

Visualization Research Center of the University of Stuttgart (VISUS)

Master Thesis

Vis2Go: Exploring the Effect of Immersive Analytics for On-The-Go Decision Making

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Abstract

The integration of Augmented Reality in various industries has seen a rise in the past couple of years. Today AR is used on a large scale for data visualization. It offers several benefits such as immersion in the data and improved presentation over the traditional methods such as using a desktop computer. In this master thesis, we focus on the impact that AR data visualizations have on the decision-making abilities of the user. We explore how the user's understanding of the data is affected when it is presented in AR. Further, we also study the idea of having *Data on the Go* where the data follows the user at all times. This has the advantage of giving live updates to the user when they are on the move. We evaluate the performance of the users in taking a decision when they are observing the data in AR and at the same time completing a secondary task of walking.

We adopt the use case of medical data for our visualizations. To prepare for this we conduct several interviews with medical staff to understand what kind of data is important for analysing the health of a patient. We also conduct an exploratory user study where the participants play the role of a doctor in a hospital. We present the participants with four unique use cases where they have to take important decisions about a patient's health within a time limit. The data is presented to the participants in 2 formats: Immersive Condition (on the HoloLens) and Non-Immersive Condition (on the Computer). We compare these two conditions in terms of the accuracy of the decisions, the time needed and preferences of the different participants.

Based on our user study we believe that the decision-making capabilities of a user remain unaffected irrespective of which condition they are in. For time-critical situations the user can swiftly reach a decision in both conditions and for non-emergency situations the time-based performance of the Immersive Condition is better as compared to the Non-Immersive Condition. Based on the subjective feedback we received, we believe that the *Data on the Go* scenario has a lot of potential if the movement and orientation of the data are improved.

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List of Acronyms

AR - Augmented Reality
VR - Virtual Reality
IA - Immersive Analytics
ER - Emergency Room
HUD - Heads-Up Display
HMD - Head Mounted Displays
IoT - Internet of Things
IATK - Immersive Analytics Toolkit
MQTT - Message Queue Telemetry Transport
MRTK - Mixed Reality Toolkit
VST - Video See-Through
OST - Optical See-Through
UI - User Interface

1 Introduction

Augmented Reality is an ever-growing field that has got applications in several industries such as medical, construction, manufacturing, education and automobiles [CA15] [HH16] [BV19] [Lee12]. In this day and age, the usage of augmented reality (AR) in the healthcare industry is experiencing growth and has a wide range of possible applications. It is used by medical professionals for different purposes, such as education and training [TCMG20], preparing and planning for a surgery [AP19], remote collaboration or post-surgery treatment and observation. It can also be used to assist doctors or nurses with their everyday tasks as well as complex tasks.

A doctor manages and treats many patients and hence needs to process, understand and look at a lot of data. Humans are visual creatures who learn better and retain more information if it is presented in a visual manner which has been studied by experiments conducted by Bobek et al. in [BT16]. Their experiments show that visual learning is clearly beneficial for understanding and mastering even complex systems. Authors Raiyn et al. in [Rai16] have also studied how the analytical thinking skills of students have improved when a visual learning concept is used. Data visualizations in AR can potentially transform the way users can interpret, interact and analyse the data. The users can interact with the data which surrounds them and offers a 360-degree sphere of space. Such data representation can have several benefits such as immersion in the data, greater space and improved presentation. Hence AR visualization is a promising new technique for data visualization which can render large information virtually in the real environment.

In this project, we focus on the use of AR in the medical scenario, for medical data visualization. Whenever a person is admitted to a hospital or kept under observation after surgery, their health is tracked by the medical staff by monitoring their vital signs such as temperature, oxygen rate, heart rate and blood pressure. These vital signs reveal noteworthy information about the patient's well-being. When they are monitored uninterruptedly over a longer duration they help the doctor to draw important conclusions and take decisions about the treatment of the patient. To assist the doctors in this decision-making process, we propose the use of AR for data visualization. We explore how data visualization in immersive condition affects the understanding and decision-making capability of the user. We compare how data visualization and decision-making is different in immersive condition as compared to traditional methods such as using 2D devices like a computer. We discuss what advantages and shortcomings AR have over the currently used standard practice.

Furthermore, we also investigate the idea of having *data on the go*, where the doctors can have a look at the data while they are going toward the patient. We investigate to what extent this easy access to the data visuals will help the doctors. The purpose is to provide information on the go as they can take the data along with them with the use of the head-mounted AR glasses, which in our case is the Microsoft *HoloLens 2*¹. We examine whether the medical data provided on the HoloLens is easier to understand and contributes towards faster decision-making while also

¹<https://www.microsoft.com/de-de/HoloLens>

1 Introduction

being accurate. To check this, we also conduct an exploratory user study in a study environment to understand the different reactions that people have to data visualization using HoloLens. The details and results of this user study are discussed in the chapter called *Results*. By comparing data visualization using this next Gen of potential devices (HMD) with the more conventional way of computers, we hope to contribute to the benefits of using AR more frequently in different sector for everyday use.

For the implementation of this master thesis, a new toolkit for situated analytics called *RagRug* is used [FCH+22]. The abilities of RagRug go beyond previous immersive analytics tool kits by focusing on specific requirements emerging when using augmented reality (AR) rather than virtual reality (VR).

In the following chapter *Background and related work* (Chapter 2), we attempt to incorporate significant studies and prior research in the area of augmented reality and data visualization. *Design and Implementation* (Chapter 3) gives a brief explanation of the tools and platforms used for the design. To gain more insight into everyday work in a hospital and the interaction between a patient, their data and the doctor, we conduct the first interview with some doctors. The chapter *Evaluation* (Chapter 4) gives a brief description of those interviews. Based on those interviews the design of the user study is finalised and other details related to the implementation and user study are carried out. The outcome of the user study in terms of time, accuracy and subjective feedback is discussed in the chapter *Results* (Chapter 5). In the chapter *Discussion* (Chapter 6) we talk in detail about the improvements that can be done based on our user feedback along with the challenges we had to overcome during the implementation of the user study. Here we also discuss the future work that can be built upon this user study. In the final (Chapter 7) *Conclusion and Outlook*, we discuss what our views are after conducting the user study on the benefits of using AR for data visualization on the go and how it can be used for different tasks.

2 Background and related work

2.1 Augmented Reality in Medical

The fascinating immersive technologies which were earlier seen only in science fiction movies are now becoming a reality thanks to Augmented and Virtual Reality. The field of medicine and surgery has also seen several uses of these technologies in different ways such as training and education, pre-surgery planning and guidance for diagnostic and rehabilitation. Monsky et al. in [MJS19] summarize the history, current use and potential future uses of AR and VR in the medical field. The authors talk about the development of AR and VR through the years and discuss how their scope has expanded since their birth in the mid-1960s.

There are two types of Head Mounted Displays (HMDs) available: Video See-Through (VST) and Optical See-Through (OST). The first ever HMD was developed by Morton Heilig in 1960 called the *Telesphere Mask* which had stereoscopic 3D and surround sound. Since then there have been many developments in the field of AR and VR devices. The sensation of feeling was first incorporated into a system called *GROPE* in the 70s. The HMDs were available commercially from the 80s. Today's AR and VR devices are very sophisticated and major companies have released their products. FDA approved Google Glass¹ and HoloLens² are used widely today. The HoloLens is a type of OST that provides an immersive AR environment.

The use of AR for open surgeries has become more common nowadays. Some surgeries can benefit greatly from the use of AR. Topsakal et al. [TM19] have tried to identify the common features necessary for an AR app that can be used during surgery. They collaborated with experienced surgeons and tried to identify the type of information that can be presented to the surgeons before, during and after surgery and came up with a user interface (UI).

Neurosurgery is also a field where AR plays a key role to provide accurate neuronavigation. This is achieved by superimposing the images on the surgical sites thereby reducing fluoroscopy time and blood loss. The usage of HMDs in neurosurgeries shows promise for the future as it can enhance visualization and guidance. In the systematic review by Chidambaram et al. [CSD+21] they have analysed the incorporation of AR in neurosurgery. Several studies have also been conducted to analyse the use of AR in different types of surgeries and how they have improved the outcomes. In a study by Qu et al. [QHX+15] they have used an AR toolkit for precise positioning of an intraoral distractor. The results showed that the placement using AR was more accurate.

To treat patients with psychological disorders such as phobias, AR/ VR approaches have been very successful. Freeman et al. [FRR+17] discuss these approaches using a form of immersive AR (HMD, CAVE, large projection screen, screen with 3D glasses). Exposure theory is used where the

¹<https://www.google.com/glass/start/>

²<https://www.microsoft.com/de-de/hololens>

2 Background and related work

patient will face their fears in a simulated environment that feels realistic to them thereby allowing them to confront their fears without any real bodily harm. Similarly, patients with chronic pain can be distracted from their pain with the help of the virtual world which leads to increased pain tolerance among them. Malloy et al. give in their work [MM10] a systematic review of this technique using a head-mounted display helmet. Furthermore, the authors also discuss the limitations in the current technologies which we need to overcome to embed AR/ VR in our everyday life.

The use of AR in education and training has seen a rise in the past years due to its advanced developments. Many different mobile simulation technologies are being designed to facilitate nursing education. Kurt et al. [KÖ21] conducted a user study with 112 first year nursing students which showed that mobile AR can have a positive effect on the knowledge and skills of the nurses in terms of injection practices. There are several mobile AR applications in the market today that provides a solution to many challenges in the healthcare system such as *Anatomy 4D*³, *Holo Eye Anatomy*⁴, *Virtual interactive presence and augmented reality (VIPAR)* [SDS+11]. The figure 2.1 shows how VIPAR can be used for remote surgical assistance.

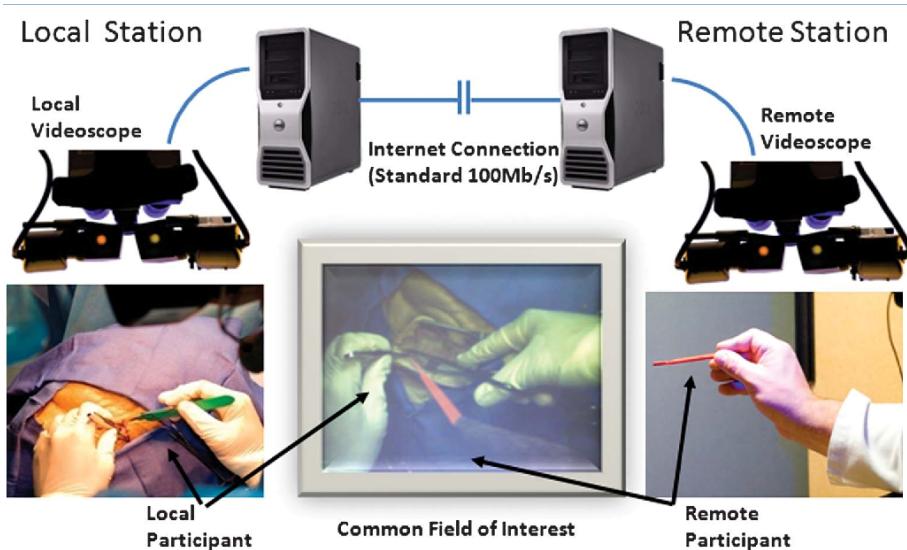


Figure 2.1: This is the schematic diagram of VIPAR system which consists of local and remote station, each equipped with a videoscope. Digital renderings are added to the surgeon's reality with the help of a standard internet connection. The videoscopes provide a point of view for the local and remote surgeon and they both have a common field of interest which they work on together [SDS+11]

2.2 Immersive Analytics

In today's world, the amount of data available to humans for decision-making and analysis is huge and also complex. Simple computer applications are not sufficient for visualising the data. What we need are more efficient and engaging tools for examining the data. For this purpose Immersive

³<https://www.4danatomy.com/>

⁴<https://www.microsoft.com/en-us/p/hofo-eye-anatomy/9ng9cl1qfz7n?activetab=pivot:overviewtab>

Analytics (IA), a new research field is being studied. The main aim of Immersive Analytics is to bridge the gap between the people, their data and the tools used for analysis. In Immersive Analytics, the user can immerse themselves in the virtual space surrounded by data with the help of Head Mounted Displays. The book *Immersive Analytics* by Kim Marriott et al. [MSD+18] discusses in detail the meaning, importance and benefits of Immersive Analytics in our personal and professional lives. The book is based on two major workshops held in Japan and Germany where several experts gathered to discuss Immersive Analytics and its impact.

Around 2014 the Data Visualisation and Immersive Analytics Research Lab at Monash University were the first to use the term Immersive Analytics. They have also investigated embodied interactions in IA. For that, they developed *ImAxes* [CCD+17] which is an authoring tool where the users can grab or rearrange the data visualizations. They studied this tool with more than 30 data scientists and explored how the scientists placed and presented different visualisations.

Experts like Cordeil et al. collaborated to develop the *Immersive Analytics Toolkit (IATK)* [CCB+19]. It is a software package for Unity that is mainly used for visualising data in the immersive world. With IATK the user can create as well as assemble immersive visualisation designs with ease. To support collaboration in IA, Lee et al. also designed *FIESTA system* [LCPD19] which is a visual analytics system that provides collaboration in a virtual room. *FIESTA* also acts as an extension to IATK. A system for local and remote collaborations was developed by Klapperstuck et al. [KCG+16]. Users who were at remote locations could work together with the help of a virtual desktop where content could be shared using touch devices and displays.

Several studies have been conducted to find the best way information can be presented in a wearable environment. These techniques need to be different than the two-dimensional interfaces. The main idea is to consider different techniques in which the information is easily accessible to the user but avoid interfering with their work at hand when it's not necessary by staying out of the way. M. Billinghamurst et al. in [BBDM98] have designed and evaluated different spatialised interfaces for wearables. The three main settings: head stabilised, body stabilised and world stabilised has been studied by the authors. Similarly, Feiyu Lu et al. in [LDL+20] propose and evaluate three glanceable AR interfaces which are: Eye-Glance interface, Head-Glance interface and Gaze-Summon interface. Several hypotheses were tested and the conclusion was that for information access, the Head-Glance and Eye-Glance were more preferred than the Gaze-Summon. For the continuous monitoring task, Eye-Glance was more preferred. The figure 2.2 shows these three glanceable techniques.

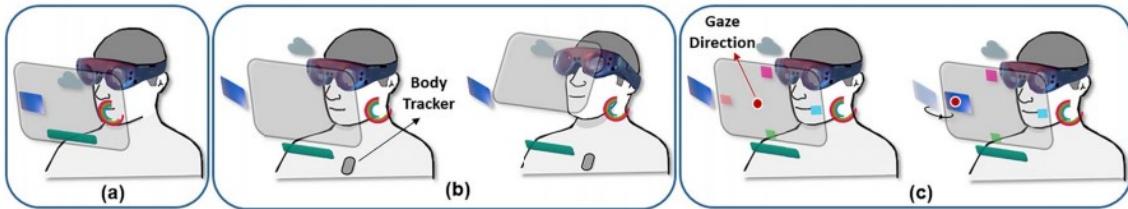


Figure 2.2: (a) The Eye-Glance interface is the a baseline Heads-Up Display (HUD) technique where the virtual content is fixed to the user's head. (b) In the Head-Glance interface the virtual content is hidden from sight when facing straight, but is visible when looking in the peripheral direction. (c) Gaze-summon interface is the one in which 0.5 seconds of focused peripheral viewing can bring virtual content into the field of view of the user. [LDL+20]

An important factor that must be considered when designing wearable computing such as Head Mounted Displays (HMD) is that the users feel natural and that they do not lose their productivity. One of the main problems with the current HMDs is that sometimes the virtual content occludes the user's view of the surroundings or is restricted in a fixed location. Furthermore many tasks require switching between multiple applications and the cost of switching is high. To address all these concerns, Barrett Ens et al in [EFI14] present a solution for multitasking on HMD while moving around. The solution called *Personal Cockpit* was also tested in a user study and compared with the baseline interface for switching between multiple applications. This research is based on past work by Feiner et al [FMHS93] where world and body fixed virtual windows have been studied.

The display sizes and distance of the windows from the users also affect the performance of the users to a certain extent. Having a large display helps in certain tasks such as searching for data or comparing between data. These advantages have been explored by Ni et al. in [NBC06]. Shupp et al. [SBY+06] have studied the impact that large, high-resolution windows have on time, accuracy and mental workload. They concluded in their work that having a curved display reduced the task completion time. These findings have been taken into consideration by Ens et al. when designing the *Personal Cockpit*. The results indicated that when using the *Personal Cockpit*, the participants completed the tasks 40% faster while also switching between the various applications. The figure 2.3 shows the curved placement of windows for the Personal Cockpit.

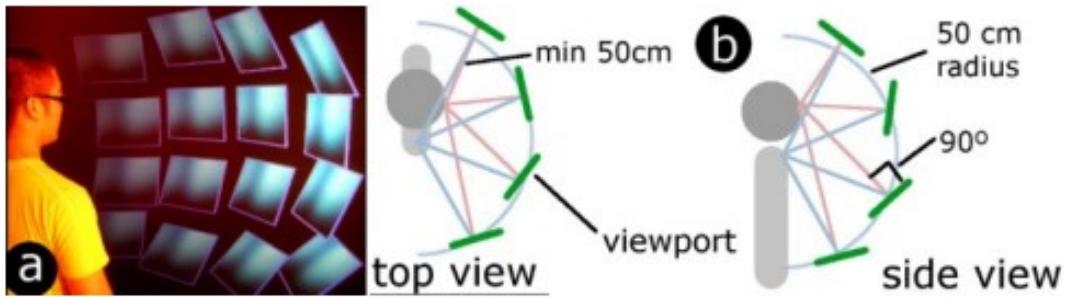


Figure 2.3: (a) Design and Placement of multiple virtual windows where a larger environmental space is utilised (b) Final window positions in Personal Cockpit with a min 50 cm viewing distance and a curved layout [EFI14]

AR can give users the ability to access information everywhere they go; even when they are on a move. They can maintain the virtual workspace of multiple windows they have created when they walk in a different physical environment. The interfaces can also support the users when they are walking around in such different physical environments. However, in some situations, it is difficult to manage the windows and virtual content when walking. Lages et al. [LB19b] have explored how AR interfaces can support walking and movement in the physical world. The authors have evaluated different options and established crucial interaction patterns that the AR interfaces should support for walking. The goal was to improve the experience users have with any change in the context when they are walking and the focus was on position adaption. The authors combined their results to make design guidelines that can help make future AR interfaces more comfortable for the users.

Prior research has also been conducted to check the user's gait variability when using smart glasses (HMD), smartphones and paper notebooks. Sedighi et al. in [SUN18] conducted a study to compare the gait variability of user's when they have to complete multiple tasks simultaneously. During such dual tasks, the speed of walking, stride and cadence obviously is affected. However, after their user studies, the authors concluded that the risk of falling is reduced with the heads up display when doing dual-tasks as compared to a smartphone or a paper-based system.

In another paper by Lages et al. [LB19a], they designed as well as implemented a system that will further fine-tune a person's spatial representation. The authors have created a single interaction framework that enables speedy switching between multiple windows with the help of a small number of adaptive behaviours. The authors have combined four possible goals for accessing information while on the go: Retrieve information for tasks, arrange the information for easy access, be aware of the physical surroundings and synchronize the information with the real world. Their design provides automatic placements along with adjustments that can be made by the user when they look in a new direction.

2.3 Immersive Analytics in Medical

Klaudia Proniewska et al. in [PDD18] discuss the idea of using the HoloLens as a doctor's assistant for visualising the heart rate reading. They have created an application on the HoloLens so that the doctors can have hands-free access to the patient data. The paper discusses the vast possibilities and advantages of treatment on any organ if the medical visualizations can be viewed through augmented reality. To obtain simulated pulse readings, they used a simple plug-and-play pulse sensor. With the help of a Raspberry Pi micro computer the analog data from the sensor is converted to digital and through WiFi passed to the HoloLens. The figure below shows the entire setup.

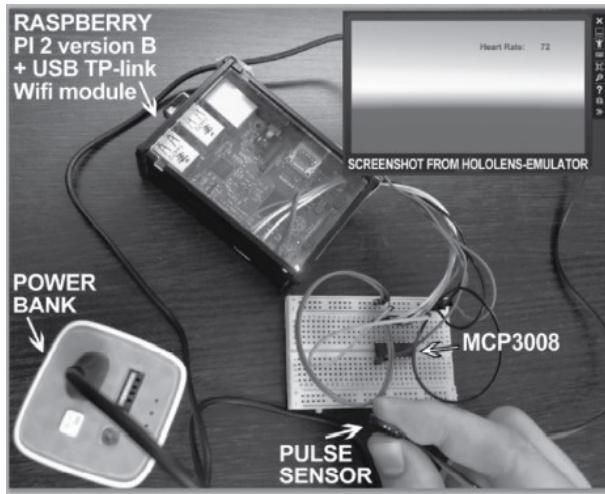


Figure 2.4: Setup for the project: Pulse sensor generate the data which is converted to digital form with the help of MCP3008 ADC. The readings from the sensor are handled by the Raspberry Pi with a custom Python code and then passed on to the HoloLens with UDP communication. The power bank is used to power the Raspberry Pi. Image taken from [PDD18]

The incorporation of augmented reality devices in surgery has shown what demands are fulfilled by them and what not. Although there is a lot of potential for these devices to succeed in the medical field, a hybrid solution that combined virtual and augmented reality features is expected to work best. This technology called *Mixed Reality* has been used by Trepper et al. in [TRL+17] in the operating room. The authors have described in this article how the decision-making of the surgeons was affected when using Mixed Reality

Furthermore, during complex surgeries, it is highly beneficial to have an expert who can give instructions and guide the trainee. Currently, teleconferencing is the main way to establish communication between doctors. However, in an emergency scenario, these systems are inadequate. To address this issue, the article [WPS+17] uses a telepresence application using the HoloLens. This AR system will be used to provide expert assistance and training to the learners so that they can perform complex surgeries as shown in the figure 2.5 and figure 2.6. Through mixed reality capture, this study employs the HoloLens to capture the first-person perspective of a simulated rural Emergency Room (ER). The expert or mentor can guide the learner as their hand gestures are captured by the application and then virtually displayed in the HoloLens.



Figure 2.5: Mentor training a trainee involving real-time remote pointing and gesture capture.
Image taken from [WPS+17].

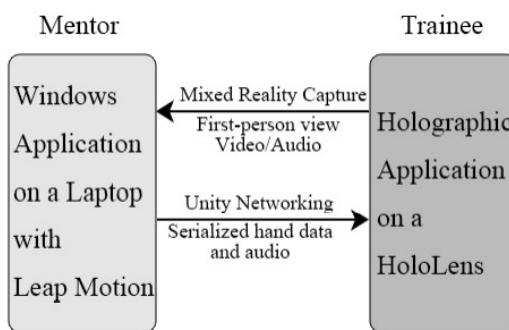


Figure 2.6: Overview of the system: Leap sensor captures hand gestures and send to the computer which then exchanges the data with HoloLens. On the trainee's side the position and inclination of the hand gestures are simulated [WPS+17]

Several papers discuss how medical data can be visualized in AR. However, in most cases, the main objective is the usability of the system. The performance criteria like correctness of the transmitted data and latency are not measured. Several factors which affect the real-time transmission such as transmission bandwidth, number of interruptions per time unit and monitoring delays need to be analysed. In the work [ACB+21] AR is being used to display the real-time vitals of a patient during surgery. The error rates and latency of the system are also measured. This paper highlights the requirements and challenges of real-time data transmission and tries to measure the success of using AR in real-time medical procedures.

HMDs are becoming increasingly popular in different healthcare sectors. However, it is important to study how they affect a person's attention. Cole et al. [CH22] conducted an evaluation to check if the anesthesiologists can perform different medical procedures while keeping an eye on the patient when using the HMDs. 39 anesthesiologists participated in this study where they performed different procedures within a time limit and at the same time monitored the physiological state of a patient. Their studies revealed that the group that used HMDs needed less time to recognise any derangements and were also able to perform the other procedures successfully.

Based on these different papers and articles we researched, the user study for our thesis is designed. We realise that there is vast research going on about the different forms of visualization and how they can be integrated into the medical field. However, their impact on the understanding of the data has not been explored in depth. It is very important to make sure that the user's decision-making

2 Background and related work

capacity is not diminished or lagging in the immersive setting. So we have decided to add use cases in which the participants have to see and comprehend the data they are seeing and then take a decision. There are multiple choices that will be presented to the participant out of which only one is the correct choice. This way we can examine if the understanding of the data is affected. Furthermore, we explore what the participants experience when walking and simultaneously looking at data. We want the data to follow the participant around and get feedback from them about how the movements of the visualizations affect their comfort. We use the Head-Glance technique for this where the data follows the head movements of the user. We chose this glanceable interface because according to Lu et al. [LDL+20] Head-Glance performs well for information access. Considering the results and observations of the above-stated papers we design our user study and implement it.

3 Design and Implementation

For the implementation of this Master Thesis, we use the toolkit *RagRug* [FCH+22]. RagRug is an open-source toolkit that focuses on specific requirements of situated analytics. It weaves together different virtual or physical components to form an efficient toolkit. The AR visualizations receive the data using a distributed data flow. The visualizations are context-aware which means that they change as per the changes in the real world. RagRug builds on *Immersive Analytics Toolkit (IATK)* which is already a fast toolkit where the code can be maintained easily and is well integrated into Unity. Hence RagRug inherits all these advantages of IATK and provides the same visual representation. What RagRug does is that it extends the interaction capabilities of IATK. These interaction capabilities consist of the input provided by the users as well as the interaction between the user and the environment. RagRug extends the standard IATK model by combining it with several other components thereby also acquiring the benefits of these components. Thus it is a unified programming model which also provides reactive programming in the entire system. The way RagRug combines the different components and the way they interconnect with each other is shown in the figure 3.1.

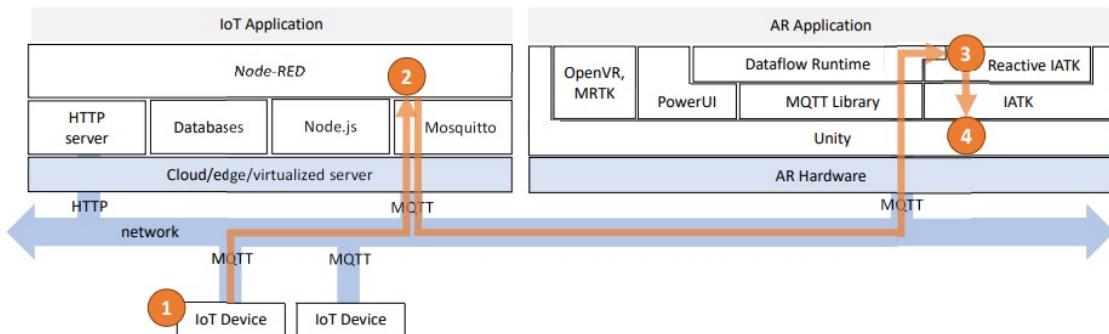


Figure 3.1: Design of RagRug: Standard IATK is extended in RagRug with components such as MQTT, PowerUI and custom components like Reactive IATK (1)) Data is acquired using MQTT; (2) Data is filtered using dataflow in Node-RED; (3) Data is visually encoded in Reactive IATK; (4) Rendering in Unity; Image taken from Fleck et al. [FCH+22]

*Node-RED*¹ is an important part of the RagRug toolkit. It is a development tool that uses flow-based design where different nodes are connected to create an interconnected graph. The data flows through these nodes where each node can have a different operation. The Node RED uses JavaScript

¹<https://nodered.org/>

3 Design and Implementation

functions for its operations. These operations can be chosen from a standard library or can also be customised by writing short codes. The data is put together as a stream and given to the source node. These source nodes further pass the data to its dependent nodes and sequentially the data passes through the entire graph. Data distribution is an important part of Node RED and it uses the publish-subscribe method for communication using the *Message Queue Telemetry Transport (MQTT)* protocol. Publishers assign a topic to their message so that the subscribers can easily subscribe to that message. The RagRug uses an open-source tool *Eclipse Mosquito*² as a broker which sends the messages to the correct subscriber. Since the topic is known by the publisher and subscriber in advance, at runtime there are no additional services needed. The Node RED and Mosquitto together are referred to as *hub* in RagRug. To store the physical-virtual model, RagRug uses a database called *Influx DB*³. The advantage of using such a backend database is that there is no need to manually push the data set to the client. The client can query it dynamically from this data set.

Thus as it is seen in 3.1 we have two standalone platforms: an AR client which is running the Unity, Microsoft Mixed Reality Toolkit (MRTK) and IATK and the other platform is for the IoT application containing Node RED, Mosquitto and some other platforms. The data acquisition can be done by IoT devices like sensors and actuators, but for this thesis, we are using simulated data that is generated in Node RED itself. This data is then processed in Node Red as per the requirements, where the nodes can be customised by the designer to achieve the required form of data. The visual encoding is achieved by the Reactive IATK and the final rendering is established by Unity. To have uniformity in the application, pub-sub is also used inside the Unity instance.

The Node RED programming is done in JavaScript while the AR Client uses C# programming language hence there is no unified programming. However, a solution to this is *PowerUI*⁴ which is an extension to Unity. Hence all the codes can now be written in JavaScript and PowerUI will dynamically reveal the C libraries to JavaScript. As a result, RagRug uses a uniform Node RED style data flow which is easy to use and understand. The developers can use only JavaScript as a programming language and all the processing of the data can be done in Node RED.

In this thesis, we conduct a user study to evaluate the medical data visualizations and its impact on a user's understanding of data. The simulated data will be presented to the user in various graphical formats. We created several flows in Node RED to design the different cases of the user study. The data generation, designing how the graphs will be visualised, creating the menu of the application and several different functionalities were all done in multiple Node RED flows. In the following sections, we explain how the different nodes in the flow work together to pre-process the data and make it ready for rendering in Unity.

3.1 Data Generation in Node RED Flows

In this section, we explain how the flows were designed so that appropriate data could be generated at the correct frequency for each vital. The data which is plotted as a line or bar graph is simulated data. It is not obtained from any human or sensor. Hence we have to design different flows which

²<https://mosquitto.org/>

³<https://www.influxdata.com/>

⁴<https://powerui.kulestar.com/>

would generate data for each vital. For that initially, we researched what are the normal ranges, thresholds and critical values for the different vitals. Based on that and the different use cases, we simulate the data in the nodes. The basic connection between the nodes which will generate the data for graphs on the HoloLens or the computer remains the same. Even for real-time graphs and bar graphs, the basic algorithm remains the same. The data generation flow for the graphs looks as shown in figure 3.2 . The figure 3.2 shows how the different nodes are connected to generate the Blood Pressure data. The graph below is a snapshot taken directly from the visual programming front-end of Node RED. The *timestamp* triggers the data flow every second. Hence a new reading is generated every second which mimics how the data is collected by actual hospital equipments. Then the *function node* generates the data as per the algorithm and then sends it via *MQTT* to the other flows. A unique *MQTT* topic is given to the function node so that other nodes can subscribe to the data acquired from it. The *Raw msg* is a debug node where the generated readings can be seen in the debug window. Each vital has such a data flow where the data generation takes place. The figure 3.3 shows how data generation for weekly Heart Rate is designed. The values are passed in to the Node Red UI Dashboard, where they can be displayed as per the designer's customization. Similarly, the data generation for all the other vitals is achieved.

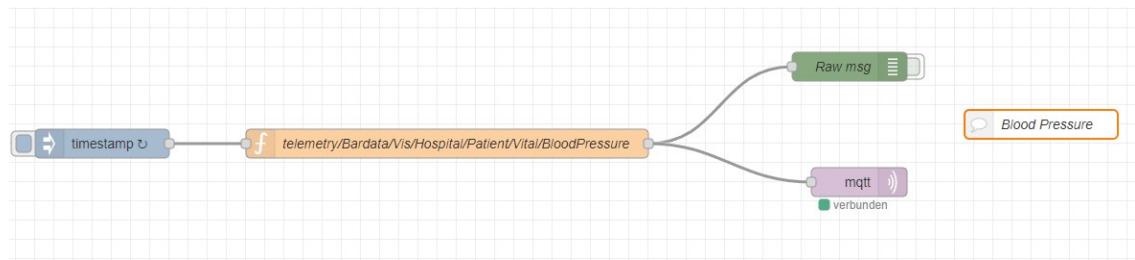


Figure 3.2: Interconnection between nodes for customised data generation using timestamp and mqtt nodes, where the data generation is performed in the function node with custom code as per requirement

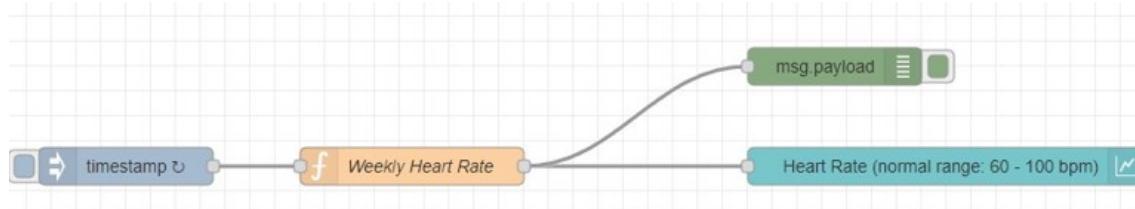


Figure 3.3: Interconnection between nodes for weekly data generation for Heart Rate. The values are passed on to the Node Red UI dashboard.

For real-time data generation, we want to get a value for every second which is in the pre-decided range. As per the design, the range can be the normal range or it can be the critical range. Using the *Math.random* function we simulate the data points such that they will always be in the specific range. These data points are then plotted on a line graph. For the previous week's data generation, the basic connection between the nodes remains the same. However, the code for data generation differs slightly. In that case, we want to display the average value for a day. So instead of generating data points within a certain range, a fixed array of data is sent every second. This array consists of

3 Design and Implementation

7 fixed values for 7 days of the week. These values are then plotted on a bar graph and seen on the HoloLens. For other conditions where the graphs are to be seen on the computer rather than the HoloLens, we have used *Grafana*⁵ to visualize the real-time data and *Node RED UI* to see the average daily readings for a week. Grafana is multi-platform open-source analytics and interactive visualization web application. It accesses the data generated in the flows through Influx DB which is the database used in RagRug. Node RED UI is a live dashboard that can be created with the help of dashboard nodes. Hence the data can directly be sent to the UI and the designer can customize the dashboard.

3.2 Designing of Graphs and their Placements

In the previous section, we explained how the data is generated in the data flows. This data needs to be presented to the users in a visually appealing manner. The size and position of the line and bar graphs, their colors and their axes have to be designed and customised. The colors of the line graphs and how they change based on the values have also been implemented in Node RED. The figure 3.4 shows how the design of the line graph was done.

⁵<https://grafana.com/>

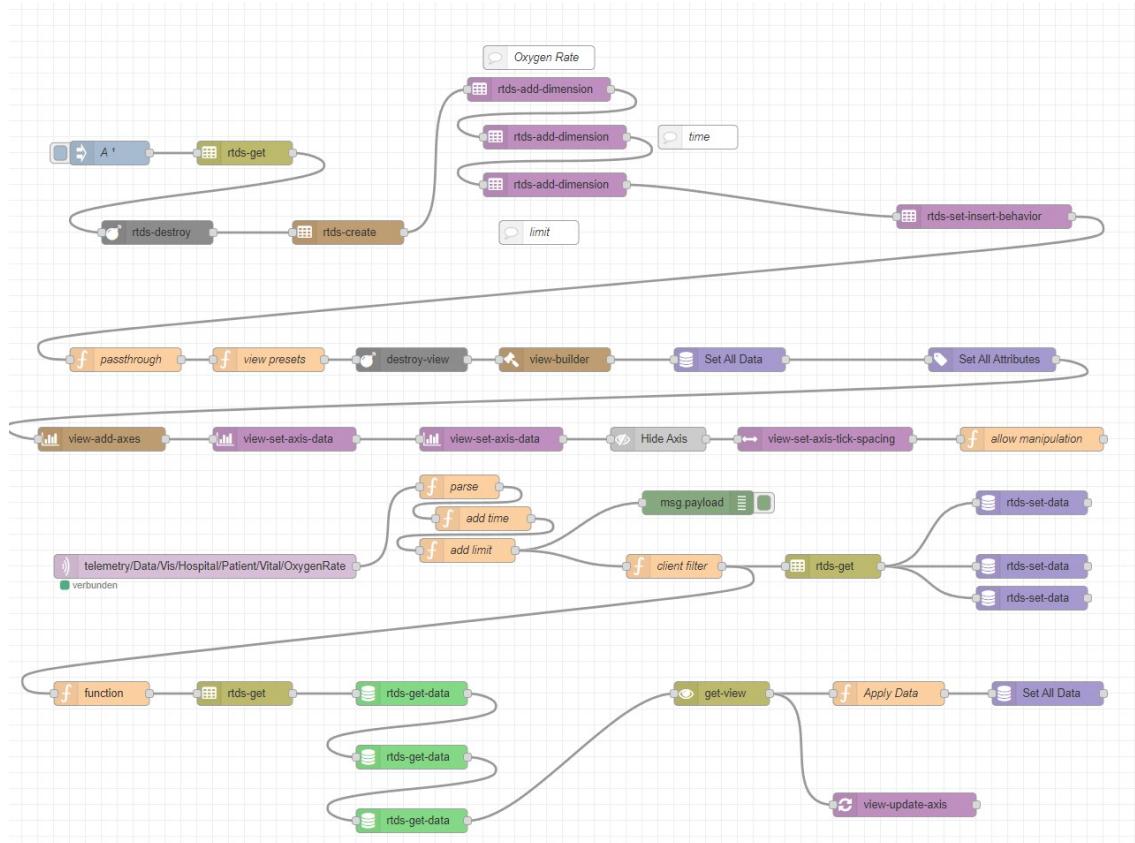


Figure 3.4: Line Graph Designing where multiple nodes are interconnected so that they can work together to showcase the data on the HoloLens. Here we specify the size, positioning, orientation and colors of the line graphs.

For this implementation, we use the standard Node RED library as well as some custom RagRug nodes. These nodes interact with IATK on the RagRug client. Each node has a specific operation. The entire flow for this design has been broken down into sections and presented here. Initially, we create the visualization and set the dimension of the graphs. We also specify the maximum number of data points that can be shown on the graph. In the *rtds-add-dimension* nodes we specify the range of the y-axis (the vital) and what is on the x-axis. For the real-time line graphs, we want the time on the x-axis with an interval of 1 second. Along with that, we display the threshold limits of the vital as horizontal white lines. The *view presets* function sets up the number of data points and the number of lines that the graph will display. Furthermore, the plotting of the data points is coded here. There are several nodes in between, which set up the axis data, the number of axes, the spacing between the points on the axis and so on. All these aspects can be customised by the designer. The *allow manipulation* node is used to set the position of the graph on the HoloLens. Furthermore, we have enabled the *Tag Along* offered by MRTK in this node. This feature will enable the visualization to follow the user's eye movement and position. The tag along uses the *Radial View* script where different components such as *move lerp time*, *smoothing*, *min-max view degrees*, *min-max distance*, *aspect V* have to be customised as per requirement. The graph gets its data points from the *MQTT in* node. With the help of the unique topics given to the nodes while generating data, the subscriber can subscribe to the topic and receive its data stream. We also set

3 Design and Implementation

the horizontal threshold lines and add the current time after that. Another important node is the *Apply Data* node. The important meaning of the colors of the lines is implemented here. For our application we want the line graph to have a specific color depending on its value. We also want the lines to change colors when they cross a certain limit. These features are coded here. One by one the data points are pushed and the color is assigned to them based on their value.

For bar graph visualization design, the flow is slightly different. The figure 3.5 shows the interconnection of nodes. Here as well the first step is to create the visualization and specify the size of the graph. Here on the x-axis instead of having time we have only 7 points: the 7 days of the week starting from Monday. This is set in the *Fill RTDS* function node. In the *View Setup* function, we specify the number of points in the graph which will be 7 in this case and we push these points and set their positions. The *allow manipulation* node will set up where the graph will appear in front of the user when they are wearing the HoloLens and the *Tag Along* is also implemented here. With the help of the unique topic, the *MQTT in* will bring in the data stream from the publisher. There are no threshold lines in this graph. The data is parsed and accurately plotted in the form of bars.

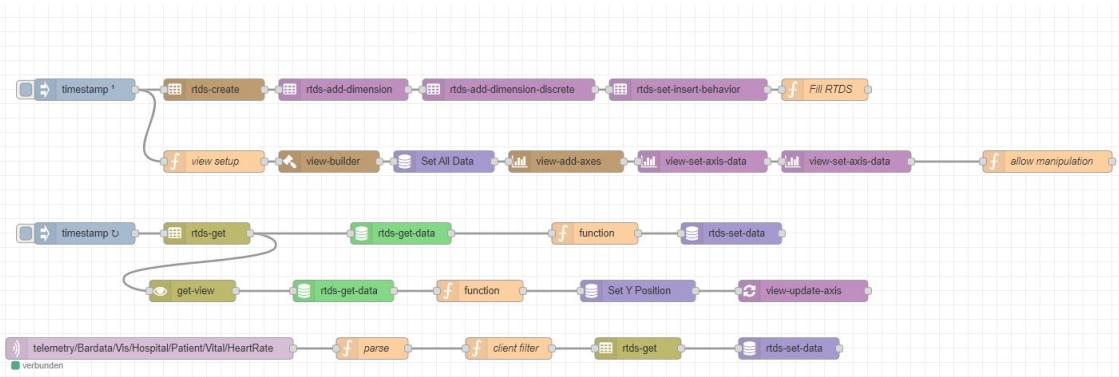


Figure 3.5: Bar Graph Designing. Here we have nodes connected together each having a different specifications so as to design the bar graphs. The data points are obtained from the *mqtt-in* node and then parsed along to the other nodes where their positioning and orientation is decided.

3.3 Designing of Menu

We also create a menu in the application from where we can select which vital graph to see. This menu has 6 buttons: the four vitals (*Heart Rate, Oxygen Rate, Blood Pressure and Body Temperature*) and the *Real Time* button to see all 4 line graphs and the *History Data* button to see all 4 bar graphs. For designing of this menu, we use a *mrtk button group* node which is further connected to six button nodes. The designer can decide what happens when the button is pressed. For our design we have coded it such that, when the button is pressed, if the graph is already visible it is disabled and vice-versa. The *toggle vis* function contains the logic for that. The *init vis/ref* node sets up the initialization of the graphs which can send the data accordingly. If the button press triggers multiple graphs, then, after a delay of half a second the second graph is also visible. The connectivity of the nodes is as shown in the figure 3.6.

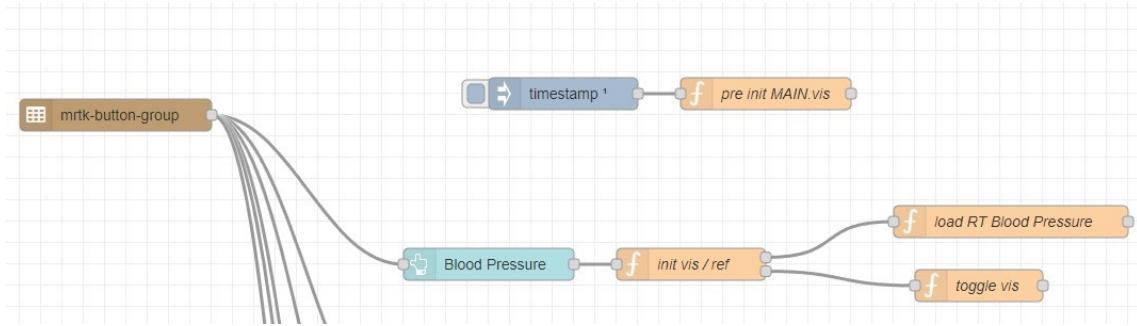


Figure 3.6: Multiple buttons can be connected to *mrtk button group* like Blood Pressure as shown in this figure. The *toggle vis*, *init vis/ref*, *load RT Blood Pressure* each have a specific function which contributes to the button press logic

In the figure 3.7, we show how the logic flows through the nodes when the button labelled *Body Temperature* is pressed by the user. The initial visualization is set up first and then we load the bar graphs for Body Temperature first. After a delay which can be customised as per the requirement the line graph becomes visible. Here we have used the *flow id* to make sure that the correct flows are connected to the buttons. The *toggle vis* contains the logic for alternatively showing and hiding the graphs.

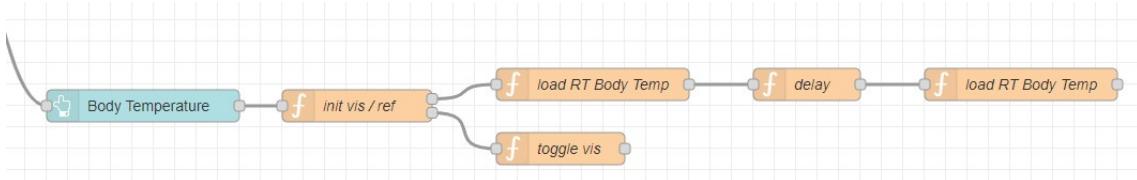


Figure 3.7: Button Press logic for Body Temperature where after the initialization of the visualization, the *toggle vis* checks if the graphs are visible or not. If they are visible initially they are hidden and vice versa.

In the figure 3.8 we have four graphs which will be displayed when *Real Time Data* button is pressed. Similar to this, the *History Data* button also has nodes connected in the same manner.

3 Design and Implementation

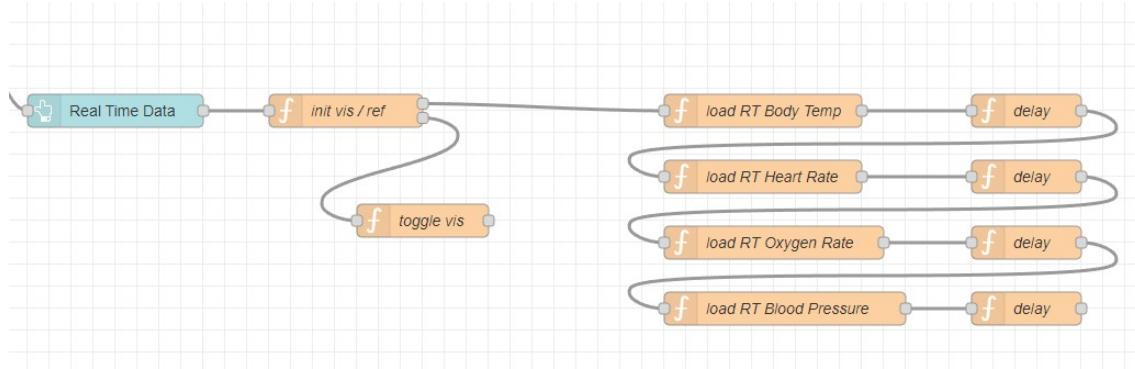


Figure 3.8: Button Press logic for Real Time Data where all four line graphs of the four vitals are displayed to the user with a half second delay between them. Again the toggle vis node toggles their visibility to the user.

4 Evaluation

To compare the data visualizations techniques in an immersive and a non-immersive environment, we conduct an exploratory user study. In this chapter, we discuss in detail the preparation for the user study and the exact study procedure. For this master thesis, we have focused on the medical data visualizations in AR. Hence it is important to understand how the medical data is currently presented to the medical staff. We also have to understand which data is important to the doctors to determine the health of a patient. In the following sections, we will present our findings from the interviews which we took with different doctors at the beginning of the thesis. Based on our research, we then designed our user study and conducted it with a total of 15 participants. To gain more insight into how the participants would react in different situations, a total of 4 unique cases are designed, each with a specific purpose. The participants complete these cases and the details of them are presented in the following sections.

4.1 Preparation: Interviews

We have adopted the use case of medical data for our visualizations. We think that the medical data is the kind of use case that can provide us with insightful results. For this, we talked to several doctors and nurses to get more insight into how the day-to-day activities are conducted in a hospital. We ask them several questions about how they interact with the patients, in what manner the doctors and nurses communicate and how the data is collected, stored, monitored and displayed over time. We discuss with them what shortcomings they experience daily and how the current process can be made more effective and efficient. These interviews helped us to shape the use case and identify which kind of data visualization would be useful to solve the real-life challenges that doctor faces. Since we are experts in computer science, the interviews made it easier for us to understand critical points in the decision-making situations that doctors face every day.

Eight doctors are interviewed for this purpose (a Physician, an Anesthesiologist, an Emergency Physician, two Surgeons, a Neurologist, a Nurse, a Psychiatrist and a General-practitioner). The different roles of these specialists helped us understand how different users can have different requirements and points of view. Out of these seven doctors, only two surgeons had some experience with using AR glasses for work. Both these doctors used HoloLens while planning and preparing for surgery. The rest of them were not using AR glasses in their professional life. Although they were all working in different medical sectors, the basic method of data analysis and visualization remained the same.

These doctors were firstly given a short presentation to help them understand the concepts of AR and VR and their applications in the world. After that, they were introduced to the thesis idea and asked a series of 12 pre-determined questions. The answers to these questions are documented to determine the structure of the use case. What we learned from them was that currently when a

patient is admitted to a hospital, especially in an ICU, their vital signs are measured continuously by several machines. These readings are then collected and stored in a patient file, which is then available for the doctors to look at as per the requirement. Although the minute details of this process might change from hospital to hospital, the basic overall procedure remains the same. The data once collected can be accessed by the doctor on their computers and laptops in their offices. To take important decisions for the treatment of the patient, the doctors have to log in from their computers and then look at the data from their offices. Whenever they have to check any updates on the data, they go back to their offices and check it. Hence the option of looking at real-time data on the go while they are doing their duties outside their offices is not possible. This is unless they are continuously carrying a tablet or have someone carrying a tablet for them at all times. Carrying a tablet by themselves means that they cannot have both their hands free, which is a major disadvantage for a doctor. So the idea of being able to look at data while on the go is encouraged by the doctors. This will be one of the main focuses of the thesis where we will provide data on the fly so that the doctors do not have to go back to their offices to look at the data to see any updates. This way we try to solve one of the issues the doctors are currently facing.

Furthermore, we discuss with the doctors their opinions on the use of AR in the medical field. The majority of the responses of the doctors were encouraging and enthusiastic. They are keen to explore how AR can help them in several aspects, especially if AR could help reduce the complexity and their workload. They are even interested in discussing different possible applications of AR in the medical sector. When asked for any suggestions regarding the proposed thesis idea, they also had a number of ideas. This showed the interest the doctors have in using AR/VR.

However, there were also a few concerns that the doctors had when it came to using AR. One of which was the ease of use. Since many doctors have none to minimal experience of using HoloLens in their professional life, the time needed to get used to the head-mounted devices could be significant. The other concern was how the patients would feel if they see their doctors wearing the head-mounted glasses; especially older patients who would maybe not react kindly to their doctors and can be scared. This is of particular concern for psychiatrists who treat patients with mental disorders. These are some key points that need to be considered when discussing AR in the medical sector.

4.2 User Study

The details about the exploratory user study that we conducted for our thesis will be explained in the following sections.

4.2.1 Participants

We conduct the exploratory user study with 15 participants (7 females, 8 males) between the age of 20 to 30 years from the institute and the university. These participants are either Master students or PhD students. Out of these 15 participants, 5 of them have never used the HoloLens before, 2 of them use the HoloLens regularly while the others have some minimal experience using the HoloLens. All of the participants are competent using the desktop computers.

4.2.2 Study Procedure

For this user study, the participant has to play the role of a doctor, who is checking up on their patients. The participant can see the graphs of different vital signs of the patient such as heart rate, oxygen rate, body temperature and blood pressure. The graphs which the participant sees are of two types: line graphs and bar graphs. The line graph represents the real-time data while the bar graph represents the average data for each day of the previous week. Based on the different graphs they see, the participants have to take a decision regarding the health of the patient. The different decisions and the conditions that must be fulfilled to be able to take a decision are explained below. In some cases, the participant has to take a decision within the given time limit while in other cases the time taken by the participant to reach a decision is measured for analysis.

The user study is conducted for 2 separate conditions of data visualization: Immersive (On the HoloLens) and Non-Immersive (on the Computer). Each method has 2 separate scenarios one: time-dependent (emergency) and the other non-time dependent (non-emergency). So, in total there are 4 scenarios or cases. For the time-dependent scenario the participant has to take a decision within the given time interval while in the non-emergency scenario, the time needed by the participant is measured. The participant will hear a beeping sound which indicates that it is an emergency. The time factor and the accuracy of the decisions in both the conditions help us answer our research question of how medical data visualization in AR affect the understanding and decision-making ability of users.

CONDITION 1: Data Visualization in Immersive Condition (On the HoloLens)

The participant puts on the HoloLens and opens up the application

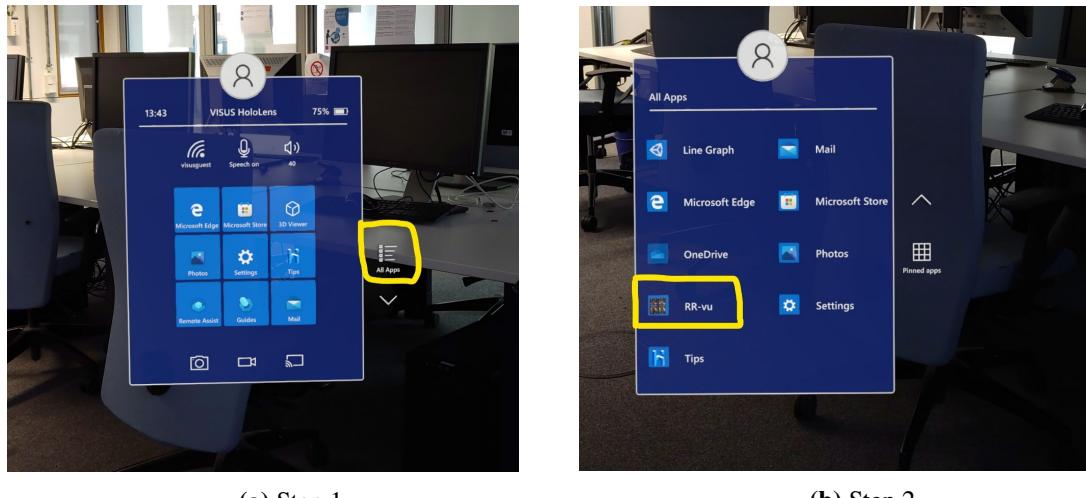


Figure 4.1: Steps to open application on the HoloLens

Once the app opens up the participant will see a menu as follows:

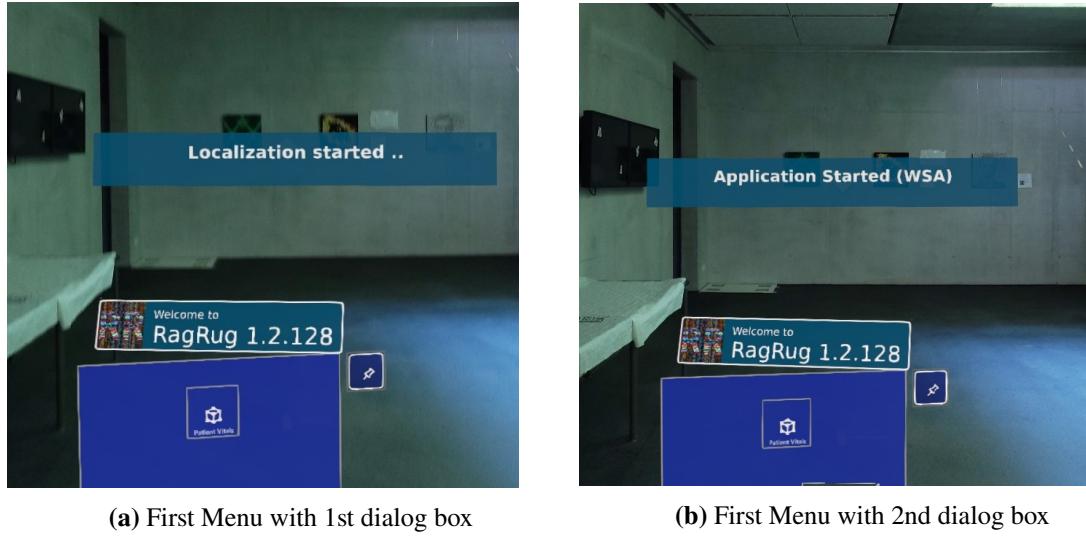


Figure 4.2: Menus of the application I

Initially there is a dialog box called *Localization started ..* which is then followed by another dialog box called *Application Started (WSA)*. This is essentially the set up of the application. The main menu has only 1 button called *Patient Vitals*. Once the dialog box called *Application Started (WSA)* has disappeared, the user can click the button marked *Patient vitals* and take a step ahead, leaving the menu behind them. Afterwards they see another menu that looks as follows:



Figure 4.3: Menus of the application II

In this second menu, the user sees a total of 6 buttons, namely: *Blood Pressure*, *Heart Rate*, *Oxygen Rate*, *Body Temperature*, *Real Time Data* and *History Data*. The button *Real Time Data*, will open up the real-time graphs of all the vital which are shown by line graphs. Similarly, the button *History*

Data, will open up the bar graphs of all the vitals. These bar graphs represent the data from the previous week. The buttons marked with the vital names will open up the bar graph as well as the line graph for that particular vital.

Based on the instructions given for each case, they select and press a particular button and take a step ahead, again leaving that menu behind them. The graphs now appear in front of them. The participant who is now acting as a doctor has to walk down the hallway toward the patient while looking at the graph. The patient is indicated by the image pasted on the wall.

Once the participant reaches the patient, they must be ready with a decision. The graphs have the vital readings on the Y axis and time (for line graph) and weekday (for bar graph) on the X axis. The horizontal white lines indicate the thresholds for the vital, which ideally should not be crossed. The colors of the line have a significant meaning. When the vital readings are in the normal range, the line is *green* in color, when they approach the extremes the line color is *yellow*. When the readings go beyond the upper and lower limits, the line changes its color to *red*. The colors of the bar graphs also have a similar meaning. When the bar graph is green in color, the average value for that particular day was in the normal range. When the color is yellow, the average value for that day was slightly above or below normal and red means the average value was critical. The user has to read the values, check if they fall in the normal range and then take a decision.

CASE A: Emergency scenario

Consider the scenario that a patient has undergone a heart operation. Today the participant who is acting as a doctor is going to check up on the patient. While going toward the patient, they hear a beeping sound. A beeping sound means that there is some kind of emergency and the participant has to figure out what the emergency is and take a decision as quick as possible. In this case, the participant has been instructed to press the button *Real Time Data*. All the real-time line graphs of the four values will be displayed as shown in the figure 4.4. Only a vital which is giving critical readings can cause an emergency. So the participant has to look at the different line graphs and figure out which vital is in the critical condition. Based on the color and readings of the graph they can take one of the following decisions. It should be noted that each decision should be taken only if the stated condition is satisfied.

1. Use Defibrillator: If the readings of the *Heart Rate* have crossed the extreme range, indicated by red color line.
2. Use Oxygen Mask: If the readings of the *Oxygen Rate* have crossed the extreme range, indicated by red color line.
3. Cardiogenic Shock treatment: If the readings of the *Blood Pressure* have crossed the extreme range, indicated by red color line.
4. Cold Bath: If the readings of the *Body Temperature* have crossed the extreme range, indicated by red color line.

After reaching the patient, the participant has to tell the researcher their decision. The time taken by the participant is then recorded. The application is now restarted so that the participant can check the next case. The figure 4.4 shows how the four real time graphs will be seen by the participant in the application.

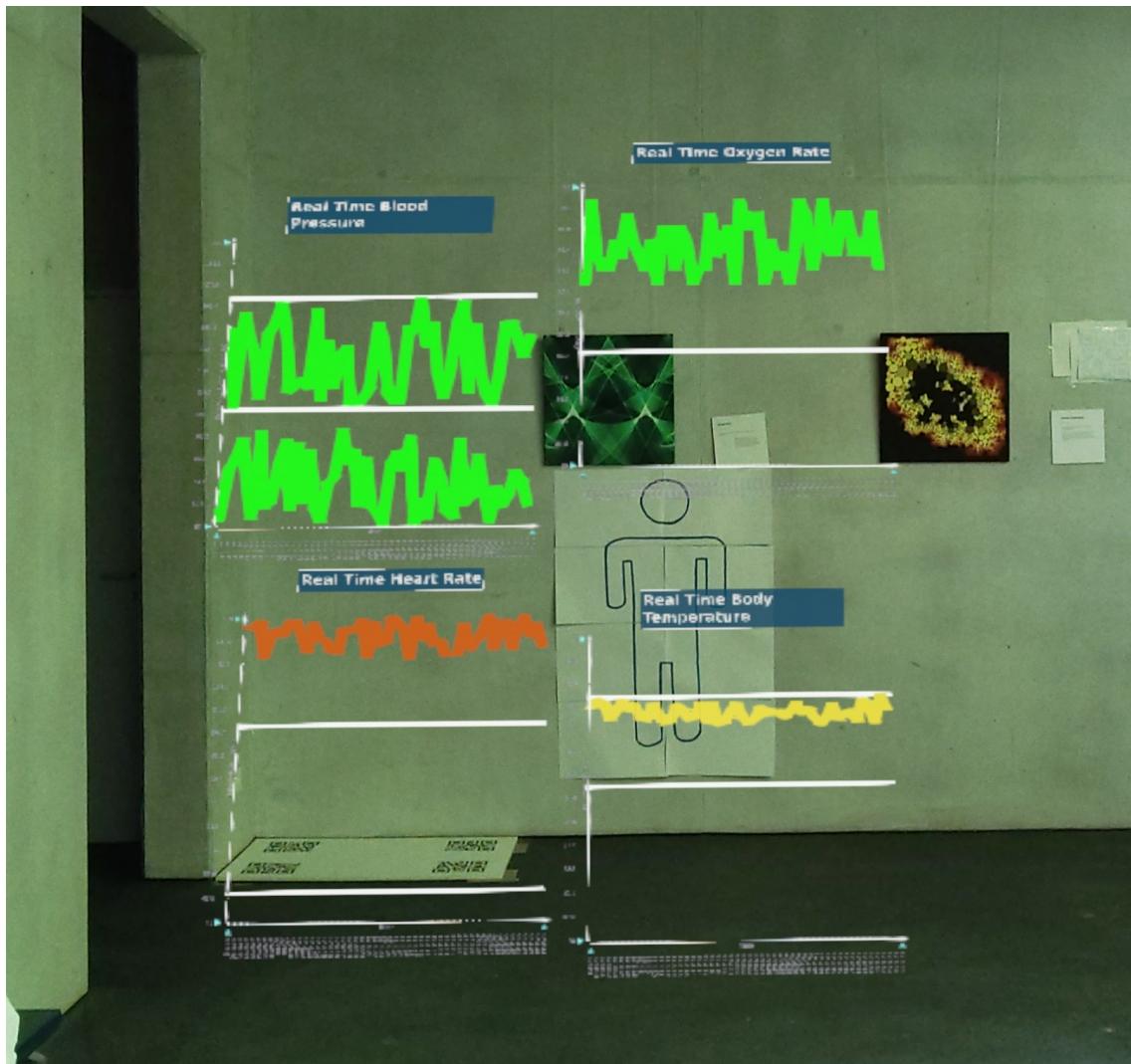


Figure 4.4: Real Time readings of all vitals as seen by the user is shown here. The color of the lines have a specific meaning associated with them. *Green* indicates that the vital is in its normal range and healthy. *Yellow* depicts that the particular vital is approaching its threshold limit but is not at a critical stage yet. *Red* shows that the vital is critical where it has crossed its limit and needs immediate attention. As seen from the figure, the *Heart Rate* is the most critical vital which needs immediate attention by the participant

CASE B: Non-Emergency scenario

Similar to Case A, consider that a patient has undergone a minor surgery yesterday. Today the participant who is acting as a doctor is going to check up on the patient. This is a non-emergency scenario and so the participant will not hear any beeping sound. They have to take a decision within 2 minutes. The participant is asked to press the button *Body Temperature* and observe the graphs. Here the participant will see a line graph and a bar graph. Based on the colors of the graph the participant has to take any one of the following decisions. It should be noted that each decision should be taken only if the stated condition is satisfied.

1. Do nothing: If the readings fall in the normal range, indicated by the green color line and bars.
2. Give Medicine: If the readings are close to the extreme range, indicated by the yellow color line and bars.
3. Emergency: If the readings have crossed the extreme range, indicated by red color line and bars.

After reaching the patient, the participant has to tell the researcher their decision. The time taken by the participant is then recorded. The figure 4.5 is how the participants will see the Body Temperature of the vital.

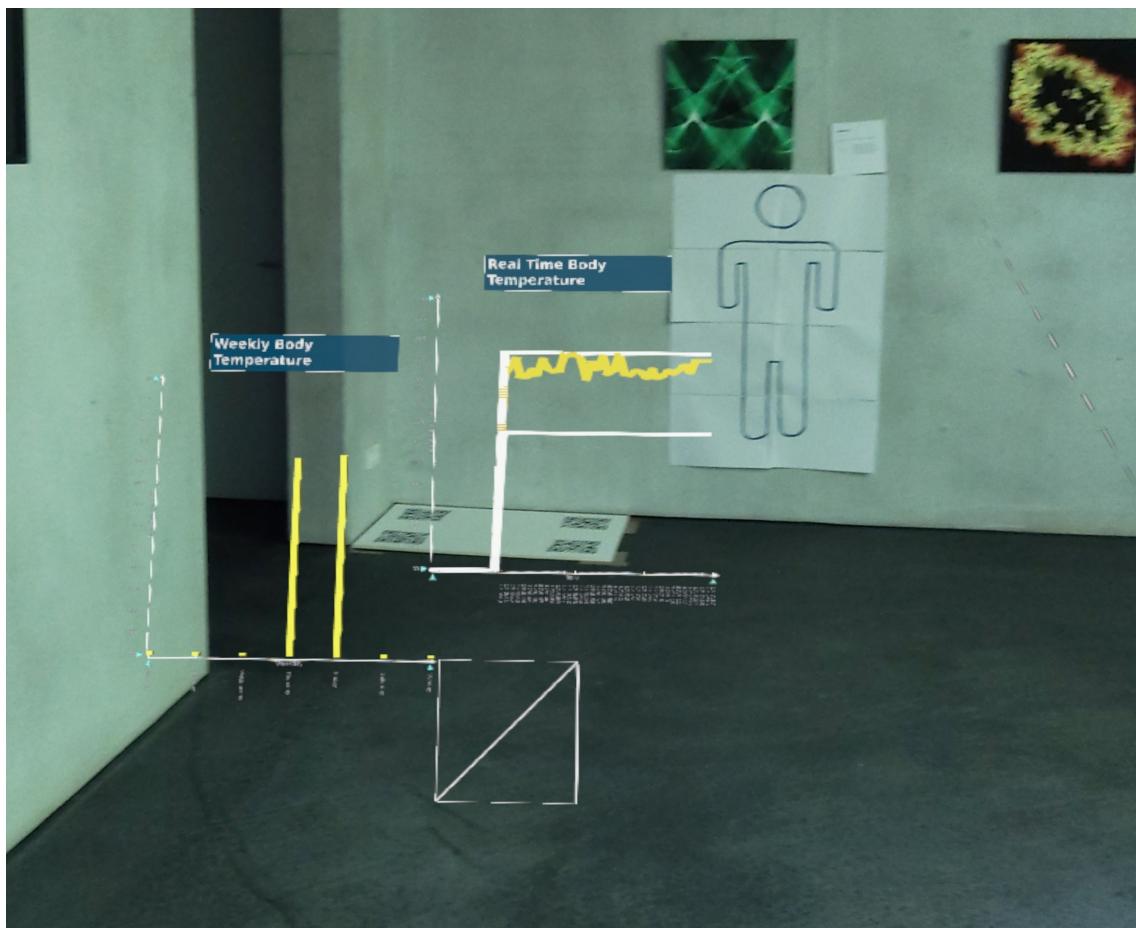


Figure 4.5: Body Temperature of a patient is seen by the user as shown here. The line graph shows the real time reading while the bar graph shows the average readings from the previous week. As seen here on Thursday and Friday, the patient had a slight fever and even at that moment, the patient is having slight fever.

CONDITION 2: Data Visualization in Non-Immersive Condition (on the Computer)

The participant who acts as the doctor is sitting in his office to look at the patient data. The participant chooses one of the options as per the instructions for each case from a menu. Similar to the 1st method we have one emergency and one non-emergency case. For the emergency case again the participants hear beeping sounds and they have to take a decision. For the non-emergency scenario the aim is to take a decision as quickly as possible within 2 minutes.

For the emergency scenario they only look at the real-time data and for the non-emergency scenario they will look at both, the real-time line graphs and the historic bar graphs. They will be informed of the normal range for each vital. For watching the real-time readings they will access Grafana. Here as well the threshold values for the vitals have been specified beforehand. If the readings cross these threshold the background color of the graph changes to yellow or red, depending on how critical the readings are.

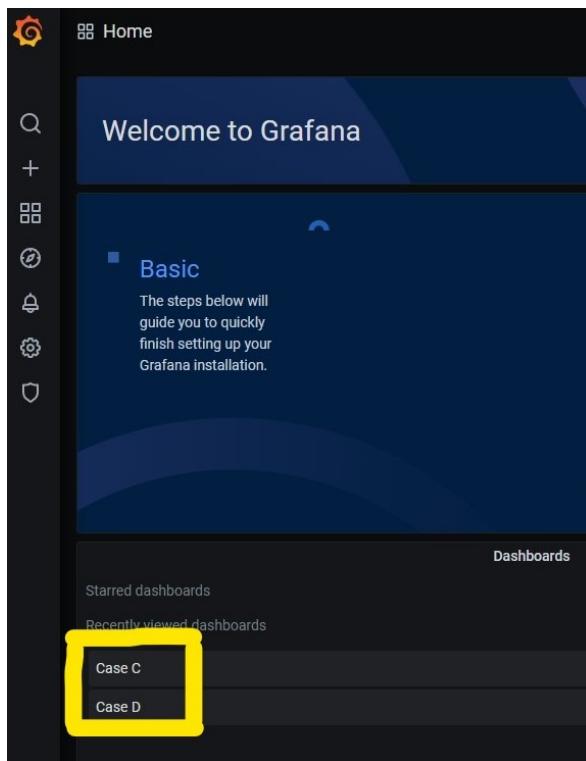


Figure 4.6: Screenshot of the Grafana Dashboard as seen by the participant. Here the participant has to select either *Case C* or *Case D* as highlighted in the screenshot.

The figure 4.6 shows how the Grafana dashboard looks like. From this dashboard the participant will be able to see the real-time graphs for case C and case D. Similarly figure 4.7 and figure 4.8 represent how the graphs are visible on the Grafana dashboard.

4.2 User Study



Figure 4.7: Grafana graphs when every vital is in the normal range as indicated by the *green* color. Here since all the four vitals are in the normal range the patient is healthy and can be released from the hospital.



Figure 4.8: Grafana graphs when a few vitals are either critical or slightly above threshold. This is indicated by the colors of the background. *Red* shows that the vital is at its extreme limits and needs immediate attention. *Yellow* means that the readings are slightly above/below the normal range but not dangerous. *Green* shows that the vital is in its normal range and healthy

4 Evaluation

For taking a look at the data from the past week, the participant will access the node-red UI, which is a dashboard to view data in different formats. Here the participant will see the bar graphs of all the vitals along with their normal range mentioned as shown in figure 4.9

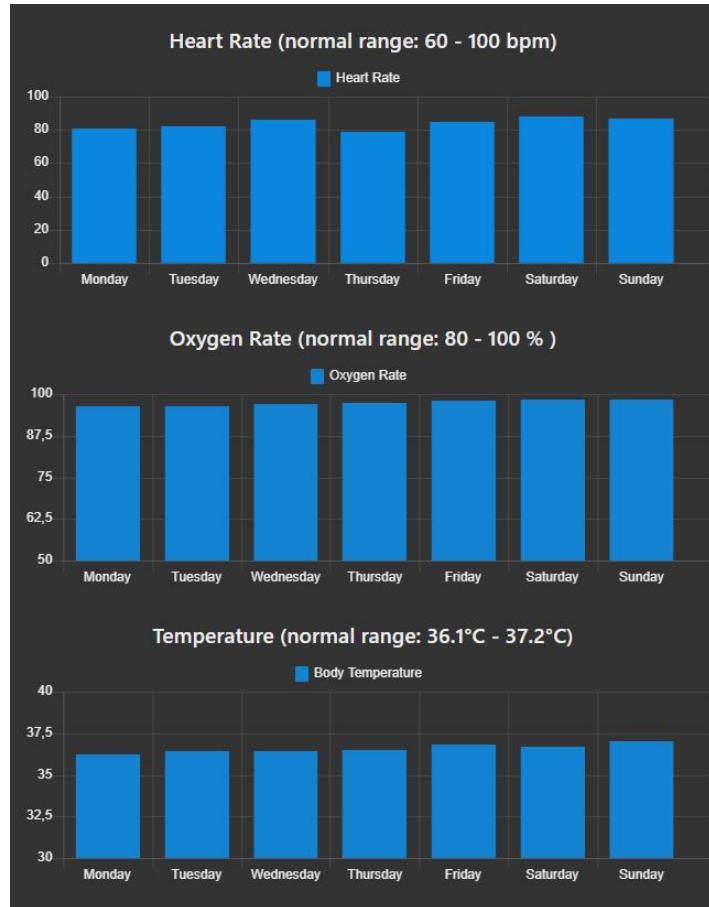


Figure 4.9: Node red UI shows the readings of each vital for the past week. The normal range for that vital is specified as shown here and the participant has to check the average readings for all days before taking a decision about the patient

CASE C: Non-Emergency scenario

The patient had undergone a surgery last week and was in the hospital for recovery since then. The participant who is playing the role of the doctor has to take a look at all the vitals of the patient and decide what to do next. Since this is a non-emergency scenario the participant will look at both the real-time data as well as the readings for the past week. The user will select *Case C* from the Grafana dashboard and check the color of the graphs. Then they will see the Node RED UI and observe the readings for the past week. Based on the values, they will take any one of the decision. It should be noted that each decision should be taken only if the stated condition is satisfied.

1. Release: If the readings of ALL the vitals fall in the normal range for ALL the days of the week and the current readings are also in the normal range.

2. Keep under observation: If the readings of ALL the vitals were in the normal range for a few days but NOT ALL days.
3. Emergency: If the readings of ALL the vitals were a little above/below the normal range for a few days but then SUDDENLY became very high/low today.

The participant has to tell the researcher their decision. The time taken by the participant is then recorded.

CASE D: Emergency scenario

The patient had undergone a surgery last week and was in the hospital for recovery since then. The participant is in an office and hears a beeping sound. This will indicate that it is an emergency scenario. They have to select option *Case D* from the Grafana dashboard and check the color of the graphs. As explained before, *red* color background means critical values, *yellow* color background means slightly above/below threshold. *Green* color in the background means everything is in the normal range. The user has to decide which vital has critical readings and is causing the beeping sound. Based on the color of the graphs they can take one of the following decisions. It should be noted that each decision should be taken only if the stated condition is satisfied.

1. Use Defibrillator: If the readings of the *Heart Rate* have crossed the extreme range, indicated by red color background.
2. Use Oxygen Mask: If the readings of the *Oxygen Rate* have crossed the extreme range, indicated by red color background.
3. Cardiogenic Shock treatment: If the readings of the *Blood Pressure* have crossed the extreme range, indicated by red color background.
4. Cold Bath: If the readings of the *Body Temperature* have crossed the extreme range, indicated by red color background.

The participant has to tell the researcher their decision. The time taken by the participant is then recorded.

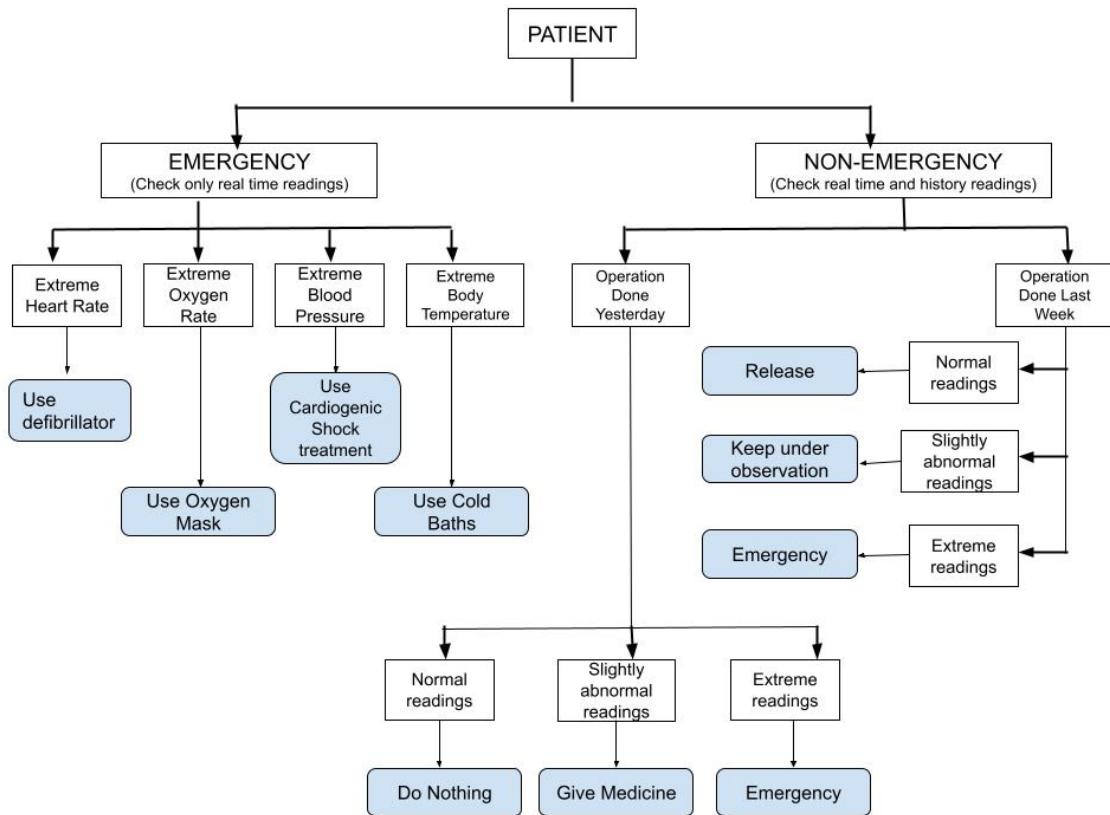


Figure 4.10: Possible decisions that a participant can take have been shown in this figure. Based on the different criteria and conditions the different options are available to the user. The decisions have been sectioned based on the situation: emergency or non-emergency. The decisions have been indicated by the blue boxes.

All the possible decisions that can be taken in the different cases have been summarized in the figure 4.10.

5 Results

In this chapter we report the results of our user study with respect to three types of assessment: time of completion, accuracy of decisions and subjective user feedback. We report the results for the immersive and the non-immersive condition for emergency as well as non-emergency situations.

5.1 Accuracy of Decisions

In the user study that we conducted, we asked the participants to take a decision regarding the health of the patient in each case. Each use case was distinct and it was designed such that there was only one correct decision that should be taken. In this section we talk in detail what the correct decisions were for each case and the reasoning behind that decision. Then we examine the accuracy of the decisions taken by the participants for the immersive and the non-immersive conditions. This is one of the important aspects of our user study and helps us understand how much the understanding and decision-making capability of the user is affected.

5.1.1 Immersive Condition

In *Case A*, the participants see the four line graphs of the four vitals. It is an emergency so the participants also hear a constant beeping noise. Here the participants have to take a decision as to which vital is the most critical and needs immediate attention. The graphs and their data points are generated such that, the *Heart Rate* is the vital that is the most crucial with its line being red. So the decision the participant should ideally take is: *Use Defibrillator*. From the 15 participants that took part in the user study, only 1 participant took an incorrect decision. This participant saw that instead of the Heart Rate, the Blood Pressure graph had red colored lines. Hence this participant took the decision: *Use Cardiogenic Shock Treatment*. All the other participants took the correct decision which is a very high success rate of 93.33%.

For *Case B*, the situation is a non-emergency and the doctor only needs to look at the graphs for one vital sign. For this case, the participants are looking at the real-time and bar graphs for the *Body Temperature* of a patient. Both the graphs are yellow and hence we depict that the patient had a slight fever for the past few days as well as at the current moment. The correct decision in this scenario is: *Give Medicine*. Again out of the 15 participants 14 of them took a correct decision while one participant took the decision: *Do Nothing*. This participant saw that the bar graph was yellow but the line graph was green. The participant explained why they took this decision by saying that the patient had a fever for the past 2 days but currently they do not have a fever as the line is green in color and hence they will do nothing.

5 Results

5.1.2 Non-Immersive Condition

Case C and *Case D* are performed by the participants on the desktop computer. For *Case C*, the participant has to see the previous week's data for a patient and the real-time graphs. This case is designed such that all the vital signs of the patient are in the normal range for the past week as well as at that moment. Hence the correct decision is: *Release the patient*. Out of the 15 participants, all of them were able to take this correct decision with no confusion which showed a 100% success rate.

Case D is an emergency scenario where the participant have to figure out which vital is most crucial and needs to take an immediate decision. For this case, we designed the data points such that Diastolic Blood Pressure, Systolic Blood Pressure and Heart Range were more than the normal range but not critical. The Body Temperature is green indicating that it was normal. Only the Oxygen Rate is red and so the correct decision is: *Use Oxygen Mask*. Out of the 15 participants, 13 of them took the correct decision. Hence 86.67% took a correct decision. One of the participants had slight color blindness and hence they could not properly differentiate between the colors due to which they could not take a decision. The other participant who took the wrong decision focused on the difference between the normal range and the current reading and ignored the importance of the color. They took the decision: *Give Defibrillator*. They explained that the difference between the real-time readings and the normal range for the Heart Rate was the largest and so they thought that using a defibrillator was the correct decision.

5.2 Task Completion Time

The time that the participants need to complete the tasks and reach a decision is also an important factor of the user study. We want to find out how the time needed to reach a decision is affected by data visualization in the immersive condition. We also want to explore to what extent a primary task of taking a decision is affected by a secondary task of walking. We compare the decision-making time for the immersive condition and non-immersive condition in an time-dependent and time-independent tasks.

5.2.1 Time-Dependent Tasks

For the time-dependent tasks, the participants have to take a decision as fast as possible. The figure 5.1 shows the time needed by each participant to reach a decision in seconds. The average time needed by the participants while using the HoloLens was 18.54 seconds and the average time needed when using a desktop computer was 18.87 seconds. Hence there is no significant gap between the task completion time for an time-dependent task using the HoloLens and a computer. Some participants could take a decision quicker when using the HoloLens as compared to the desktop computers while for others it was the opposite. The longest time needed to reach a decision while wearing the HoloLens was 51.2 seconds while the shortest time was 7.68 seconds. On the other hand, while using the desktop computer the longest time needed was 66 seconds while the shortest time was 6.2 seconds.

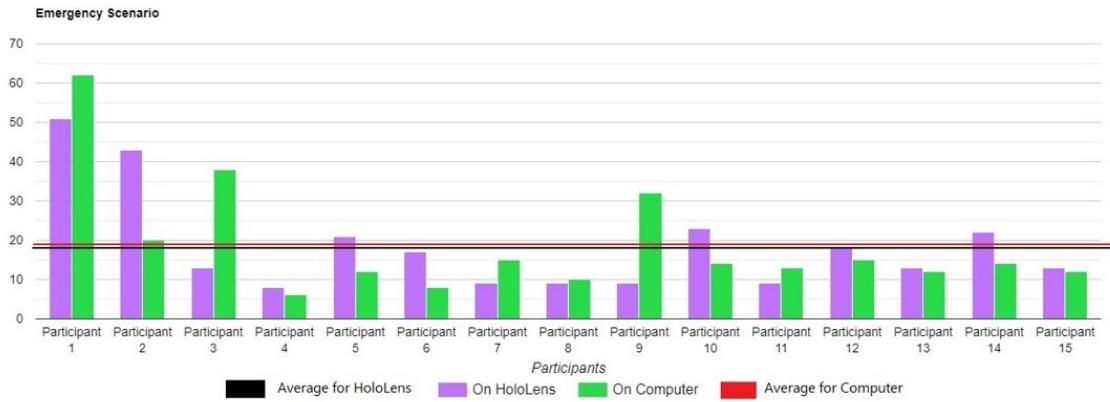


Figure 5.1: Average time needed during time-dependent tasks for 15 participants with time on the y-axis in seconds. This shows that during an emergency the average time needed using the HoloLens and the computer remain almost the same.

5.2.2 Time-Independent Tasks

In the time-independent tasks, the participants are asked to take a decision within 2 minutes (120 seconds). As can be seen from the figure 5.2, the difference between the average time needed to reach a decision on the HoloLens and on the computer is large. The average time needed by the participants while using the immersive condition was 40.98 seconds and the average time needed when using a non-immersive condition was 69.09 seconds. Once again some participants could take a decision quicker when using the HoloLens while for others it was the opposite. The longest time needed to reach a decision while wearing the HoloLens was 97 seconds while the shortest time was 7.98 seconds. However, when using the desktop computers the longest time needed was 118 seconds while the shortest time was 42 seconds. Overall it is noticed that in time-independent tasks the participants could take faster decisions in the immersive condition.

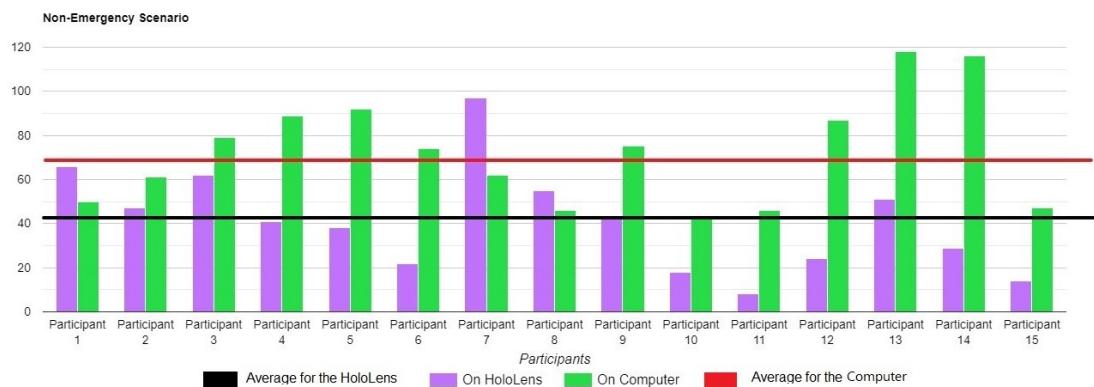


Figure 5.2: Average time needed during non-emergency for 15 participants with time on the y-axis in seconds. As seen here, the average time needed by the HoloLens is less as compared to the computer. This shows that for non-emergency scenarios the immersive condition performed better.

5 Results

5.3 Subjective Feedback

After the participants have completed the 4 cases of the user study we ask them to fill out a feedback form. In this form we ask them several questions to get more insights about their preferences. Their responses are as shown in the figure below.

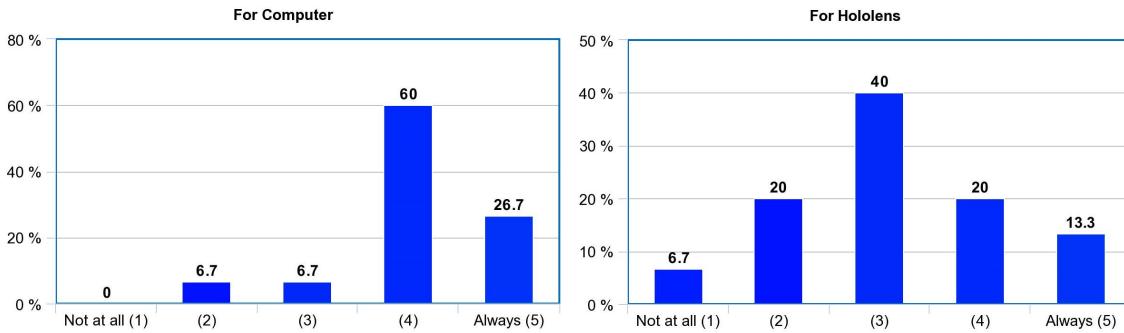


Figure 5.3: Response to : How frequently would you like to use this system? The comparison between the immersive condition and the non-immersive showed that some users still prefer to use the computers than the HoloLens if given a choice.

One of the important questions we asked was how frequently they would like to use the immersive condition and the non-immersive condition. They could answer from a range of 1 to 5 where 1 meant *Never* while 5 meant *Always*. As seen from the figure above, only one of the participants preferred to never use the immersive condition while the rest were willing to try it out. Two of the 15 participants would even prefer to always use the immersive condition for data visualizations. For the data visualizations which are seen on the computer 60% of the participants were willing to use this non-immersive condition almost always. We believe that one of the main reasons for this difference in preference is that the people are not yet used to the HoloLens. The participants reported that while using the HoloLens they were curious at first but then they found that it was a little cumbersome. Participants showed enthusiasm saying, "This is so cool and I have never experienced something like this before". They thought this was a unique experience and a cool, futuristic technology but expressed that the computer feels more familiar. Some participants showed some hesitation while interacting with the game objects, saying things like, "I feel stupid and awkward waving my hands in the air". The participants were given a tutorial before the start of the user study where they learned the different interaction techniques with the holograms. Some participants could complete this tutorial easily while some needed more time. The participants who needed more time were getting a little frustrated and said that the non-immersive condition feels more natural to them.

5.3 Subjective Feedback

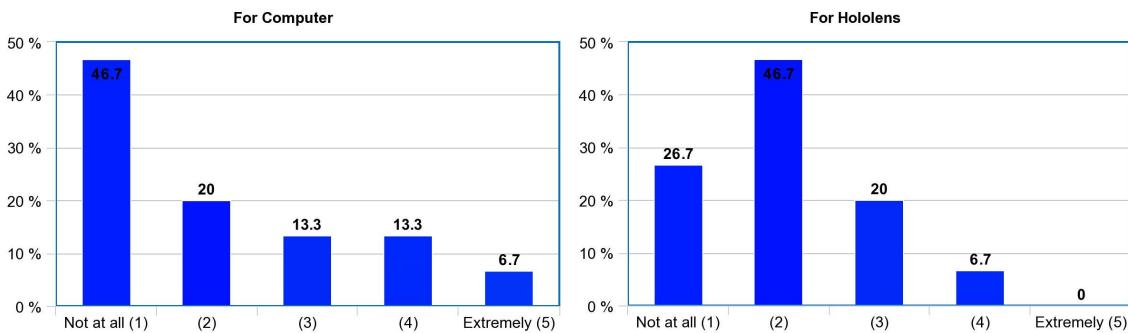


Figure 5.4: Response to : How complex was the system? In terms of complexity our studies showed that the participants did not find the immersive condition too complicated. For the non-immersive condition, there were 3 participants who thought it was too complicated for them.

The next question we asked the participants was how complex did they find both the systems. They could answer from a range of 1 to 5 where 1 meant *Not at all* while 5 meant *Extremely*. For the immersive condition none of the participants thought that the system was extremely complicated. In fact, four of the participant thought the system was *Not at all* complicated and easy to understand. Seven of the participants (46.7%) thought the system was only slightly complicated. On the other hand, for the non-immersive data visualizations, one of the participant thought that the system was *Extremely* complicated. But 46.7% of the participants chose 1 (Not at all) on the complexity scale. Overall we found that the non-immersive data visualizations were less complicated for the participants. However, some of the participants were confused when deciding on the computer. Participants were confused between the line graph colors and the colors of the background for the graphs displayed in Grafana.

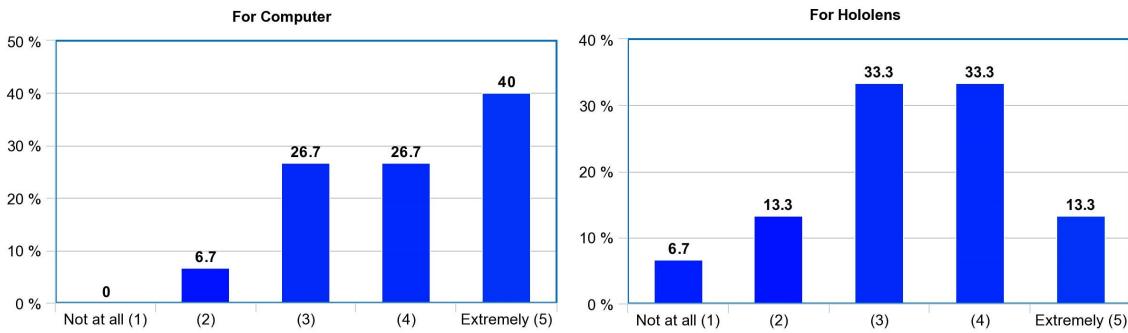


Figure 5.5: Response to : How confident were you using the system? In terms of confidence, the participants were more confident in their answers when using the non-immersive condition as compared to the immersive condition. However, that does not mean that they were extremely under confident in their answers when using the HoloLens

5 Results

When the participants were asked to express how confident they were using the HoloLens and the computer, only one of the participants was not at all confident while taking a decision using the HoloLens. When using the computer, 40% of the participants were extremely confident in their decisions in comparison to only 13.3% when using the HoloLens. To understand the lack of confidence we asked the participants to give more details about their experiences. They said that the graphs which they saw on the HoloLens were not very stable. The graphs were sometimes a little far from their eye-sight or were shaky when they were walking to the patient. For some participants, the graphs were jumping around or sometimes overlapped. A participant said, "For the computer part, it's straightforward and easy to read the value because the charts are in the fixed position". Another factor that must be considered here is the lighting condition. Some participants reported that they sometimes got confused about the colors they were seeing. From one angle the color of the line was red but if they moved toward the light or moved their head the color could change to yellow/orange. Due to this, they were not very confident in the decision they were taking while using the HoloLens. On the other hand, while using the computer, there was no confusion when it came to identifying the colors.

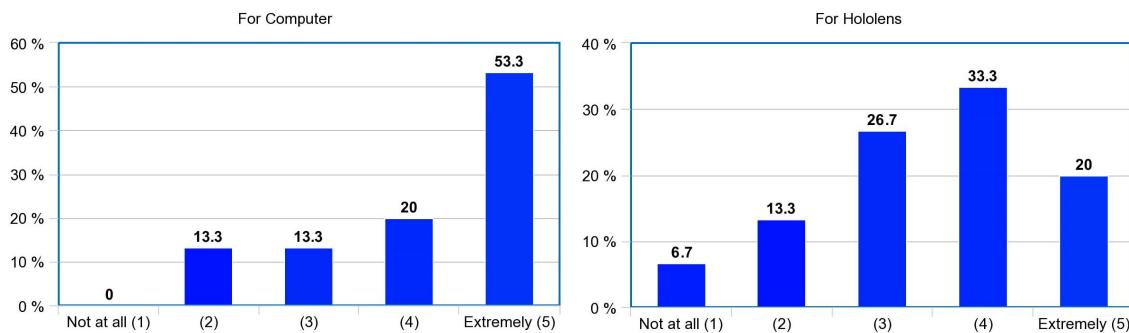


Figure 5.6: Response to : How comfortable were you using the system? When it comes to comfort level of the participants the non-immersive condition scored better with more than 50% of the participants being extremely comfortable

One important factor we want to understand is the comfort level of the participants when using both systems. For the immersive condition, one of the participants reported feeling not at all comfortable while three participants said that they were extremely comfortable. 33.3% of the participants were quite comfortable while using the HoloLens. However when it comes to the non-immersive condition more than half the participants (53.3%) reported that they were immensely comfortable and felt natural. Only two participants were fairly uncomfortable using the desktop computer. When asked to elaborate one participant said, "The non-immersive condition felt safer". The participants were not discouraged by the headset which they had to wear but were in fact unaccustomed to seeing holograms and interacting with them. The graphs which followed their head movements and tagged along with them while walking toward the patient felt to a certain degree strange to them.

6 Discussion

6.1 General Observation

In this master thesis, we try to find out how the decision-making abilities of a person is affected when visualizing data on the immersive condition. We also want to find out how feasible the *Data on the Go* works. From our studies we found that the accuracy of the decisions is not affected greatly. In most of the cases in terms of correctness, the participants are able to reach a correct decision. When the participants have to take a quick decision for a sufficiently simple data visualization, they can do so. Hence there is precision in terms of taking a correct decision. However, when it comes to confidence in that decision, at this moment our studies indicate that people are still more confident in their answers when using the non-immersive condition. This could also be because of the unfamiliarity that the participants have with the HoloLens. If the participants are more familiar with the HoloLens, their confidence and comfort levels will definitely increase. For time-dependent situations, the two conditions of data visualization: immersive and non-immersive performed almost the same. The average time needed while using the HoloLens is 0.33 seconds less than while using the computer. Hence using the HoloLens in such time-critical situations even outperformed the computer by a small amount.

The immersive data visualizations also gave the advantage of carrying the data with the participants while *on the go*. As per the participants, the task of walking and taking a decision like a doctor was considered to be a really helpful feature. They acknowledged the potential of offering data updates on the go which could save significant time in a real time-dependent scenario. For non-emergency scenarios, again the time performance of the HoloLens was better than that of the computer by 28.11 seconds. Thus we can report that in terms of time needed to reach a decision, the immersive condition performed better than the non-immersive. The feedback that the participants gave about having data on the go was that graphs could be more stable and not move around as much. The *Tag Along* feature which we added to the graphs made them follow the head movements of the participant. This could be made more smooth. If the positioning and movements of the chart could be improved, we believe that the HoloLens will give superior performance. Due to the familiarity of the computers, the comfort level for the computers was higher than that of the HoloLens. Hence when asked how frequently the participants would like to use the HoloLens there was some hesitation. However, we believe that if users are given multiple trainings on the HoloLens, they will get more used to the data visualizations and then the comfort level and feeling of familiarity will increase. This was also tested out by Bach et al. [BSB+17], where they found out that the performance of the participants increased after practice sessions. The task completion time was decreased significantly in their studies.

In many applications getting data updates immediately is very essential. Using the Augmented Reality HMD helps in such situations. The user can be doing some other task and get the updates immediately without having to go back to their offices or check their computers. The data is

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summoned to the user on the HoloLens instead of the user going to see the data on the computers. They can have both their hands free to do something else while watching the data in the immersive condition. There is also privacy while watching the data as only the person wearing the HoloLens will be able to see the displayed data. There is no special requirement of having a place or room or additional device for the data to be displayed. The entire surrounding environment of the user can be utilised to display the maximum amount of data. Thus we believe that immersive data visualization offers many advantages over non-immersive condition.

6.2 Challenges

The biggest challenge we faced while designing was the orientation and movements of the graph. The graphs were designed to be positioned in the direction where the head of the participant is when the application starts. The size and their orientation are hard-coded so that they remain common for all participants. However, some participants had some issues seeing all the graphs on the HoloLens. The head movement of the participants plays a very important role in the positioning of the graphs. The graphs appear at the place the head of the participant was oriented when the application started and the buttons are pressed. Due to this, some participants had difficulty seeing all the graphs comfortably. For some, the graphs were slightly overlapped while for others they were a little out of their range of visibility. The Radial View script has various components which affect the ease of visibility of the graphs. We adjusted many of these components to find a suitable combination such that the graphs are satisfactorily visible. However, from the feedback we received, we think there is still room for improvement. The graphs move with the head position and this causes the graphs to move around the participant. These movements need to be slowed down and made more smooth. If this is improved we believe that the participants will be even more comfortable and confident in their decisions.

Some of the participants were a little confused because the colors of the line were affected by the lightning condition of the environment. The head movements and light in the room sometimes caused the line graph to be perceived as a different color than the original color. This colour shifting affected the performance of the participants. This caused one participant to take a wrong decision in both, the emergency and non-emergency scenario in the HoloLens. This is also an important criterion that needs to be improved. In real situations, the user will not always have control over the lighting of the room. The colors in the HoloLens should remain the same irrespective of the lights and the head position.

6.3 Future Scope

However, we believe that there are a lot of potential uses for immersive data visualizations. In this master thesis proposal, we are only showing data visualizations and have very limited interactions between the participants and the holograms, where they only press buttons. The participants do not move the graphs or make any changes to them. However, in future work, we can add some interaction techniques which will enhance the experience of using these AR visualizations. We can add features where the data that is related to each other is interconnected and then the user can switch

between the related visualizations. The users can make markings, highlight specific data points and add voice recordings for the other users to listen to. This can avoid any miscommunication between the users and exact information can be conveyed.

Furthermore based on the designation of the user, different views can be established. Users who do not have high-level clearance or do not need to know the details can only see the basic information and users having the highest clearance can be allowed to see a different form of data visualization with more details. With this, we can design a different scene for different categories of users. The combination of AR with Artificial Intelligence could be very powerful. Based on the trends in the data we could display suggestions and possible next steps for the user. This may help the users take a quicker decision. Remarks and possible deductions can be added to their field of view which can help the users analyse the information which they see much more easily.

Additionally in our user study, we only tested one form of glance technique where the data is fixed to the participant's head position. There are other forms of glanceable interfaces such as Gaze-Summon or Periphery Gaze where the data can be summoned in the user's field of view or it remains at the periphery where it can be brought in front of the user when desired. We can test these different glanceable techniques while the user is also performing a secondary task of walking. There are a lot of possibilities for extending this idea and test its performance. We believe that many such interesting user studies can be carried out to get more idea about where and how AR visualizations can play an important role.

7 Conclusion and Outlook

In this work, we have tried to explore AR visualizations and their effects on a user's ability to understand data and reach a conclusion. We compared the immersive and the non-immersive condition on many factors such as time, accuracy, user preference, comfort and so on. We wanted to offer the user data updates instantly on the HoloLens and tried to understand how walking and completing different tasks can affect them. Several related works were examined to gain knowledge about the research going on related to this concept. The past research did not focus much on the decision-making abilities of the participants. Moreover, research based on *Data on the Go* is still limited. Hence we wanted to find out efficient and most comfortable ways of presenting data to the users while they were walking.

We focused the use case around a medical scenario and designed the visualizations for specific conditions. To prepare for this we conducted multiple interviews with medical staff and tried to understand the day-to-day workings of a hospital. With the help of an exploratory user study, we tried to find out if the ability to comprehend data changes while in an immersive condition. We believe that the participant's understanding is not affected greatly in the immersive condition. We also wanted to study the difference between the task completion time in the immersive and the non-immersive condition. From our studies, we can conclude that for time-dependent tasks, both the immersive and non-immersive conditions performed almost the same. For non-emergency/time-independent tasks, the immersive condition performed better. With the help of a feedback form, we tried to understand what concerns the participants have when using the HoloLens. Their issues and the reasons behind their preferences were explored. The participants have different preferences and opinions about the AR visualizations. These results were discussed in detail to find out what improvements can be made in the design of the visualizations. By taking into consideration the feedback we got from the participants, improvements can be made to the visualizations so that the users feel more comfortable and confident. The common grievance was the positioning and movement of the graphs. The visualizations need to move more slowly and smoothly while the user is walking. Hence based on our results the future work should focus more on how to place and present the visualizations. If the participant preferences are taken into consideration and improvements are done based on that, the *Data on the Go* will also yield better results than now.

We think that although there is enthusiasm when it comes to using AR/VR for data visualizations there is also some hesitancy. The main reason for this is the lack of familiarity with the HMDs. However, from our user study, we gathered the information that people acknowledge the advantages and convenience associated with using AR glasses. There is definitely potential for using such visualizations in the future for data analysis. The advantages associated with using the immersive data visualizations cannot be ignored. They provide a hands-free approach to visualising data without the need for any other instrument. There is no need for any special place where the data can be displayed and it can also provides privacy while viewing the data. The user can interact with the

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data and get more in-depth knowledge of it. More studies and use cases need to be designed to get a solid understanding of what works and what doesn't for the majority of people when using the HMDs.

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All links were last followed on August 26, 2022.

A Appendix

A.1 Interview Questions

Question asked to the Doctors during the Interview:

1. Are the current medical professionals familiar with AR/ VR? What would you consider is common technological knowledge amongst them?
2. Please describe to me what happens when a patient is admitted to the ICU/ normal ward
3. How do you capture the readings (manual, software app, tablet, mobile)? Is it continuously captured?
4. How easy is it to read/understand the readings from the software?
5. How different is the patient monitoring method for each hospital?
6. How do you communicate any instructions to the nurses (change in medication, points of interests)?
7. How often is an ICU and normal ward patient visited manually by the doctor?
8. For any new infection (COVID), is the process of monitoring and capturing data any different?
9. When doctor goes to check up on the patient, how do they look at the data history? Do they carry laptop/tablet or a file?
10. How are you alerted in serious or abnormal conditions?
11. Who do you think would be the main users of the proposed idea (doctors, nurses, assistants)?
12. How beneficial do you think the proposed idea is?

A Appendix

A.2 Consent Form

Study Description

Description of the user study “Vis2Go: Exploring the Effect of Immersive Analytics for On-The-Go Decision Making” of the Visualization Research Center of the University Of Stuttgart (VISUS)

At VISUS we are doing research regarding the development and design of visualizations, as well as Virtual and Augment Reality applications. The study “Vis2Go: Exploring the Effect of Immersive Analytics for On-The-Go Decision Making” wants to investigate how medical data can be visualized in AR and how efficient decision making is in this scenario. For the results to be evaluated, the study procedure has to be completed. However, the study can be cancelled at any time. In this case, the incomplete results are deleted during evaluation and not considered further.

1. Procedure

- You will now test various forms of data visualization techniques in the Hololens and the computer.
- First you can get a trial run on the application and then the actual user study will begin.
- You will do this for 4 times with different setting and conditions.
- When having completed all the tasks we ask you to, fill out a concluding questionnaire.
- In total, the study will take 60 minutes.

2. General Conditions of Participation:

- You have no visual impairment (short or long-sightedness not included)
- You have no physical injury.
- You are between 18 years and 55 years old.

Figure A.2: First page of the Consent Form.

3. Data Usage and Processing

- Each questionnaire and recorded movement will be given an ID in form of a number, to map the results together. The ID is given by the researchers involved and is in no relation to your name.
- Within publications, the data will be provided in an anonymized form.

4. Further usage of the data

The data will only be used in research purposes.

Point of Contact

In case of questions please contact:

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Figure A.3: Second page of the Consent Form.

Form of Consent

Please read this form carefully. In case of questions, feel free to ask the present researcher.

- I have read the study description and agree with the concerned data usage and processing.
- The agreement and participation is entirely voluntary. Not participating does not result in any kind of disadvantage.
- I'm free to cancel the study at any point and thereby withdraw my consent.
- Withdrawing the consent after completing the study is not possible, as the data from one specific person cannot be identified in retrospect.
- I have read the privacy information and agree to it.
- I have received a copy of the information sheets.

Location, date Signature volunteer

Location, date Signature investigator

Figure A.4: Third page of the Consent Form.

Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

place, date, signature