being able to look around and see the graph."

[8] "very difficult to mess up"

[9] "interesting way to visualize data"

[10] "It encourages more attention paid to the task at hand and pushes out more of the distractions."

[11] "It visualizes everything 3D, which makes the environment more realistic."

[12] "Still enjoying being in the world- there's something really enjoyable about being somewhere in VR that would not be able to exist in reality."

[13] "It's easier to differentiate the values with height rather than colors since the change in colors was too dull when it became too bright/dark"

[14] "It is fun"

[15] "The environment created is fun and different"

[16] "This time the task was simpler. I did not feel too stressed out. Since it was just based on the Y axis, I got the task done very quickly and correctly. I got more confident using the headset as well."

[17] "It was easy to maneuver. The plot was easy to understand. The instructions were clear."

[18] "If I stand in the same line along a particular month or city, it s really easy to distinguish different heights"

[19] "It was easy to use and find what I wanted to find"

[20] "It was pretty straight forward, not much confusion in doing this."

[21] "It is easy to navigate and use"

- [22] *"3D visualization is pretty clear"*
- [23] *"It is easy to control and read each data point"*
- [24] *"Fun to use"*
- [25] *"Only having to pay attention to location and not being concerned with size or color"*
- [26] *"It is super easy to learn and pick up quickly, plus its super fun"*
- [27] *"unique learning style"*
- [28] *"This version was extremely simple and easy to pick up, especially for someone like me with little experience in VR."*
- [29] *"It is very time efficient. I could pinpoint the data almost instantly"*
- [30] *"this was the easiest to use out of the three because height is easier to differentiate between than shades of colors and size"*
- [31] *"Analyzing the data through size was definitely the easiest."*
- [32] *"It was very easy to use and made the data easier to comprehend"*

3D Desktop

Negatives

- [1] *"The controls were difficult for me to use via the mouse and the arrow keys (W,A,S,D) made me feel slow and not accomplishing my task at hand"*
- [2] *"The movement speed could be increased (hold CTRL to speed up?)"*
- [3] *"It is difficult do identify heights as the data isn't displayed numerically"*
- [4] *"I wish I could use the scroll wheel to zoom in and out like google maps. I also wish that the mouse only rotates the screen when I click on it."*
- [5] *"The movement"*
- [6] *"stimulation felt cluttered/confusing to sort out."*
- [7] *"It was difficult to tell he lowest emission, unless you move all the way out from the model and position yourself to look through the axis at a zero degree angle."*
- [8] *"For the second question it was sort of difficult to locate the minimum point on August due to the large amount of data surrounding it. With more practice I could probably have developed a way to find the point easier."*
- [9] *"Perhaps the visualization on the screen made it hard to identify which point was where; too many points and the axis wasn't visible. In terms of control, there needs to be a \"ascend and*

descend\" command, perhaps the shift key, because it's a little rudimentary to have move along the y-axis only through your mouse"

[10] "Movement speed was slow at times in all directions, moving up/down was a bit difficult to learn"

[11] "hard to see everything at once"

[12] "The grid was harder to follow as I moved higher on the Y-axis"

[13] "If the point that has the lowest value is far from the observer, it becomes harder to distinguish"

[14] "There is a bit of lag sometimes"

[15] "It doesn't have an overhead view to see the coordinates clearly"

[16] "It would be cool if you could see the specific value of each ball by clicking on it in case two of them were close to the same value."

[17] "None I could think of"

[18] "The most negative aspect is the visual of it, it doesn't look fun to use."

[19] "Size is difficult to compare in a 3D environment when points are far away"

[20] "I couldn't differentiate between the markers separating the months."

[21] "No real negatives"

[22] "The spheres in the background sometimes distracted me."

[23] "It was a bit difficult to determine the height when not being to see the spheres from a completely horizontal aspect"

[24] "This was the least laggy of the trials, but it is still somewhat laggy"

[25] "There's no button to have a horizontal view over the axis."

[26] "It is difficult to tell what points correlate to which city/month because they are all the same color."

[27] "sometimes difficult to determine which point is higher depending on perspective"

[28] "When comparing data points that are super close to each in terms of values but are far away, it made it difficult for me to differentiate the value of the points. I think this is caused by the freedom of camera angle because I don't know if I'm looking at the two points on a horizontal level."

[29] "It required the most movement inside the simulation"

[30] *"With only one color, it is harder to use as it requires more effort to carefully select the answer"*

[31] *"I wish I could move a bit faster."*

[32] *"Seeing slight differences is difficult"*

Positives

[1] *"It is definitely fun to be in the 3D space with the data points."*

[2] *"Sky is pretty and the data chart is easy to conceptualize"*

[3] *"Easy to move around the environment"*

[4] *"I like that I can move using the keyboard."*

[5] *"The visual appeal"*

[6] *"ease of control and usage."*

[7] *"It makes statistics look fun/."*

[8] *"The program is a cool way to show data. It is a good way of storing three-dimensional data and it is relatively easy to look at and process."*

[9] *"The program was organized wonderfully. The points, although a little difficult to comprehend initially, provide excellent visualization to the user and allow them to comprehend the information more easily."*

[10] *"Easy to learn and use, I could eventually answer with confidence"*

[11] *"easy to get the hang of"*

[12] *"It was easy to understand and use. It was interactive and made it fun to read data"*

[13] *"Height is intuitive"*

[14] *"This was much better than the 5D graph. I feel that this software is much suited for 3D than 5D."*

[15] *"It wasn't too hard to navigate"*

[16] *"I liked that I could move to a different angle to easily find the value I want."*

[17] *"Ease and use, 3-D environment"*

[18] *"The best part of this is that it is very easy to use."*

[19] *"The controls and user interface become more and more comfortable and navigating the space is effortless"*

[20] *"User-friendly, easy to understand without instructions, and intuitive."*

[21] *"I like the organization of the data on the graph, and how easy the graph is to interpret in terms of height."*

[22] *"This time however, since I only needed to focus on the height and not the color or size, I felt I could do it much faster. Also the distraction in the background wasn't as bad as before."*

[23] *"It is easier to spot the difference when the sphere is further from others"*

[24] *"Helps visualize data well"*

[25] *"It is the easiest one to use of the 3 trials I had"*

[26] *"It is more interesting than looking at a traditional graph."*

[27] *"Great way to show data on multiple axes"*

[28] *"Comparing data points using heights was easier for me than using size and color. It was closer to what we do in 2D data analysis, so I was more used to it."*

[29] *"It was very easy to visualize and see all the points and answer the questions"*

[30] *"comparing real outliers are easier in terms of height and vertical position"*

[31] *"It was easier to differentiate the heights of the dots than the size."*

[32] *"Very easy to see all the data at once, for quick inferences"*

4D VR

Negatives

[1] *"Inconsistency in between control buttons (right and left hands); hard to spot; requires movements"*

[2] *"I think the most negative aspect of the program is that it's difficult to look at, I can understand what's being shown but I would rather look at something a little more pleasing to look at and less convenient"*

[3] *"Standing in the graph makes analyzing the data difficult because it's hard to distinguish the height of each point, and some points are obscured by other points."*

[4] *"Fitting it according to my size"*

[5] *"I cannot move upwards, like if I am looking at something higher up in the air I cannot get to that level."*

[6] *"It took me a minute or so to understand what all I was looking at, but after I looked around for a little bit it was easier to understand."*

[7] *"I felt it was hard to distinguish between neighboring shades of the colors and it was a little difficult to rotate the viewing axis at first but eventually I was able to get used to it."*

[8] *"the feed sometimes gets shifted making it hard to read at points"*

[9] *"The time to interpret data may be longer than 2d representations because 3d models in vr you have to walk through."*

[10] *"It is slower than looking at a physical graph, the speed of movement is a bit slow"*

[11] *"In this case the mobility was the primary negative aspect. Wanting to move faster (especially when used to using a computer and mouse) held me back time wise it felt."*

[12] *"It still takes a while to find the answer"*

[13] *"Difficult to understand what the points represent and what the questions are asking"*

[14] *"The color thresholds were difficult to distinguish for me at the highest/lowest levels."*

[15] *"Staying on the same plane and not easily being able to move up or down"*

[16] *"I forgot the color coding and think it'd be useful to have it on the reference example when pressing the right trigger"*

[17] *"Made me a little dizzy"*

[18] *"some of the colors appeared to be the same shade of red, probably because they were really close."*

[19] *"When comparing a large data set, colors that are far away and close to each other in terms of color make it seem like they are the same color"*

[20] *"text is still hard to read in instructions"*

[21] *"Once again having to move around isn't the most intuitive."*

[22] *"Having things in 3D does not help with differentiating colors."*

[23] *"Turning- same as before"*

[24] *"N/A"*

[25] *"It causes some stress"*

[26] *"Having to turn your head a lot to try and find smallest or largest point."*

[27] *"The setting of this trial set me off. It said me to use the colour values but the varying height had some effect of my decision to choose the answers"*

[28] *"Very hard to move around, it was slow. If it was faster and smoother I would've enjoyed it a lot more"*

- [29] *"I found it hard to differentiate between two close shades of the same color, maybe if there were less shades on the scale it would be more clear"*
- [30] *"It was hard to gauge the size in this last study"*
- [31] *"Colors we're hard to compare from a distance."*
- [32] *"It would be easier to analyze data on a desktop computer when working with data."*

Positives

- [1] *"Straight visualization in 3D"*
- [2] *"I could easily see the data points and compare with different months and cities."*
- [3] *"it's easy and fun to use."*
- [4] *"The virtual reality was fun and it was easy to move and go through the graph"*
- [5] *"It is super easy to use and straightforward. Took seconds to learn and feel comfortable using it."*
- [6] *"It was easy to use. The instructions were clear. The images were clear. The key for the size/color of the dots was very helpful."*
- [7] *"Using the VR headset allowed the experience to be very engaging and is great for visual learners like myself."*
- [8] *"very easy to use and fun as well"*
- [9] *"3d models of data are more easily understood when comparing different datasets"*
- [10] *"It motivates me to get the work done because I am having fun while doing it, when I move I don't get motion sick, easy to understand"*
- [11] *"The visualization of the information made it easy to understand the data as well as fun to use."*
- [12] *"The colors were very helpful in interpreting the data"*
- [13] *"Easy to understand where you are in relation to the VR world"*
- [14] *"I was able to partially separate similar red colors by highlighting them: the material change on slightly more intense red dots would appear more pinkish from their shading than their slightly lighter red neighbors, which would appear more white when highlighted. This did not help with blue dots for me in the same way."*
- [15] *"Being able to adequately evaluate the question and answer"*
- [16] *"The selection (right trigger) feels very organic"*

- [17] *"Fun to use - would recommend to a friend"*
- [18] *"Having the reference chart, and being able to see the varying colors"*
- [19] *"Its very very time efficient"*
- [20] *"it is visually interesting"*
- [21] *"Visually the system is very immersive."*
- [22] *"It is more engaging to have to physically turn around and look at things."*
- [23] *"Environment- same as before"*
- [24] *"it actually got easier with the more trials"*
- [25] *"It is user friendly"*
- [26] *"It became easier to use after second trial."*
- [27] *"The application itself is easy to navigate and easy to learn. This task was moderately challenging so it was an okay experience overall. I did not feel too stressed out like the first trial which is a benefit."*
- [28] *"It was visually easy to see the different objects and decipher the answers"*
- [29] *"The colors are easier to see from a distance than the size and height"*
- [30] *"you can move around very easily"*
- [31] *"It was simple to understand"*
- [32] *"It makes work more enjoyable, and increases engagement when opposed to a normal desktop computer."*

4D Desktop

Negatives

- [1] *"Without instructions, it can be overwhelming at times. A constant companion on the screen would make it much more user friendly."*
- [2] *"It might be better to set the distance between balls a little larger to make it more easy to observe"*
- [3] *"Laggy, for the desktop version maybe make it so using the spacebar makes you move upwards."*
- [4] *"Maybe if there was an overhead view of the plane, it would be easier to navigate"*
- [5] *"It is difficult to travel up and down."*

- [6] *"Honestly none that I could think of. It did its job perfectly with no faults. The only suggestion I can make is that reference or important text be accessible by a button."*
- [7] *"It's hard to distinguish the colors sometimes, and the dots get confusing when there is a large size of data."*
- [8] *"Moving around the space with the controllers felt slow, sometimes the directions text was off center and hard to read"*
- [9] *"The balls were positioned too close to each other."*
- [10] *"There could be more organization or the plot could be more spread out so that it is easier to interpret."*
- [11] *"There is a learning curve while using it that requires a little practice to use."*
- [12] *"The same thing As I mentioned about with the controllers on the mouse. It is very difficult to move around n the 3D space using a mouse and keyboard."*
- [13] *"The slight difference in the color could be a bit hard to distinguish."*
- [14] *"Being able to see all the data in one go would help instead of traversing each time"*
- [15] *"The colors degrees are so close for each other which makes it harder to read the colors"*
- [16] *"The movement"*
- [17] *"sometimes points are blocked by other points and it is difficult to determine color when not all the points can be seen"*
- [18] *"Again, I would say that the colors are tough to tell apart at time, if the emission levels are similar."*
- [19] *"Sometimes it was a little hard to determine some colors that were very close to each other"*
- [20] *"The color reference is missing a legend i.e sulfur comp. For this it can be easy to confound pollution and sulfur together."*
- [21] *"Some of the colors did look very similar."*
- [22] *"the balls seemed to blend together so it was hard to see which ones went with each month"*
- [23] *"the difference in y position made it confusing sometimes"*
- [24] *"Again, it would be nice to have a key to move vertically only"*
- [25] *"The learning curve may still be a bit steep. I can imagine someone else requiring a bit more time to get t grips with the software."*
- [26] *"I wish the colors looked the same regardless of the angle and distance from the ball. It makes it harder to know if the ball has a stronger color or its just the lighting and position"*

- [27] *"A few of the colors were difficult to tell apart."*
- [28] *"Reminder on what the color means. Took time to move around the map."*
- [29] *"There is a difficulty in telling the difference between similar colors."*
- [30] *"It was hard to differentiate between colors that were very similar. For a couple of the questions, the correct choice had a very similar color to other bubbles."*
- [31] *"I couldn't differentiate between the different blue colors due to the lighting in the back, and I couldn't move up without changing my orientation."*
- [32] *"I was less confident in this trial than the first. The colors seemed difficult to differentiate because of some of the lighting in the graph."*

Positives

- [1] *"Once I got used to it, it was a breeze to use."*
- [2] *"Color is intuitive for differentiating different values"*
- [3] *"The information is easy to understand, you can answer questions easily"*
- [4] *"It wasn't too hard to use"*
- [5] *"It is a much more engaging and interesting way to present data."*
- [6] *"I love the 3-D environment. It was definitely easy to use and understand."*
- [7] *"It's cool to look at, and a nice way to visualize data."*
- [8] *"The data was presented in an easily readable and comparable format"*
- [9] *"The different colors and sizes makes it easy to understand"*
- [10] *"Being able to select any data point and have it identify its data and significance."*
- [11] *"Once understood, it is easy to remember and then use."*
- [12] *"The colors were easy to find and identify among all the sizes of the same shape. This was easier than the first trial."*
- [13] *"The distances to the spheres do not affect the judgement."*
- [14] *"Color identification worked better for me"*
- [15] *"Doesn't require a lot of efforts if you can read the colors"*
- [16] *"The 3-D representation"*
- [17] *"the color index makes it easier to determine outliers"*
- [18] *"If there are a wider range of colors, this program will be very useful in comparing data points. It's also very fun."*

[19] *"It was very easy to see outliers"*

[20] *"Overall, the colors do provide valuable insight on the correlation between pollution and sulfur concentrations."*

[21] *"I was able to easily navigate through and click on an answer."*

[22] *"the colors made it easy to tell which one was lower than the others"*

[23] *"it was colorful and fun, easy to use"*

[24] *"This time the color scale by itself was useful because I was selecting outliers based on only one criterion"*

[25] *"It runs very smoothly and is easy to navigate through."*

[26] *"I think color is the easiest way of differentiating between balls. This is because I can't be sure if some balls are higher than others since I have to move around to find them."*

[27] *"The colors that were not close to the same shade were easy to find."*

[28] *"Became more easy to use and understand. Color and size."*

[29] *"The biggest positive aspect is that through the size, height and color, the chart shows a lot of information."*

[30] *"It is a good way to show data. It is easy to differentiate between data that is not very similar."*

[31] *"Easy to separate red and blue shades"*

[32] *"The application was still consistent. I was more confident in this trial than the second trial as color seemed easier to compare than size."*

5D VR

Negatives

[1] *"Turning can be very disorienting, as it is not continuous"*

[2] *"Hard to understand the z axis as well as what the size of the balls mean"*

[3] *"The head set was uncomfortable, makes me feel dizzy or like I'm about to fall, I occasionally got confused with the controls which bothered me as I was completing a task"*

[4] *"Understanding how to use everything and getting around"*

[5] *"The virtual reality headset gives me a nausea like feeling. I felt very weird and out of focus while using it. There were times in the task when I just wanted to get done with the task rather*

than actually focus on what is going on due to the bulky nature of the headset and the unpleasant feeling while wearing it."

[6] "Inability to move"

[7] "The headset is a bit heavy which makes it uncomfortable to use for longer periods of time"

[8] "The player/Viewer is too low and the movement speed is too slow as well. I believe a free floating camera that wasn't grounded would make it way easier to visualize the data"

[9] "The thumbstick turning 90 degrees is a bit confusing, I would prefer it rotate smoothly."

[10] "Moving around with the thumb joysticks wasn't the most intuitive."

[11] "Inconsistency in controls; requires a lot of effort"

[12] "N/A"

[13] "The size of each point is not intuitive because their sizes also depend on the distance to you."

[14] "The text above screen is shifted to the left which makes it hard to use. Also, in the graph you cannot really tell what dot looks bigger compared to other big dots."

[15] "Its kind of hard to see and compare every aspect of the graph even if I am moving around."

[16] "I wish it were easier to move around in order to accomplish the tasks"

[17] "In this round it was once again difficult to distinguish between sizes that are very similar and may be far away from each other on the layout. If they were right next to each other it was a little bit easier but I still didn't feel confident in choosing the larger option if they were very close."

[18] "sometimes the text is hard to read"

[19] "Since there are no numbers correlated to the ball size visible when selecting a ball, it is difficult in being confident in one's choice when selecting the largest or smallest ball when a lot of them are similarly sized."

[20] "Some projects would just be more accurate, and easier to do on the desktop, like the pollution activity."

[21] "The most negative aspects come with the speed once again. Some of the data would block another piece of data from being seen and there was not a quick remedy to find the other data."

[22] "The slow movement of the right joystick was a little frustrating; I think that is why it took so long to find the answers"

[23] *"It's hard to tell the difference between the size of some of the balls especially if the two that I'm comparing are on opposite ends of the graph"*

[24] *"In all three trials, having to discern between highly similar data without accessing the data itself was stressful. I realize this may be part of the research goal, but I thought it was worth mentioning. I did not feel comfortable with many of the selections I made, even when trying to perform my own physical measurements (e.g. holding my hands apart to measure one dot, then sliding horizontally to the next dot to compare size)."*

[25] *"the head gear can be irritating and uncomfortable"*

[26] *"I am not able to unselect, or at least don't know how to"*

[27] *"The size was a little difficult to differentiate when looking at the overall plot."*

[28] *"For this one, the size was easy to differentiate between for the first two questions, for the last question it appeared to have similar sizes for a few of them so it was a little hard to distinguish between."*

[29] *"You don't have more information about the spheres, which be helpful since many of them were similar in size and far away from each other so choosing was hard"*

[30] *"turning was difficult"*

[31] *"When I mis-clicked I had to start over"*

[32] *"The speed of walking is too slow and it slowed me down a lot, because I wanted to see the balls at different distances."*

Positives

[1] *"Feels like you are in an exciting, exotic space"*

[2] *"easy to move and read the data"*

[3] *"It is fun, it is a new experience, it gives a different perspective."*

[4] *"Being able to move around and visualize the process with my own eyes"*

[5] *"It is certainly a fun way to try statistics. The task was fun and challenged me to apply some logic based on the reference provided to actually make decisions. It is creative idea to present statistics to someone."*

[6] *"It was entertaining to use"*

[7] *"Very fun and easy to use"*

[8] *"It's fun to use and no motion sickness"*

- [9] *"It is easy to move and select things and gauge depth."*
- [10] *"Definitely very immersive visually. I could easily forget I was in a room."*
- [11] *"3D visualization"*
- [12] *"n/A"*
- [13] *"It might be interesting as a teaching tool."*
- [14] *"It is easy to move around when not using rotation feature."*
- [15] *"It is super easy to use"*
- [16] *"Visually pleasing and easy to use"*
- [17] *"It was very easy to pick out the sizes you were looking for and was much more effortless to use the size than color. There was no need to consult a scale to identify what I was looking for."*
- [18] *"easier the more you use it"*
- [19] *"Very similar to the color version."*
- [20] *"It is far more engaging than just sitting in front of a computer screen."*
- [21] *"the most positive aspect was how visual it was and how I was able to be much more productive than looking through a data sheet on my own."*
- [22] *"It was fun to move around, now that I understand the environment a little better (on the third trial)"*
- [23] *"I really like being able to visually be in the space and compare the different data points"*
- [24] *"Through these trials, I can clearly see how combining attributes makes for a much stronger guess, which can then be followed up with by checking the exact data."*
- [25] *"The VR environment is fun"*
- [26] *"The 3D experience of selecting things"*
- [27] *"Looking at individual months/regions was easy. Easy to maneuver. Instructions were clear."*
- [28] *"The size made it fairly easy for the most part to select, what I hope is the right answer, and the 3-D environment was fun to use."*
- [29] *"Easy to use and pick what I wanted to pick"*
- [30] *"size was most easy factor to understand"*
- [31] *"It is really easy to navigate and use"*
- [32] *"Having the balls show up in a 3D environment is really helpful in comparing the sizes."*

5D Desktop

Negatives

[1] *"The keys are confusing, I could not understand/recall what represented what (size, color, y values)"*

[2] *"The difference in distance made it a little bit difficult to judge the size."*

[3] *"There may be a slightly steep learning curve associate with this specific trial."*

[4] *"I can't move up without moving my mouse up"*

[5] *"I was a little confused on whether or not to take in consideration the height of the balls."*

[6] *"slightly difficult to figure out which axes you are on when not all the way to one edge"*

[7] *"The most negative aspect was that I was not able to go back and choose a different answer."*

[8] *"I wish there was a way to go back to the instructions after reading them because I accidently pressed spacebar and couldn't read the instructions."*

[9] *"Cannot backtrack"*

[10] *"The wide arrange of dots can get a little confusing."*

[11] *"It may be the shape used perhaps, but I tend to get distracted easily by the spheres in the BG. Also the changing perspective of simulation doesn't help while identifying the correct sphere, so in the back of my head I felt I may be choosing the wrong data. Maybe if there was a way to blur everything else but the row/column/height I am viewing, would make for a much friendlier time while using it."*

[12] *"I was a little confused at first about the size scale and the color scale simultaneously"*

[13] *"This version was more laggy than the 5D"*

[14] *"I think it is hard to find specific values while starring at a 2D monitor. I think if I could look at a 2D cross section of the 3d design it would be easier"*

[15] *"It is difficult to compare the sizes of the points because of the perspective."*

[16] *"Would have liked a reminder on what the color and size meant."*

[17] *"It was hard for me to tell the size difference between some data points that are far away."*

[18] *"Since there are no numerical values assigned to the dots, it is hard to differentiate sizes when they look similar."*

[19] *"For the types of questions that were asked, the color and size of the ball made it confusing"*

- [20] *"The application was difficult to use and compare sizes of the balls due to closer ones appearing larger than others"*
- [21] *"Telling the difference between the larger sizes is difficult"*
- [22] *"After doing all the three trials, I realized the more the parameters (size, color, position), more difficult it is for me to work around the space. Indicators of the values will be very helpful as I clicked on the sphere as it is difficult to see the Y axis if I move around the space."*
- [23] *"If balls have similar size but the distance between the balls are larger then it is hard to distinguish which one is bigger"*
- [24] *"extremely difficult to go about scanning the size of each data point because distances make sizes look different"*
- [25] *"Couldn't find an overhead view if there was one, but it would be nice if there was one"*
- [26] *"The sensitivity of movement"*
- [27] *"Hard to tell the difference between sizes"*
- [28] *"I wish that the heights were the same when looking at the sizes (like a control variable). It would help me tell which one is smaller/larger more easily."*
- [29] *"Distinguishing colors at far distances was hard, there wasn't a great perspective from the ground and data points could get in the way of vision"*
- [30] *"It's hard to differentiate the size of the spheres. For example, the little ones were barely even seen, whilst the big ones couldn't be told apart"*
- [31] *"Having to interpret the size of all of the points on the graph can become a bit difficult as the size differences for many are very negligible"*
- [32] *"Hard to differentiate between ball sizes without going far away"*

Positives

- [1] *"it was smooth, fun and interactive. It was easy to use and made reading data more interesting and exciting"*
- [2] *"Information shown when clicked is helpful for making sure not selecting wrong sphere."*
- [3] *"It is surprisingly easy to navigate. So, this may help to counteract the steep learning curve associated."*
- [4] *"It is easy to use"*
- [5] *"It was fun to move around and be able to use a 3D graph"*

- [6] *"helps visualize data in more than one axis very well"*
- [7] *"The most positive is that it was very user friendly and easy to navigate."*
- [8] *"The user interface was easy and the controls were easy to learn and use."*
- [9] *"Easy to use, move around, and navigate through the space. The color scale and size were intuitive and helpful."*
- [10] *"It was very easy to use like the entering of the answer and moving around."*
- [11] *"Spheres are cool."*
- [12] *"Navigation made it easy to visualize the data points"*
- [13] *"It helps you visualize information well"*
- [14] *"I think that this would make a great 3D graphing calculator in VR. This can make understanding the behavior of multivariate functions easier"*
- [15] *"It makes it easier to visualize the data."*
- [16] *"Reference on side. Color and size coordinated."*
- [17] *"It was easy for me to use and identify outliers and size differences when the data points are close to each, for example, when comparing the data points within one city or month."*
- [18] *"Using size is an easy way to differentiate two values that are not similar. It is very user friendly in regards to how to data is shown."*
- [19] *"very intuitive in terms of usage"*
- [20] *"The application still remained consistent and I knew what I could expect"*
- [21] *"Seeing large differences is very easy"*
- [22] *"After three times, I know my controllers now. I learnt some tricks to look at the 3D graph"*
- [23] *"Size is intuitive but may be not as good as color and height in 3D space"*
- [24] *"easy to traverse the scene"*
- [25] *"user-friendly"*
- [26] *"The ability to view something from any angle"*
- [27] *"user interface, 3-D environment, ease of use"*
- [28] *"I like this one better then the height and color ones. It's even easier to compare data points and very fun."*
- [29] *"The controls and Interface were easy to manage"*
- [30] *"The combination of all of these variables is really useful for identifying correlations and trends/relationships."*

[31] *"I like all of the different aspects that went into organizing the data appropriately, it made the graph much easier to interpret."*

[32] *"easy to find where to start the tasks given the set up"*

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