UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
INSTITUTO DE INFORMÁTICA
PROGRAMA DE PÓS-GRADUAÇÃO EM COMPUTAÇÃO

YHONATAN JESUS IQUIAPAZA CCAMA

DeAR: Combining Desktop and Augmented Reality for Visual Data Analysis

Thesis presented in partial fulfillment of the requirements for the degree of Master of Computer Science

Advisor: Prof. Dr. Luciana Nedel

Porto Alegre
August 2024

CIP — CATALOGING-IN-PUBLICATION

Iquiapaza Ccama, Yhonatan Jesus

DeAR: Combining Desktop and Augmented Reality for Visual Data Analysis / Yhonatan Jesus Iquiapaza Ccama. – Porto Alegre: PPGC da UFRGS, 2024.

68 f.: il.

Thesis (Master) – Universidade Federal do Rio Grande do Sul. Programa de Pós-Graduação em Computação, Porto Alegre, BR–RS, 2024. Advisor: Luciana Nedel.

1. Augmented Reality. 2. Virtual Reality. 3. Immersive Analysis. 4. Collaborative Immersive Analytics. 5. Collaborative Visualization. I. Nedel, Luciana. II. Título.

"Computers are good at following instructions,

but not at reading your mind."

— DONALD KNUTH

AGRADECIMENTOS

I would like to thank my advisor Luciana Nedel for all the support she gave me on this path, especially for never doubting my abilities and always trusting me.

Without my dad Hugo and mom Ines, I would not have gotten here, and to my sisters who support me unconditionally. I dedicate this work to you and I thank you for believing in my potential and for respecting my decisions throughout this path.

A special thanks to Renan and Jorge who without their advice, I would not have been able to get here.

Finally, I would like to acknowledge CNPq and CAPES for the funding opportunity and thank Instituto de Informática at UFRGS and its collaborators for all the support.

ABSTRACT

Most Visual Data Analysis tools in the literature focus on conventional Desktop environments, where interactions via mouse and keyboard are typically used. While such tools can be extremely efficient for many analytical tasks, the exclusively bi-dimensional nature of both interactions and displays in Desktop environments might, in some cases, hinder the perception of details or correlations that might be more evident in a three-dimensional view of the data. We hypothesize that the combined use of conventional displays and Augmented Reality (AR) hologram views could therefore be helpful in such circumstances. We propose a novel prototype for Visual Data Analysis in Hybrid Environments, called *DeAR* (*Desktop + AR*, i.e., combining Desktop and Augmented Reality for Visual Data Analysis). In this work, we validate our hybrid interface with two use case scenarios.

For an initial validation of our prototype, we discuss two use case scenarios which demonstrate how our design would support common visualization tasks integrating 2D and 3D views of the data. In our first scenario, one analyst uses *DeAR* to interact with two different visualizations (Bar Chart and Scatterplot), one of them in a conventional screen and the other seen as a three-dimensional hologram. In the second scenario, two participants work together, carrying out similar tasks, but collaborating asymmetrically, with each one of them interacting with a different visualization paradigm.

We also discuss an experiment design that will allow a controlled evaluation of our interface in a future user study. We propose a series of tasks for such an evaluation, and discuss the most adequate questionnaires to be used.

Our main contribution in this work was the design and implementation of a proof-of-concept prototype for interaction with data in Hybrid Environments (*DeAR*) by combining heterogeneous interfaces/displays. An additional contribution of this work is the experimental design for a user study evaluating the performance of hybrid environments used either by a single participants or by multiple collaborating participants.

Keywords: Augmented Reality. Virtual Reality. Immersive Analysis. Collaborative Immersive Analytics. Collaborative Visualization.

DeAR: Combinando Desktop e Realidade Aumentada para Análise de Dados Visuais

RESUMO

A maioria das ferramentas de Análise Visual de Dados na literatura foca em ambientes convencionais Desktop, onde interações via mouse e teclado são tipicamente usadas. Embora tais ferramentas possam ser extremamente eficientes para muitas tarefas analíticas, a natureza exclusivamente bidimensional tanto das interações quanto das exibições em ambientes Desktop pode, em alguns casos, dificultar a percepção de detalhes ou correlações que poderiam ser mais evidentes em uma visualização tridimensional dos dados. Hipotetizamos que o uso combinado de exibições convencionais e visualizações holográficas em Realidade Aumentada (RA) pode, portanto, ser útil em tais circunstâncias. Propomos um novo protótipo para Análise Visual de Dados em Ambientes Híbridos, chamado *DeAR* (*Desktop* + *RA*, ou seja, combinando Desktop e Realidade Aumentada para Análise Visual de Dados).

Para uma validação inicial de nosso protótipo, discutimos dois cenários de uso que demonstram como nosso design apoiaria tarefas comuns de visualização integrando visualizações 2D e 3D dos dados. No primeiro cenário, um analista usa o *DeAR* para interagir com duas visualizações diferentes (gráfico de barras e de dispersão), uma em uma tela convencional e a outra vista como um holograma tridimensional. No segundo cenário, dois participantes trabalham juntos, realizando tarefas similares, mas colaborando de forma assimétrica, cada um interagindo com um paradigma de visualização diferente.

Também discutimos um design de experimento que permitirá uma avaliação controlada de nossa interface em um futuro estudo com usuários. Propomos uma série de tarefas para tal avaliação e discutimos os questionários mais adequados a serem usados.

Nossa principal contribuição neste trabalho foi o design e a implementação de um protótipo de prova de conceito para interação com dados em ambientes híbridos (*DeAR*) combinando interfaces/exibições heterogêneas. Uma contribuição adicional deste trabalho é o design experimental para um estudo com usuários avaliando o desempenho de ambientes híbridos usados por um único participante ou por múltiplos participantes colaborativamente.

Palavras-chave: Realidade Aumentada, Realidade Virtual, Análise Imersiva, Análise Imersiva Colaborativa, Visualização Colaborativa.

LIST OF ABBREVIATIONS AND ACRONYMS

AR	Augmented Reality
VR	Virtual Reality
IA	Immersive Analytics
CIA	Collaborative Immersive Analytics
CV	Collaborative Visualization
2D	Two Dimensions
3D	Three Dimensions

LIST OF FIGURES

1.1 Different ways of interacting and *making the invisible visible* to increase visual capacity (enhance vision), process, and reason (enhance cognition)... 13

1.2 Sketch of our initial vision of how our application can use different environments at the same time: (a) Visualizing a 2D Bar Chart in a desktop and a 3D one in the near space using AR; (b) Visualizing Scatterplots in both setups. 15

1.3 A futuristic vision of office work, where Virtual Reality and Augmented Reality transform how tasks are performed across various environments...... 16

2.1 The user can navigate the shared display using a Hololens. They is the only one who can see the red rectangles in AR (through the Hololens)......... 19

2.2 In a traditional setup (a), interaction is primarily done through the mouse and keyboard. In a hybrid setup using Hololens (b), interaction can be achieved through mid-air gestures, gaze, and mouse input. 19

2.3 On the right, the user can interact with the scatterplot and the parallel coordinates in AR using STREAM; while on the left, they are monitoring progress through a tablet........ 20

2.4 Prototype for extending visualizations with Augmented Reality: (a) Two analysts working at the same environment, (b) display showing their AR Brushing and Linking. 21

2.5 Users can interact with the visualizations through the tables and the visualizations in AR at the same time using Hololens 2, both are using the prototype MARVIS........ 21

2.6 Billinghurst et al. (2018) considered four collaboration strategies: Synchronous Co-Located – Collaborators are in the same physical place and working together; Distributed Synchronous – Collaborators are in different places and working in the same virtual space at the same time; Distributed Asynchronous – Collaborators are in different places and working in different time; Asynchronous Co-Located – Collaborators working in different places and different time. 23

2.7 A user manipulating a 3D object with VR (on the left), and another user interacting with a 3D object with AR (on the right). Both of them perform rotation manipulation tasks in a synchronous co-located environment......... 24

2.8 In FIESTA, each user can interact with different visualizations but in their environments, all using virtual reality devices, and the environment must be defined and limited........ 25

3.1 Two-dimensional environment using mouse and keyboard to interact on visualizations (A); AR environment interacting with gestures in 3D (B); the server in charge of communicating both parties and the states of all the elements (C)........ 27

3.2 In the 2D environment Bar Chart (A), information is displayed when the cursor hovers over an element of the visualization, and selection occurs via a click event. In the 2D environment Scatterplot (B), the mode of interaction is identical to that of the Bar Chart visualization. The visualizations are presented on monitor number 2, while monitor number 1 was designated for participants to write their answers to the tasks. 28

3.3 The 3D Bar Chart visualization is presented (left), with interaction facilitated through hand gestures. In the right we can see the 2D visualization of the Bar Chart. 29
3.4 The 3D Scatterplot (left) employs the same hand gesture interactions as the Bar Chart visualization. In the rigth we can see its 2D representation..... 29
3.5 In the hybrid environment where tasks are performed, participants can interact with both the Desktop Environment and the Augmented Reality Environment.... 30
3.6 Bar chart variants: 2D (left) and 3D (right). 31
3.7 When a user places the mouse over an element of the Bar Chart, it shows a label with information about the element (left). Then, when they click with the mouse over an element (right), it is selected. 33
3.8 While visualizing scatterplots, the information is also showed once the mouse is over one of the spheres (left). When clicking on the sphere, it is selected (right). 34
3.9 Moving the Hololens cursor to point to any element of the Barchart, allows the user to see information about that (left). Then, with a Hololens gesture the element is selected (right). 35
3.10 The interactions for the Scatterplot are the same shown in Figure **??**. The differences are the elements that can be selected. 36

4.1 In the desktop environment (right), Juan interact using the keyboard and mouse. In the AR environment (left), he can interact with gestures and gaze. Juan can mix both environments integrating it if he wants. 37
4.2 A user (*Juan*) using DeAR to interact with a 2D scatterplot (a); and then performing the tasks proposed in a bar chart using a 2D visualization (b). ... 39
4.3 The user is interacting with the 3D bar chart with the Hololens (a); the user selects an object from the display, and when he performs the interaction the object changes its color to white (b). The user then interacts with the 3D scatterplot. 40

LIST OF TABLES

3.1 Relationship between the given commands and the instances where they occur.......... 36

CONTENTS

1 Introduction 13
1.1 Motivation 14
1.2 Objective and Contributions 15
1.3 Structure of this Dissertation 15

2 Related Work 17
2.1 Immersive Analytics 17
2.2 Hybrid User interfaces with Visualizations 18
2.3 Collaborative Immersive Analytics 21
2.4 Summary 24

3 DeAR: Desktop and Augmented Reality – System Design 26
3.1 System Overview 26
3.2 Mapping Strategies 27
3.2.1 Desktop Interface – 2D 28
3.2.2 Augmented Reality Interface – 3D 28
3.2.3 Hybrid Interface – 2D and 3D 29
3.3 Visualization Methods 30
3.3.1 Bar Chart Visualization 30
3.3.2 Scatterplot Visualization 31
3.4 Interaction Techniques 32
3.4.1 On Mouse Over 32
3.4.2 On Mouse Right Click 32
3.4.3 On Focus 33
3.4.4 On Input Down 33
3.5 Command Activation 34
3.6 Summary 35

4 Use Cases 37
4.1 Bar Chart Scenario 38
4.2 Scatterplot Scenario 38
4.3 Dataset Used 40
4.4 Summary 41

5 User Study Proposal 42
5.1 Standard Protocol 42
5.1.1 Consent and Confidentiality Term 42
5.1.2 Testing Protocol 43
5.2 Tasks 43
5.3 DeAR Solo Mode 44
5.3.1 Solo Mode with Bar Chart and Scatterplot 44
5.3.2 Solo Mode Questionnaires 44
5.4 DeAR Collaborative Mode 45
5.4.1 Collaborative Mode with Bart Chart and Scatterplot 45
5.4.2 Collaborative Mode Questionnaires 46
5.5 Summary 46

6 Conclusion 47

6.1 Limitations and Future Works 47
6.2 Other contributions 48

References **50**

APPENDIX A — USER STUDY - Solo Mode: Pre-Questionnaire **54**

APPENDIX B — USER STUDY - Collaborative Mode: Pre-Questionnaire **55**

APPENDIX C — USER STUDY - Simulation Sickness Questionnaire **56**

APPENDIX D — USER STUDY - NASA TLX Questionnaire **57**

APPENDIX E — USER STUDY - System Usability Scale Questionnaire **59**

APPENDIX F — USER STUDY PROPOSAL - Consent and Confidentiality Terms **62**

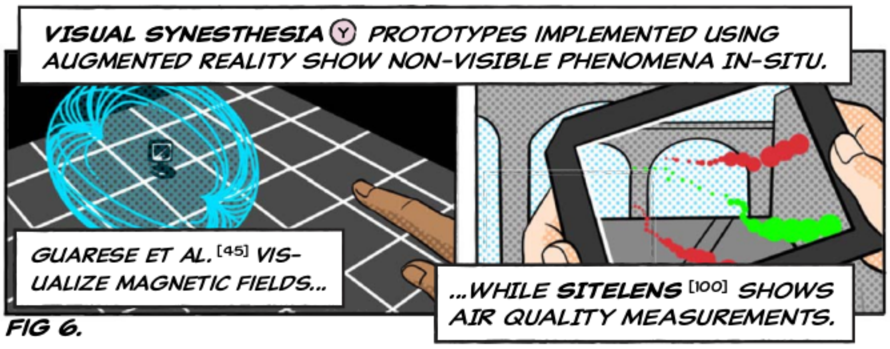
APPENDIX G — USER STUDY PROPOSAL - Testing Protocol **64**

APPENDIX H — RESUMO EXPANDIDO **66**

1 INTRODUCTION

Tools and prototypes for visual data analysis are generally focused on Desktop Environments, and the vast majority of these are controlled with a mouse and keyboard. The launch of new Virtual Reality (VR) and Augmented Reality (AR) devices allows users to experience new ways of interacting in virtual and mixed environments and new fields of study such as Immersive Analytics emerged. For example, Willett et al. (2022) proposed the use of new metaphors to promote cognitive abilities (see Figure 1.1), such as memory, pattern recognition, and new ways of understanding visualizations. The use of these new technologies allows us to know information about the world without the need to change something in it,to know the weather just by looking at the sky, the ability to see and interact with virtual objects without the need to be in an immersive environment (WILLETT et al., 2022).

Figure 1.1: Different ways of interacting and *making the invisible visible* to increase visual capacity (enhance vision), process, and reason (enhance cognition).



Source: (WILLETT et al., 2022)

The launch of new Data Analysis Tools in Immersive Environments means that users need to learn to handle new devices, interfaces, and interactions to be able to work with them. So that users do not have difficulties in using or interacting with these new tools, Hybrid Interfaces are implemented to help users in an easier mode. The use of Hybrid Interfaces (FEINER; SHAMASH, 1991) *makes us take advantage of the strong sides of some interfaces and combine them to have a better performance.*

Two dimensional visualizations have been well studied and defined in Desktop Environments for a long time, and nowadays some new tools are used in Virtual Environments with 3D and 2D visualizations. Our work uses different interfaces (displays or devices) for different environments, during visual data analysis. We combine a Desktop Environment with 2D visualizations, and an Augmented Reality Environment with 3D visualizations, where the user can interact freely. This may be compared to Plasson, Blanch and Nigay (2022) work, where one can sit and interact with an extension of the display (see Figure 1.2).

1.1 Motivation

Raskar et al. (1998) present a concept (see Figure 1.3) illustrating how future Desktop and Immersive Environments might be used together, enabling users to collaborate across different spaces using advanced technologies like Virtual Reality and Augmented Reality. In these environments, each user could enhance their perception, almost as if possessing a superpower (WILLETT et al., 2022).

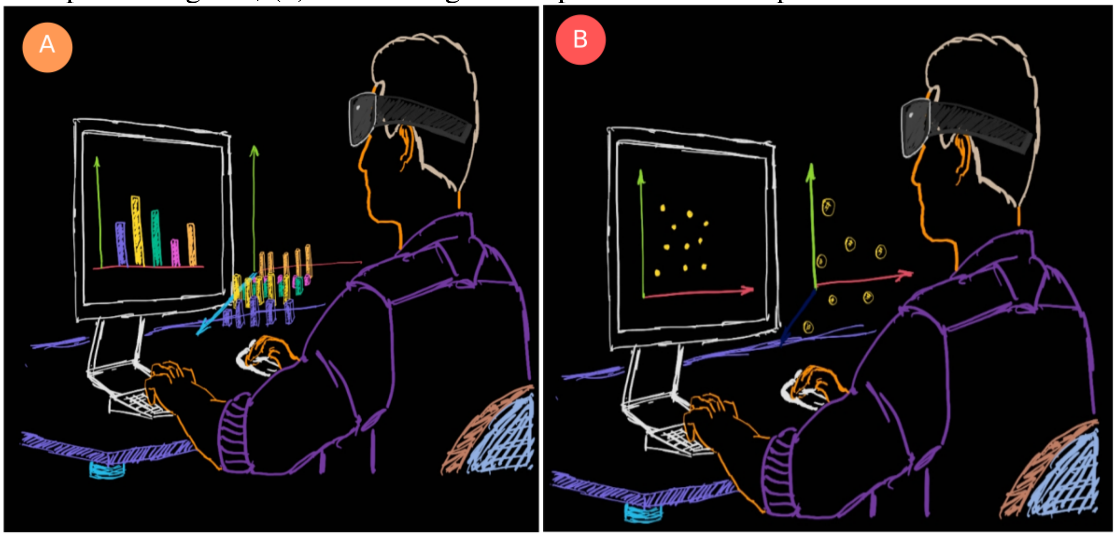
We aim to test a new approach to data exploration by developing an application that utilizes *Hybrid Interfaces combining a Desktop Environment and an Immersive Environment*, as most current applications primarily integrate with mobile devices. This new application will merge innovative interactions, such as freehand gestures, with traditional input methods like the mouse and keyboard, allowing them to be used simultaneously.

Cavallo et al. (2019) propose a framework for implementing a collaborative system utilizing different HMDs, incorporating both Virtual Reality and Augmented Reality. Their proposal is a co-located Collaborative Data Analysis System.

Our initial concept for combining two interfaces for Visual Data Analytics involved merging these two environments (see Figure 1.2). However, we realized that when the interfaces or environments are closely integrated, users are less likely to move themselves. To address this issue, we positioned the 3D visualizations at a moderate distance, allowing users to interact more effectively with both the Desktop Environment and in Augmented Reality.

We chose to use Augmented Reality because it allows for easier integration of new devices (such as tablets and mobile phones) and physical objects. In contrast, incorporating new devices or physical objects in Virtual Reality is more challenging, as it often requires the addition of trackers or other technologies that users may not be familiar with.

Figure 1.2: Sketch of our initial vision of how our application can use different environments at the same time: (a) Visualizing a 2D Bar Chart in a desktop and a 3D one in the near space using AR; (b) Visualizing Scatterplots in both setups.



1.2 Objective and Contributions

Our main objective with this work is the proposal of a hybrid application, with different ways of interaction, each one of them in a separate environment. Also, we focus on analyzing how it is being developed and how it impacts on users through use cases. In summary, our main contribution are three fold:

- The design and development of a Hybrid User Interfaces application, named DeAR (Combining Desktop and Augmented Reality for Visual Data Analysis).
- Using DeAR in two use cases with different visualization for each.
- A protocol for a future user experimentation to validate the use cases.

1.3 Structure of this Dissertation

This work is organized as follows. In Chapter 2 we carry out a review of relevant works and tools. In Chapter 4, we propose different use cases where DeAR can be used. Then, in Chapter 3 we present DeAR (Combining Desktop and Augmented Reality for Visual Data Analysis), and we show the proposal of how Visual Data Analytics tasks can be achieved with the use of hybrid interfaces in the same real environment.

In Chapter 5, we focus on case studies and tasks design. Then, in Chapter 6 we explain our conclusions, limitations and how to continue and extend our work.

Figure 1.3: A futuristic vision of office work, where Virtual Reality and Augmented Reality transform how tasks are performed across various environments.

Source: (RASKAR et al., 1998)

2 RELATED WORK

In this chapter we firstly review the main concepts of Immersive Analytics (Section 2.1), and then review previous works and use cases of Hybrid User Interfaces (Section 2.2), and Collaborative Immersive Analytics (Section 2.3). Our work remains on these areas.

2.1 Immersive Analytics

The area of IA (Immersive analytics) is growing rapidly due to novel interaction techniques, ways of interpreting 3D visualizations, creation of new applications (Section 2.2; Section 2.3), and toolkits (CORDEIL et al., 2019; SICAT et al., 2019). Immersive Analytics involves different fields of research such as: Information Visualization, Immersive Environments, and Human-Computer Interaction (HCI) in new ways for data analysis, exploration, and interaction. This is due to the recent commercial growth of new devices for Virtual Reality[1,2,3] and Augmented Reality[4] (VR/AR), and the appearance of new applications in each of these new devices (VR/AR).

Dwyer et al. (2018) define Immersive Analytics as: *"the use of engaging embodied analysis tool to support data understanding and decision making"*. IA is applied anywhere and by everyone, both working individually and collaboratively. Immersive Analytics can combine different displays (Section 2.2) or immersive interfaces, creating new approaches to data analysis and decision-making. Immersive Analytics enhances daily use activities, as shown by Lu and Bowman (2021).

According to Dwyer et al. (2018), Immersive Analytics are also being applied to other activities such as: healthcare (Immersive Analytics Applications in Life and Health Sciences), support collocated and remote collaboration (Immersive Collaborative Analytics), and urban planning and disaster management (Immersive Analytics for Built Environments).

The use of Immersive Analytics in Information Visualization can offer several benefits (MARRIOTT et al., 2018), including the exploration of immersive displays, the use of additional visual channels, and immersive work spaces.

[1] https://www.meta.com/quest/products/quest-2/
[2] https://www.meta.com/quest/quest-pro/
[3] https://www.picoxr.com/sg/products/pico4
[4] https://www.microsoft.com/en-us/hololens

Information visualization research is well judicious about the use of 3D representations, especially when dealing with abstract data, as these often provide no advantage over their 2D counterparts. Munzner (2015) warns against the *"unjustified use"* of 3D representations and immersive environments for abstract data visualization.

Immersive analytics may be used through haptic devices (CUYA et al., 2022), and physical ones as Data Physicalization (JANSEN et al., 2015). Our work is oriented to physical and virtual environments. For this reason, the works that we will describe in Section 2.2 and Section 2.3 are focused on the use of Virtual Reality and Augmented Reality (VR/AR) technologies.

2.2 Hybrid User interfaces with Visualizations

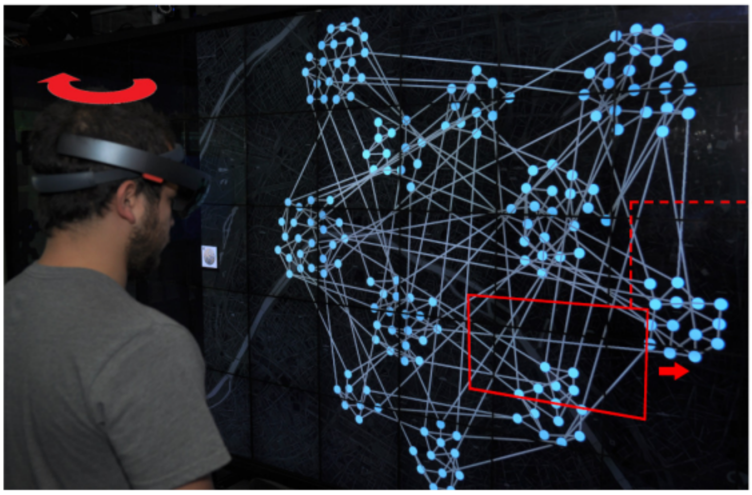
Hybrid User Interfaces aim to combine various displays and interaction methods in a way that leverages the strengths of each, creating a more effective overall system (FEINER; SHAMASH, 1991). Pavanatto et al. (2021) developed a hybrid setup designed for office tasks, which can be performed across different environments: solely on a desktop (physical environment), entirely in AR (immersive environment), and in a hybrid setup (combining physical and immersive environments). One of the findings indicates that there is no significant difference in performance between the physical environment and the hybrid environment when completing office tasks.

Several tools utilize computer displays for visual data analysis, often sharing similar characteristics while incorporating additional interfaces such as HMDs, mobile devices, or tablets. An example of this is the work by Wang et al. (2020), where they developed a hybrid data exploration setup. This setup, originally designed as a data analysis tool for particle physicists to explore and understand 3D data, integrates the existing tool with a Hololens device. The two interfaces communicate via WiFi using the UDP protocol. In Figure 2.1, another example of this strategy can be seen.

In comparison to DeAR, Wang et al. (2020) employs 3D visualization positioned close to the monitor, just above the screen (see Figure 2.2). In contrast, our visualization is situated in a nearby location that allows users to walk around it, providing them with multiple perspectives on the visualization. While Wang et al. (2020) relies on keyboard and mouse for interaction with virtual objects in AR, our setup enables users to interact using a combination of keyboard, mouse, gestures, and gaze simultaneously.

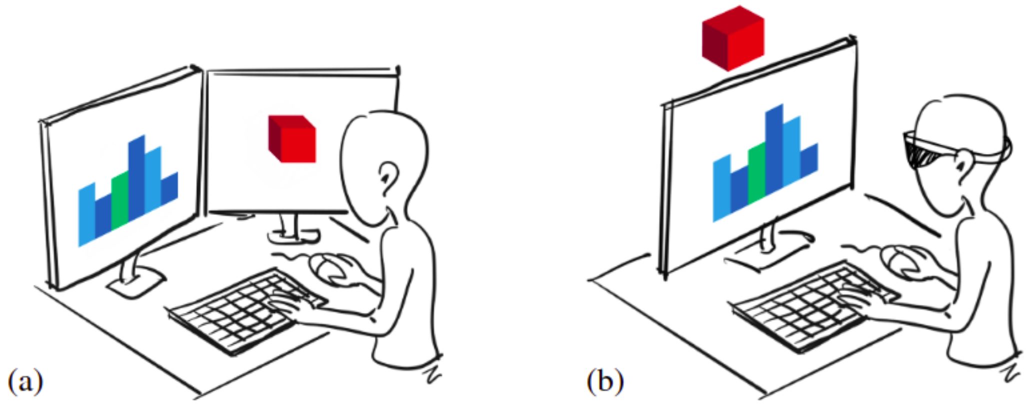
In the work by Hubenschmid et al. (2021a), STREAM (Spatially-aware Tablets

Figure 2.1: The user can navigate the shared display using a Hololens. They is the only one who can see the red rectangles in AR (through the Hololens).



Source: James et al. (2020)

Figure 2.2: In a traditional setup (a), interaction is primarily done through the mouse and keyboard. In a hybrid setup using Hololens (b), interaction can be achieved through mid-air gestures, gaze, and mouse input.

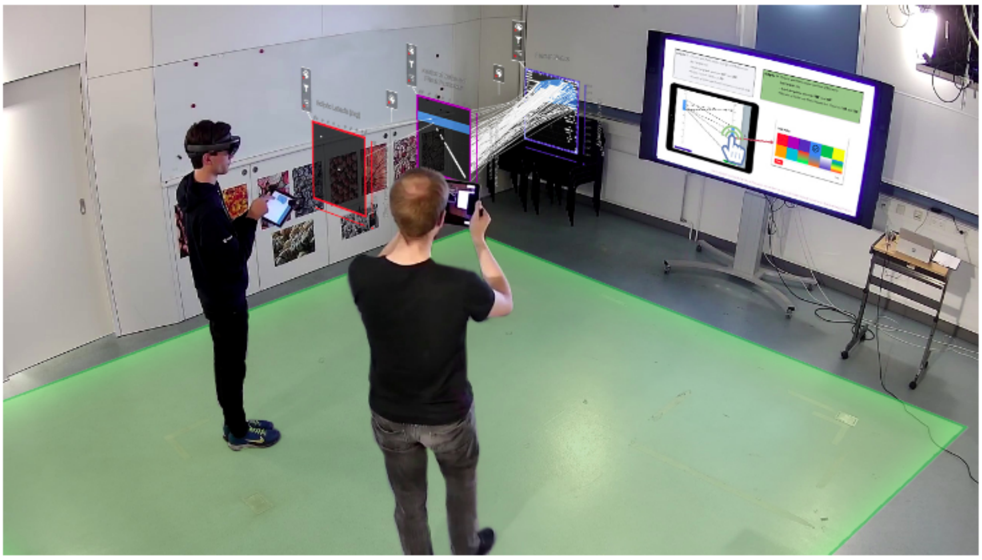


Source: Wang et al. (2020)

combined with Augmented Reality Head-Mounted Displays) allows users to interact through touch (tablet), voice (Hololens), and mid-air gestures (Hololens), either individually or in combination. The key differences between our work and STREAM are that while DeAR uses a desktop, STREAM utilizes a tablet, though both incorporate the Hololens for displaying virtual objects in AR. Mid-air gestures, while used for interaction, have been shown to be tiring (HARRISON; RAMAMURTHY; HUDSON, 2012; FILHO; FREITAS; NEDEL, 2019), unreliable (CAVALLO et al., 2019), and inaccurate (CHAN et al., 2010). Additionally, the user's progress in STREAM is monitored by another application (see Figure 2.3), which tracks how the user interacts with the display.

Some studies have also explored the use of AR with larger displays, such as wall-

Figure 2.3: On the right, the user can interact with the scatterplot and the parallel coordinates in AR using STREAM; while on the left, they are monitoring progress through a tablet.



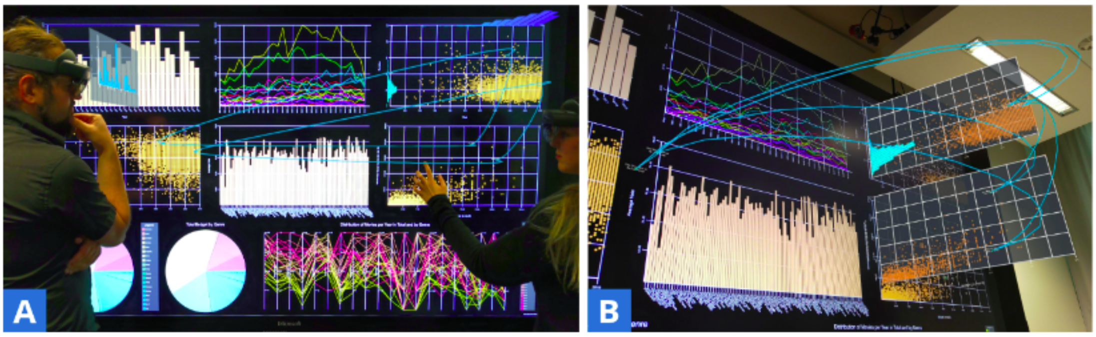
Source: Hubenschmid et al. (2021a)

sized screens. Reipschlager, Flemisch and Dachselt (2021) proposed a system that combines a large interactive display with Head-Mounted Augmented Reality (Hololens) for information visualization, aimed at enhancing data exploration and analysis. In this setup (see Figure 2.4), visualizations can be connected, joined, or moved between the two interfaces – the wall-sized display and the Hololens. Unlike DeAR, which utilizes a desktop environment for interaction, this system does not rely on a desktop. Reipschlager, Flemisch and Dachselt (2021) introduced the term *"Augmented Display"* to describe the seamless integration of interactive displays with head-mounted AR. The primary focus of their work is on the interaction between the large display and the 3D elements, and the configuration can accommodate both single and multiple users.

There are also works where Augmented Reality is combined with a tablet. MARVIS (LANGNER et al., 2021) is a prototype that implements six use cases, differing from those proposed by Reipschlager, Flemisch and Dachselt (2021) primarily in scale. MARVIS operates on a much smaller scale due to the size of the tablet screens. Interaction in MARVIS occurs (FILHO; FREITAS; NEDEL, 2019) utilizing mid-air gestures and touch input on the tablet. While MARVIS can be used by either a single user or multiple users, each user must have their own setup (Hololens and tablet) to interact with one another, as can be seen in Figure 2.5.

We incorporated some features of MARVIS (LANGNER et al., 2021) into DeAR.

Figure 2.4: Prototype for extending visualizations with Augmented Reality: (a) Two analysts working at the same environment, (b) display showing their AR Brushing and Linking.



Source: Reipschlager, Flemisch and Dachselt (2021)

Figure 2.5: Users can interact with the visualizations through the tables and the visualizations in AR at the same time using Hololens 2, both are using the prototype MARVIS.

Source: Langner et al. (2021)

In both applications, users interact within two different environments and can engage with virtual objects in AR through the Hololens. However, DeAR allows interaction via a desktop, while MARVIS utilizes a tablet. Additionally, MARVIS uses Hololens 2, enabling more interaction possibilities compared to DeAR, which uses Hololens 1. Despite this, DeAR offers the advantage of allowing users to walk around both the physical and AR environments, whereas MARVIS users are required to remain seated.

2.3 Collaborative Immersive Analytics

A significant consequence of rapid technological advancement is the increased prevalence of remote work among companies. Another factor contributing to the rise of remote work is the abundance of applications that facilitate collaboration, such as video conferencing tools[5][6], real-time interaction on virtual boards[7], and collaborative coding in virtual spaces[8].

According to Isenberg et al. (2011), modern technology facilitates seamless connections between devices and collaboration among multiple users. This collaboration can occur through various configurations, including computer networks, mobile devices, or shared displays such as interactive walls and tabletop surfaces. Information can be accessed and shared by one or multiple individuals to analyze, make decisions, and explore data. Social interaction plays a central role in collaborative visualization, emphasizing the potential for human interaction through *discussions, negotiations, or arguments surrounding visualizations* (ISENBERG et al., 2011). Furthermore, Mark, Carpenter and Kobsa (2003) demonstrated that information visualization tasks performed by a single participant are completed more quickly than those conducted in a group, although group tasks tend to yield more accurate results.

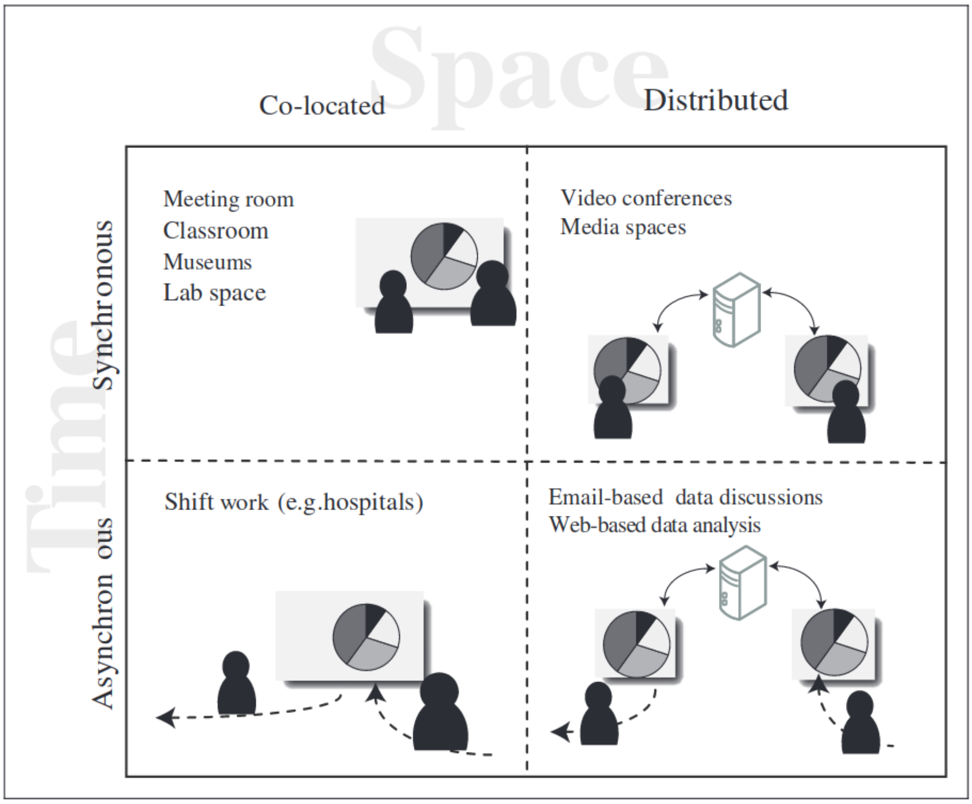
Collaborative Immersive Analytics (CIA) is a specific field that falls under the broader category of Collaborative Visualization (CV) described earlier. Billinghurst et al. (2018) defines Collaborative Immersive Analytics as *"the shared use of immersive interaction and display technologies by more than one person to support collaborative analytical reasoning and decision-making"*. In this section section, we will explore several works that utilize CIA, focusing on the *Synchronous Co-located* condition outlined by (BILLINGHURST et al., 2018). Figure 2.6 illustrates the different strategies available.

The proposal by Grandi, Debarba and Maciel (2019) combines VR and AR to facilitate collaborative tasks such as translation, rotation, and scaling applied to the same object, all performed in a co-located and synchronous manner. During these tasks, the team must make decisions, plan strategies, and engage in negotiations to resolve issues. Various types of experiments were conducted, including scenarios where both users utilized augmented reality, both used virtual reality, and a hybrid mode where one user used VR while the other used AR (see Figure~2.7). One notable result indicated that collaborative work using hybrid interfaces is comparable to, or even better than, using a single type of interface.

Similarly, Lee et al. (2021) developed a prototype called FIESTA (the Free-roaming Immersive Environment to Support Team-based Analysis), which facilitates collaborative

[5] https://zoom.us/
[6] https://meet.google.com/
[7] https://jamboard.google.com/
[8] https://github.com/features/codespaces

Figure 2.6: Billinghurst et al. (2018) considered four collaboration strategies: Synchronous Co-Located – Collaborators are in the same physical place and working together; Distributed Synchronous – Collaborators are in different places and working in the same virtual space at the same time; Distributed Asynchronous – Collaborators are in different places and working in different time; Asynchronous Co-Located – Collaborators working in different places and different time.



Source: Billinghurst et al. (2018)

visual data analysis within a shared visualization space (see Figure 2.8. The primary focus of this work was to explore how groups interact during the analysis process. Participants were asked to solve visual analytics tasks, either individually or collaboratively, using both 2D and 3D visualizations. These groups had the flexibility to organize their own workspace. The visualizations were generated using a modified version of IATK (CORDEIL et al., 2019), and participants interacted with three main types of visualizations: scatterplots, faceted scatterplots, and time series.

Ens et al. (2021) identified various challenges in achieving successful Collaborative Immersive Analytics, and we present some potential solutions to these challenges in Section 3.1. In developing our collaborative hybrid environment, we drew upon the work of Hackathorn and Margolis (2016), who outlined the steps for creating effective collaborative environments.

All the works discussed, including DEAR, demonstrate user collaboration in line

Figure 2.7: A user manipulating a 3D object with VR (on the left), and another user interacting with a 3D object with AR (on the right). Both of them perform rotation manipulation tasks in a synchronous co-located environment.

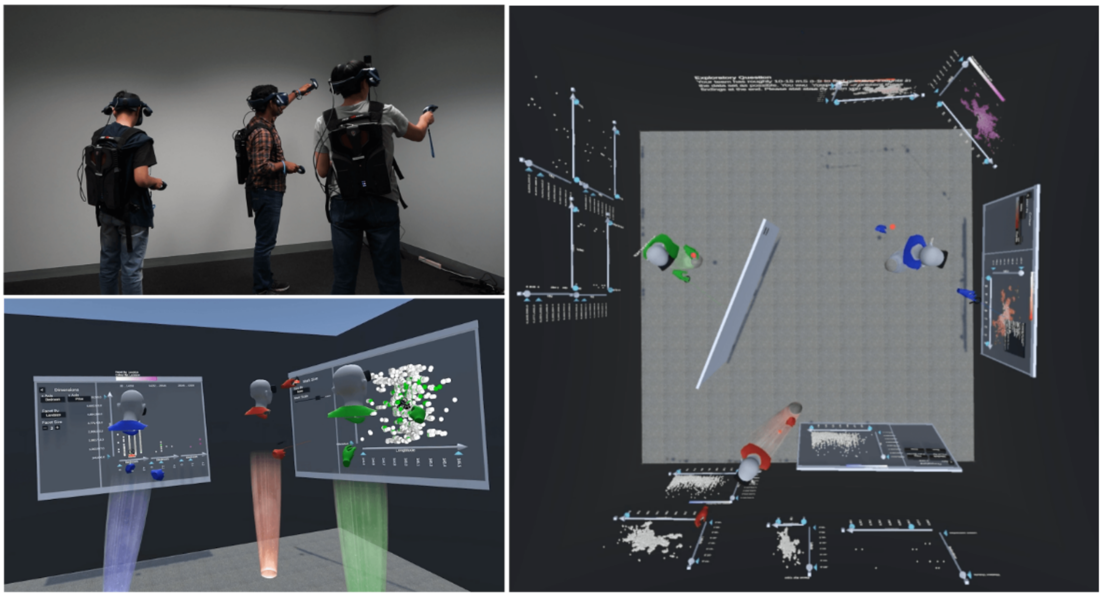
Source: Grandi, Debarba and Maciel (2019)

with the conditions proposed by Billinghurst et al. (2018). Each of these studies was conducted within the same environment during the execution of synchronous tasks, ensuring a cohesive collaborative experience.

2.4 Summary

In this chapter, we explored how the diverse range of Virtual Reality and Augmented Reality devices has spurred the development of new methods for interacting with and analyzing data. In Section 2.1, we examined definitions of Immersive Analytics (IA) and the establishment of frameworks. The following section, Section 2.2, presented examples of IA utilizing hybrid interfaces with various devices, including tablets, wall displays, and Hololens. Finally, we reviewed significant works on Collaborative AI and how they were implemented in different environments.

Figure 2.8: In FIESTA, each user can interact with different visualizations but in their environments, all using virtual reality devices, and the environment must be defined and limited.



Source: Lee et al. (2021)

3 DEAR: DESKTOP AND AUGMENTED REALITY – SYSTEM DESIGN

In this chapter we describe the design and development of our prototype. We outline the technologies employed and explain how DeAR extracts data (logs) from each of the interfaces. The visualizations supported by our prototype include Bar Charts and Scatterplots in their 2D and 3D forms, along with the ways users can interact with each of them. Each interaction is discussed in detail in the final part of this chapter.

3.1 System Overview

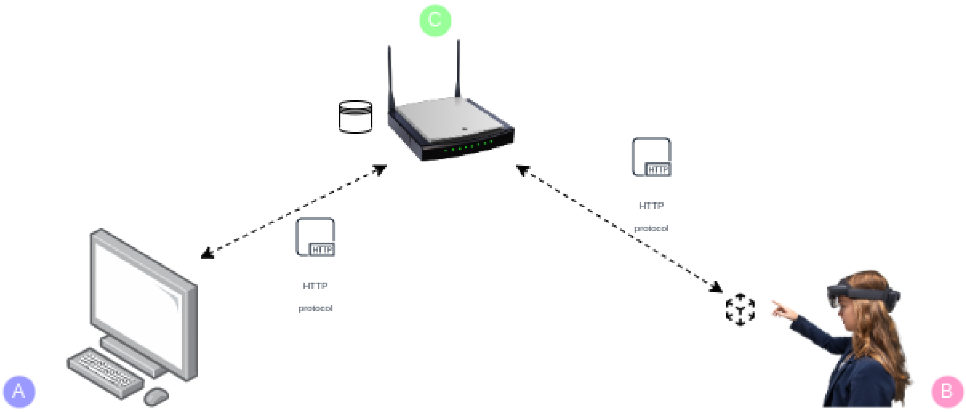
The prototype[1] developed for validating our Hybrid User Interface – DeAR (Combining Desktop and Augmented Reality) – is divided into three components: the Desktop Environment, the AR Environment, and the Server. The objective of this prototype is to facilitate Visual Data Analysis tasks, which can be accomplished using either the desktop interface or the AR interface using the Hololens. Both may be used separately or simultaneously. Our prototype was implemented across various connected devices, combining different technologies to leverage the strengths of each and compensate for their individual limitations (HUBENSCHMID et al., 2021b).

In the desktop environment, participants can interact only with the regular computer display using keyboard and mouse in a traditional manner, with visualizations available exclusively in 2D. In contrast, the AR environment allows interaction solely through the Hololens, where 3D visualizations are presented. The Desktop Environment and AR Environment can communicate through a server via WiFi using the HTTP protocol (see Figure 3.1).

DeAR comprises several components, two of which – the Desktop Environment and the AR Environment – were developed using Unity[2]. Unity natively supports C#, a programming language developed by Microsoft that is widely used for game, Virtual Reality, and Augmented Reality development. The Desktop Environment was created without any additional libraries or frameworks, while the Augmented Reality environment was developed with the assistance of MRTK[3] (Mixed Reality Toolkit) v2.8. MRTK facilitates interactions with 3D objects using the Hololens.

[1] https://youtu.be/eOjx9yhL_Uk
[2] https://www.unity.com
[3] https://github.com/microsoft/MixedRealityToolkit-Unity

Figure 3.1: Two-dimensional environment using mouse and keyboard to interact on visualizations (A); AR environment interacting with gestures in 3D (B); the server in charge of communicating both parties and the states of all the elements (C).



Additionally, the server was implemented using JavaScript with Node.js[4] and the Express library. Each client can render bar charts and scatterplots along with other relevant information, contingent upon compliance with our specified format and the file extension (JSON) that we utilize.

Users interact with various types of visualizations, each within different environments. For the **Bar Chart**, participants can engage with the visualizations either on the computer or with 3D objects using the Hololens. The same applies to the **Scatterplot**, where participants have the option to interact through either the desktop interface or the AR environment.

The data utilized in our prototype is sourced from Gapminder[5], and this dataset has been employed in other significant works related to Information Visualization (e.g., ROBERTSON et al. and BREHMER et al.). Data extraction was conducted through the logs generated in the Desktop Environment and the logs from the Augmented Reality environment using the Hololens. Additionally, we record the performance of the entire experiment using the Hololens and gather feedback through questionnaires administered at the conclusion of the experiment.

3.2 Mapping Strategies

We developed interactions that are most common for users, as explored in numerous works cited in Chapter 2. For instance, in the desktop environment, participants utilize

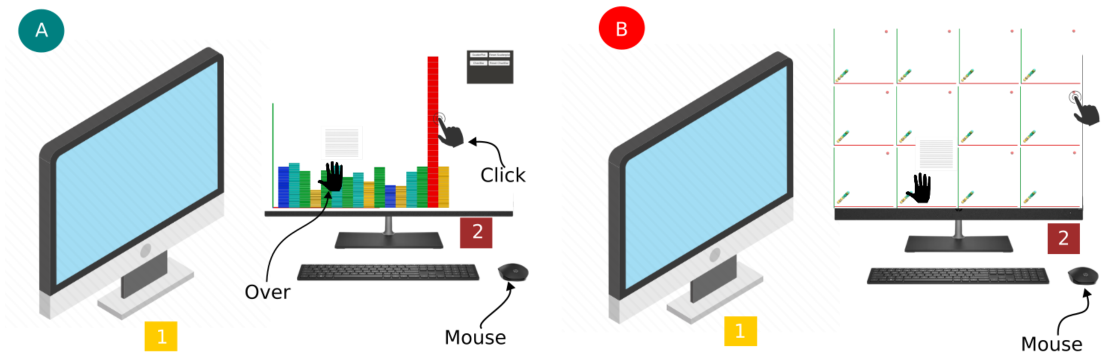
[4]https://nodejs.org/en
[5]https://www.gapminder.org/

the keyboard and mouse, similar to most Data Analysis Tools. In the AR environment, we focused exclusively on hand gesture interactions, which are the most natural form of engagement. When interacting with both environments, participants are not restricted to a fixed location; they can walk around to explore the entire space (WANG et al., 2020).

3.2.1 Desktop Interface – 2D

In the Desktop Environment we implemented two 2D visualizations tailored to the tasks and interactions required for our study (see Chapter~3. These tasks were based on relevant works in Information Visualization (SAKET; ENDERT; DEMIRALP, 2019; QUADRI; ROSEN, 2022). We selected the Bar Chart and Scatterplot visualizations because they are straightforward for executing our proposed tasks and effectively allow us to validate our interfaces. Figure 3.2 presents a sketch exemplifying the Desktop visualization.

Figure 3.2: In the 2D environment Bar Chart (A), information is displayed when the cursor hovers over an element of the visualization, and selection occurs via a click event. In the 2D environment Scatterplot (B), the mode of interaction is identical to that of the Bar Chart visualization. The visualizations are presented on monitor number 2, while monitor number 1 was designated for participants to write their answers to the tasks.



3.2.2 Augmented Reality Interface – 3D

In the AR environment, the 2D visualizations are adapted for 3D (see Figures 3.3 and 3.4). We implemented gesture interactions, as they are more natural and offer no significant difference compared to mouse usage (PAVANATTO et al., 2021). However, this can lead to some fatigue or stress in participants, as discussed in Chapter 2. Participants are not restricted to a fixed location; they can move freely. When interacting with a 3D object, it changes color, and to reset all color changes, a menu that follows the user is provided.

Figure 3.3: The 3D Bar Chart visualization is presented (left), with interaction facilitated through hand gestures. In the right we can see the 2D visualization of the Bar Chart.

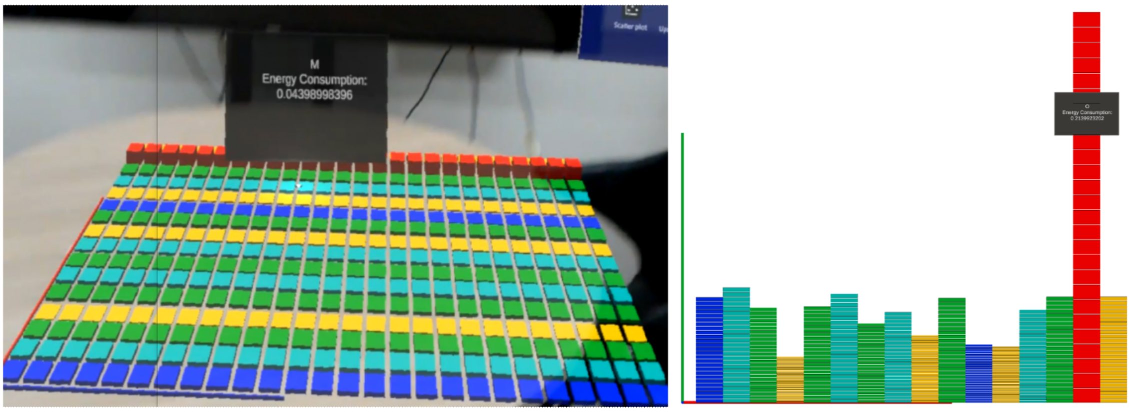
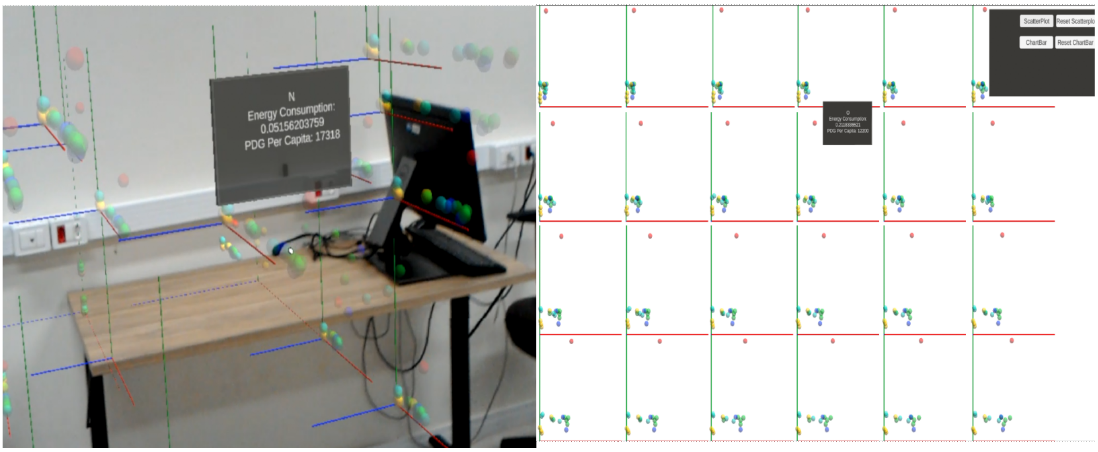


Figure 3.4: The 3D Scatterplot (left) employs the same hand gesture interactions as the Bar Chart visualization. In the rigth we can see its 2D representation.



3.2.3 Hybrid Interface – 2D and 3D

As mentioned, both interfaces are connected through a server (see Figure 3.1). Whenever the status of an element is updated, the server is responsible for updating both the Desktop Environment and the Augmented Reality Environment, depending on the tasks being performed. As tasks progress, objects change color, and the completion of tasks can occur in either environment. In some cases, depending on the visualization, one environment may be more suitable for solving the proposed task than the other. Figure 3.5 shows an example on how the real environment may be used.

Figure 3.5: In the hybrid environment where tasks are performed, participants can interact with both the Desktop Environment and the Augmented Reality Environment.

3.3 Visualization Methods

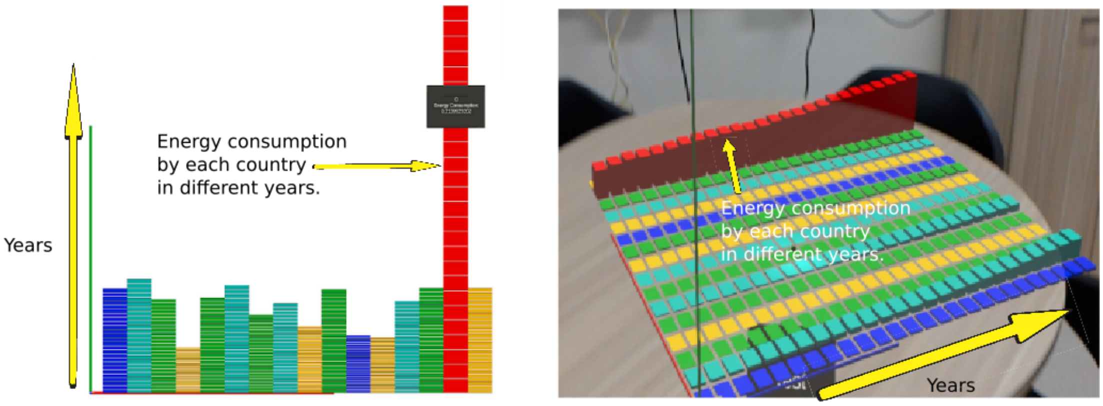
DeAR uses two different visualizations: Bar Chart and Scatterplot, each with a 2D and 3D variant (as shown in Figures 3.3 and 3.4). Users can interact with both visualization variants simultaneously. The 2D visualizations are displayed on a regular display, while the 3D visualizations are presented in the real environment using AR, and positioned in a short distance from the desktop display on another table. The elements of these visualizations are connected to a server, as mentioned before, ensuring that colors and positions remain consistent across both environments (Desktop and AR). The Bar Chart and Scatterplot were specifically chosen because both meet the requirements of our tasks.

3.3.1 Bar Chart Visualization

In the 2D Bar Chart (Figure 3.6 left), each bar is composed of smaller segments, each representing a specific year, arranged from the bottom up (Figure 3.3 right). The first segment corresponds to 1975, and the last one represents 2000. The height of each segment indicates the Energy Consumption. Bars of the same color represent a continent, indicating that they belong to the same subset, and each column corresponds to a different country.

In the 3D Bar Chart (Figure 3.6 right), the bars are arranged from back to front, maintaining the same horizontal positioning as in the 2D variant. Here, each segment from left to right represents a year, with the height indicating Energy Consumption. Each row from left to right represents a country, and the color scheme corresponds to different continents. The colors and metadata are consistent across both visualizations. When tasks are performed, selecting an element triggers synchronous events in both the 2D and 3D environments.

Figure 3.6: Bar chart variants: 2D (left) and 3D (right).



3.3.2 Scatterplot Visualization

In the 2D Scatterplot, there is a grid of visualizations arranged in a 5x4 layout, moving from left to right and from top to bottom (as shown in Figure 3.4 right). Each of these visualizations corresponds to a different year. The elements within these visualizations are color-coded, with identical colors indicating that the elements belong to the same subset. The X-axis represents Energy Consumption, and the Y-axis represents GDP per Capita. Each sphere within the plot symbolizes a country, and spheres sharing the same color signify that they belong to the same continent.

In the 3D Scatterplot, the visualizations are arranged similarly to the 2D scatterplot but are displayed within the AR environment (as shown in Figure 3.4 left). The colors used in the 3D version are consistent with those in the 2D version to prevent user confusion. This allows users to seamlessly explore and select data points within each of the Scatterplots across both environments.

3.4 Interaction Techniques

The interaction techniques employed in this project are categorized based on the environment in which they are used. For the Desktop Environment, the interactions are illustrated in Figures 3.7 and 3.8, while the AR Environment interactions are depicted in Figures 3.9 and 3.10. Each set of interactions is specifically tailored to its respective environment.

Each element in a graph can display information during interactions, but the method of interaction differs depending on the environment. For instance, in the Desktop Environment, users can hover over elements with the mouse to reveal information. In the AR environment, this interaction is performed moving the Hololens cursor with the head.

Selecting elements also varies between environments and visualizations. In the Desktop Environment, selection is done by clicking on the desired element (see Figure 3.7 right and 3.8 right). In contrast, in the AR environment, selection is performed using the Hololens cursor and a selection gesture (see Figure 3.9 right and 3.10 right).

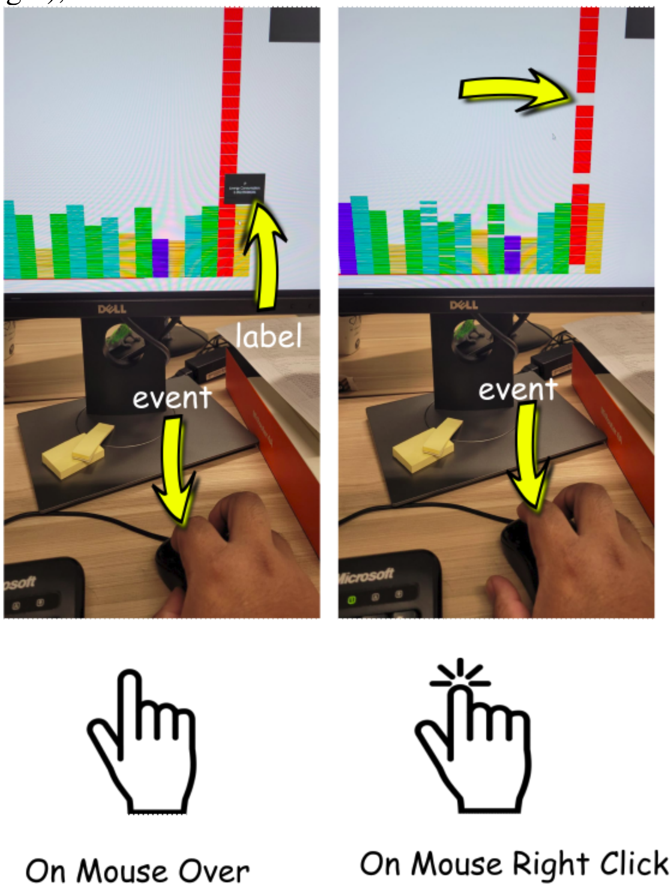
3.4.1 On Mouse Over

Interacting in the desktop environment allows users to explore objects as they would in other applications. When the mouse cursor hovers over an object, the relevant information, such as Energy Consumption and GDP per Capita, is displayed. This information is hidden once the cursor moves away from the object. The technique known as *On Mouse Over* can be used to explore all elements or focus on a specific one.

3.4.2 On Mouse Right Click

When a right click is made on each of the objects it sends the data to the server to be saved and shared for the AR environment. We can use *On Mouse Right Click* to select an element, this kind of interaction it for select. *Mouse Over* and *Mouse Right Click* were specifically developed for the desktop environment. When a right-click is performed on an object, the data is sent to the server for storage and is shared with the AR environment. The *On Mouse Right Click* interaction is used to select an element, making it the primary method for selection in the desktop environment.

Figure 3.7: When a user places the mouse over an element of the Bar Chart, it shows a label with information about the element (left). Then, when they click with the mouse over an element (right), it is selected.



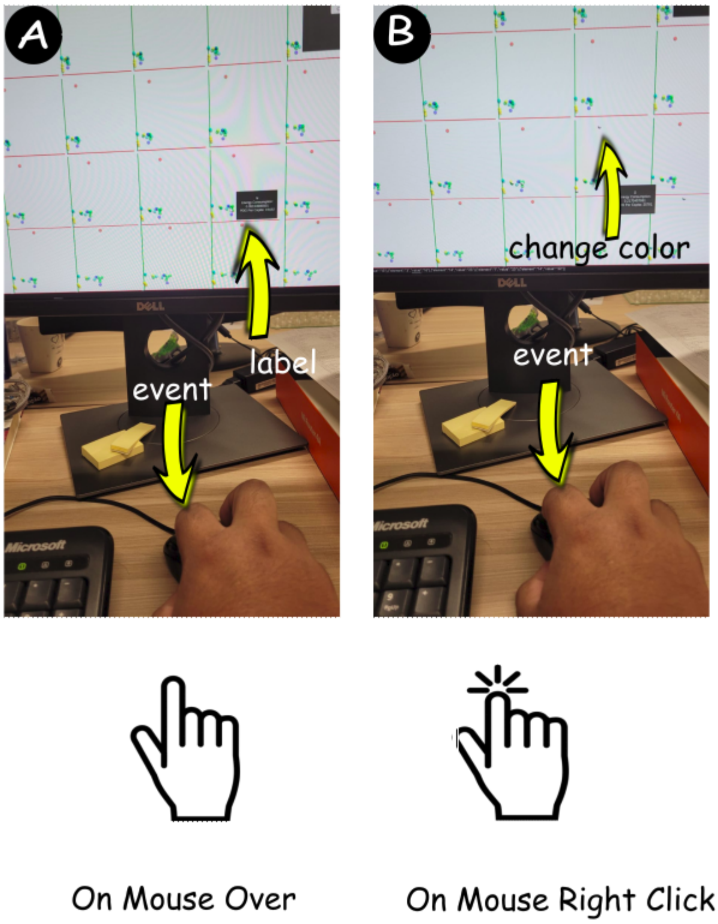
3.4.3 On Focus

Users control the Hololens cursor by moving their head. When the Hololens cursor hovers over an object in the display, the relevant information is displayed, and when the cursor moves away, the information is hidden. This interaction is used for exploration within the AR environment.

3.4.4 On Input Down

When a user performs an input gesture with their hands while using the Hololens, the information about the object is sent and shared with the Desktop Environment. The *On Focus* and *Input Down* interactions were developed using the MRTK, both of which rely on the specific interactions provided by the Hololens.

Figure 3.8: While visualizing scatterplots, the information is also showed once the mouse is over one of the spheres (left). When clicking on the sphere, it is selected (right).

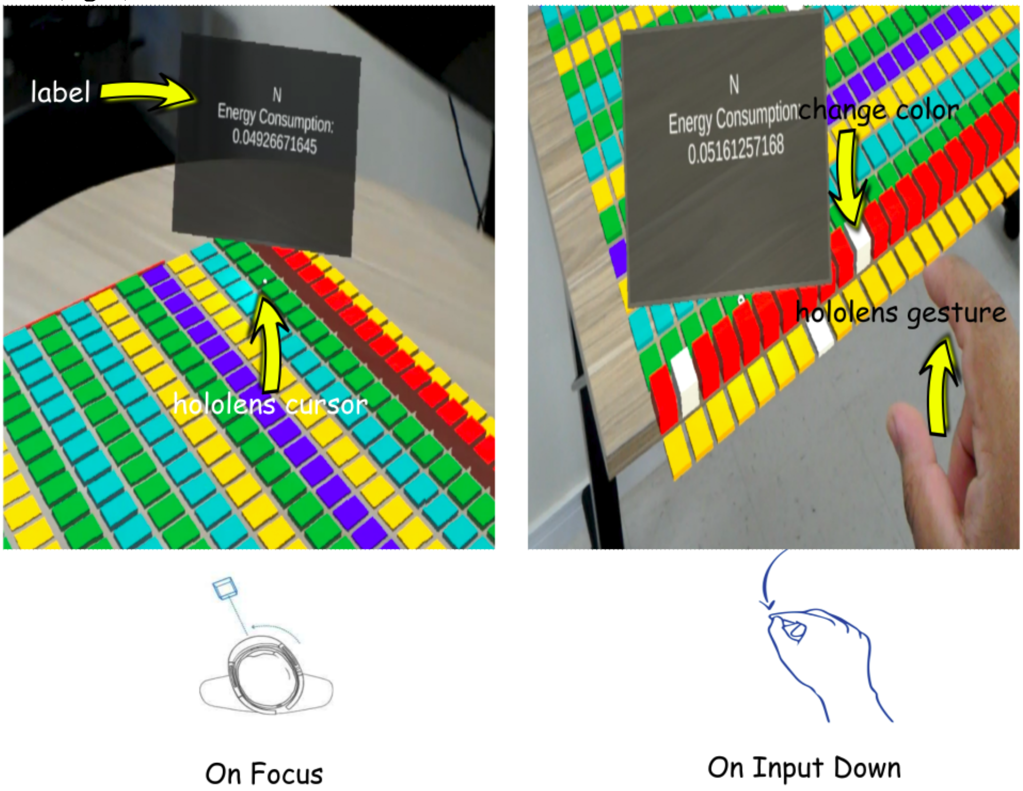


3.5 Command Activation

Command activation occurs in three parts (see Table 3.1 for all possible commands):

1. **Extraction from the Desktop Environment**: This is triggered by any use of the right mouse click on the visualizations, with the data being logged by the Unity engine.
2. **Extraction from the AR Environment**: This involves tracking interactions with each AR element and the participant's movements within the real space.
3. **Server Functionality**: The server saves responses to each task, as well as the states of the elements interacted with in both environments. Every event or interaction that occurs in either environment is recorded, with variations in how the data is saved depending on the specific visualization being used.

Figure 3.9: Moving the Hololens cursor to point to any element of the Barchart, allows the user to see information about that (left). Then, with a Hololens gesture the element is selected (right).



Direct interaction with the server is not possible; however, it is feasible to create different endpoints based on the rules we want to implement and the new data we wish to interact with. Unfortunately, the current setup does not provide flexibility for direct server interactions, limiting the ability to modify or adapt the server's functionality dynamically.

3.6 Summary

In this section, we examined the design of each environment and their connections. We also described the interactions and tasks performed, which will be used in Chapter 5. Information is collected in each environment, and any interaction with an object – regardless of the environment or event – is saved on the server. Each environment operates differently; for example, the Desktop Environment (Section 3.2.1) uses traditional mouse and keyboard interactions, while the AR Environment (Section 3.2.2) relies on hand gestures. The server facilitates communication between these environments (Section 3.2.3) and stores the relevant data.

Figure 3.10: The interactions for the Scatterplot are the same shown in Figure **??**. The differences are the elements that can be selected.

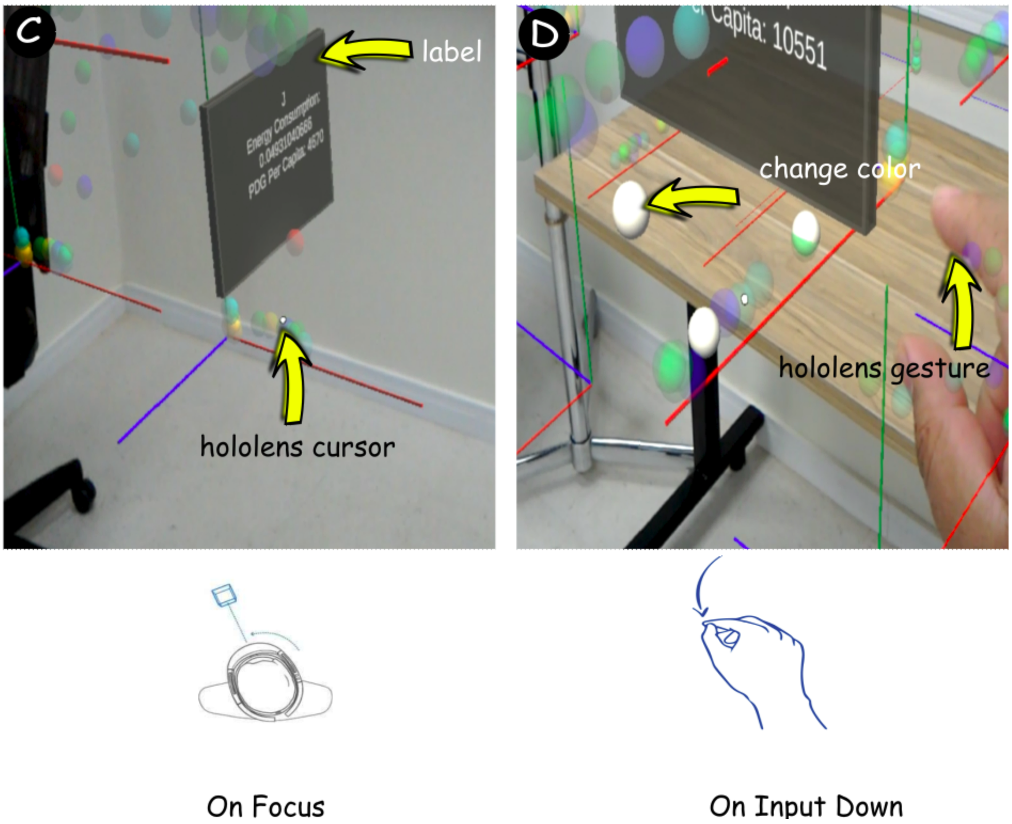


Table 3.1: Relationship between the given commands and the instances where they occur.

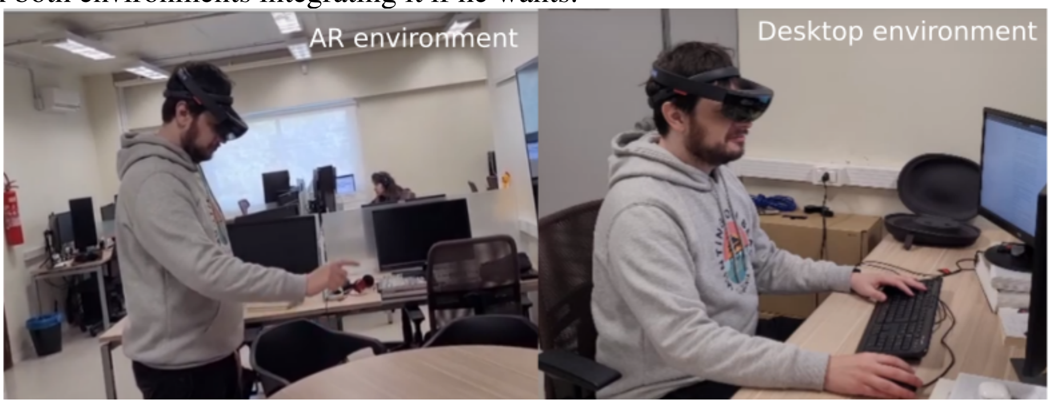
	Instances		
Command	*Desktop Environment*	*AR Environment*	*Server*
On Mouse Over detection	X	-	-
On Mouse Click detection	X	-	-
On Focus	-	X	-
On Input Down	-	X	-
POST and GET endpoints	-	-	X
Save element states	-	-	X

4 USE CASES

In this chapter, we discuss use case scenarios that demonstrate the use of DeAR for browsing and selecting visualizations. Our use cases align with the two types of visualizations implemented in our prototype.

We envisioned a hypothetical user called *Juan*, who can interact with both the desktop and AR environments simultaneously (see Figure 4.1). *Juan* has the flexibility to walk around and engage with either environment, freely choosing how to interact with the elements within each. In these use cases, *Juan* needs to interact with visualizations. For each scenario, *Juan* will work with two visualizations: a 2D Bar Chart and its 3D variant, or a 2D Scatterplot and its corresponding 3D variant as well.

Figure 4.1: In the desktop environment (right), Juan interact using the keyboard and mouse. In the AR environment (left), he can interact with gestures and gaze. Juan can mix both environments integrating it if he wants.



Juan uses two screens for the tasks: one screen is dedicated to reading the task instructions and understanding what needs to be done, while the other screen is used for interacting with the visualization. During each task, *Juan* can interact using gestures, gaze, keyboard, and mouse, either by mixing these interaction methods or by using them individually.

In our scenarios, *Juan* is interested in exploring the evolution of various metrics worldwide over time to prepare a report. To achieve this, *Juan* intends to analyze data from the World Bank dataset [1] and the Gapminder dataset [2], both of which are commonly referenced in visualization literature (BREHMER et al., 2020; QUIJANO-CHAVEZ; NEDEL; FREITAS, 2023; ROBERTSON et al., 2008). Specifically, *Juan* has selected data on Energy Consumption and GDP per Capita for 16 countries, spanning the

[1] https://data.worldbank.org/
[2] https://www.gapminder.org/data/

years from 1975 to 2000.

4.1 Bar Chart Scenario

We propose two tasks for the Bar Chart visualization scenario – using our hypothetical user, *Juan* – to illustrate how each task can be performed. We describe the steps involved in each task, highlighting how *Juan* can utilize the various interaction techniques available in our application.

Juan aims to answer the following question by visualizing the bar chart in both 2D and 3D: *"What was the highest value of Energy Consumption in Brazil from 1975 to 2000?"*.

To answer this question, *Juan* needs to explore the energy consumption data for each year within the visualization. He can perform this task in either environment. In the desktop environment, *Juan* can use the mouse to inspect potential values. Alternatively, in the AR environment using the Hololens, *Juan* can utilize gestures or gaze to explore the data, where the additional axis and stereopsis may assist in identifying the highest value if several options appear similar. *Juan* can choose to use the mouse (as discussed in Section 3.4.1 and 3.4.2) within the desktop environment or rely on gaze (as outlined in Section 3.4.3 and 3.4.4) with the Hololens. After thoroughly exploring the data, *Juan* should select the highest value.

Juan is asked to answer the question: *"Find the minimum and maximum value among the countries in yellow between the years 1975 and 2000"*. To accomplish this, *Juan* must explore each element of the bar chart. He can choose to explore the 2D and 3D environments separately or together, using either the mouse or the Hololens. After completing the exploration, *Juan* should identify and select the item with the lowest energy consumption. Finally, he must fill out the form to complete the task.

4.2 Scatterplot Scenario

In this use case, *Juan* needs to perform additional tasks using a different visualization: the 2D Scatterplot and its 3D variant. *Juan* can use the various interaction techniques developed in DeAR, as described in Sections 3.4.1, 3.4.2, 3.4.3, and 3.4.4. These interactions will assist *Juan* in effectively exploring and analyzing the data within these visualizations.

Juan is asked to identify anomalies in the relationship between GDP per Capita and Energy Consumption. Specifically, he needs to answer the question: *"Find the anomalies (outliers) in the scatterplot for GDP per Capita and Energy Consumption from the years 1980 to 1990"*. To do this, *Juan* must explore the scatterplot – using either the 2D or 3D visualization – to detect any data points that significantly deviate from the expected patterns.

Juan needs to locate the scatterplot visualization for the year 1980. Once he finds it, he must analyze the visualization to identify any anomalies (outliers). He can utilize either the 2D visualization or the one from the AR environment for this task. After successfully identifying the anomalies, *Juan* must fill out a form with the names of the countries he discovered as outliers.

Juan is also asked to find the anomalies between the years 1980 and 1990 in the parameters of GDP per Capita and Energy Consumption. He must explore all the visualizations and locate the scatterplots for the years 1980 to 1990. Once he identifies the relevant visualizations, *Juan* should analyze them to detect any anomalies. After finding all the anomalies, he can select them and note down the names of the countries that were identified as outliers.

Figure 4.2 illustrates *Juan* using our prototype in a desktop, while Figure 4.3 shows the interaction flow in AR.

Figure 4.2: A user (*Juan*) using DeAR to interact with a 2D scatterplot (a); and then performing the tasks proposed in a bar chart using a 2D visualization (b).

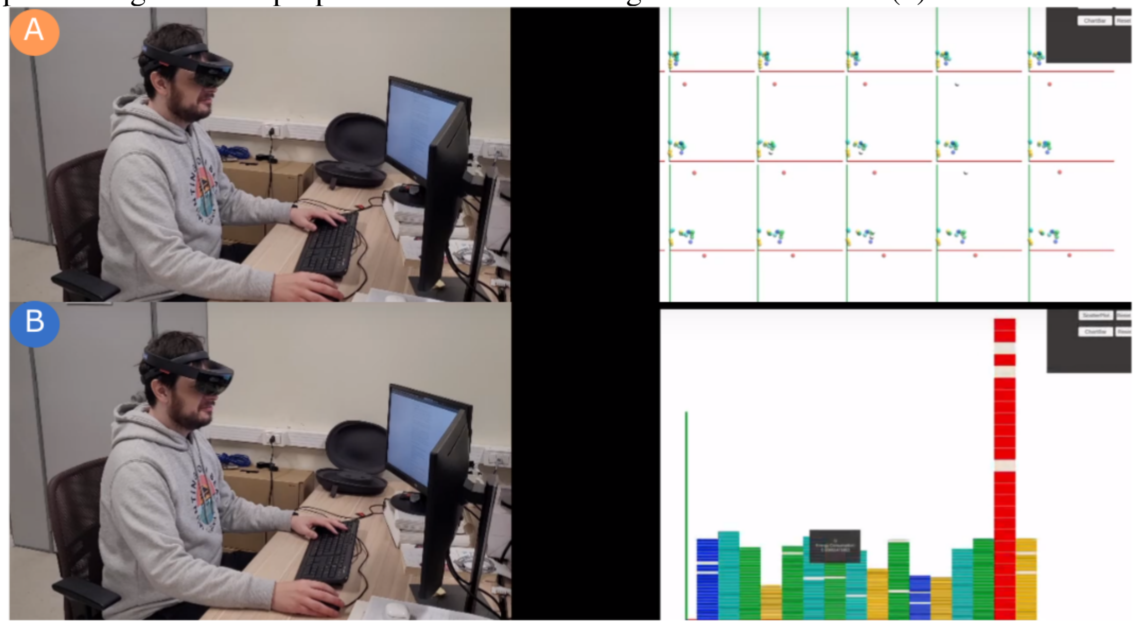
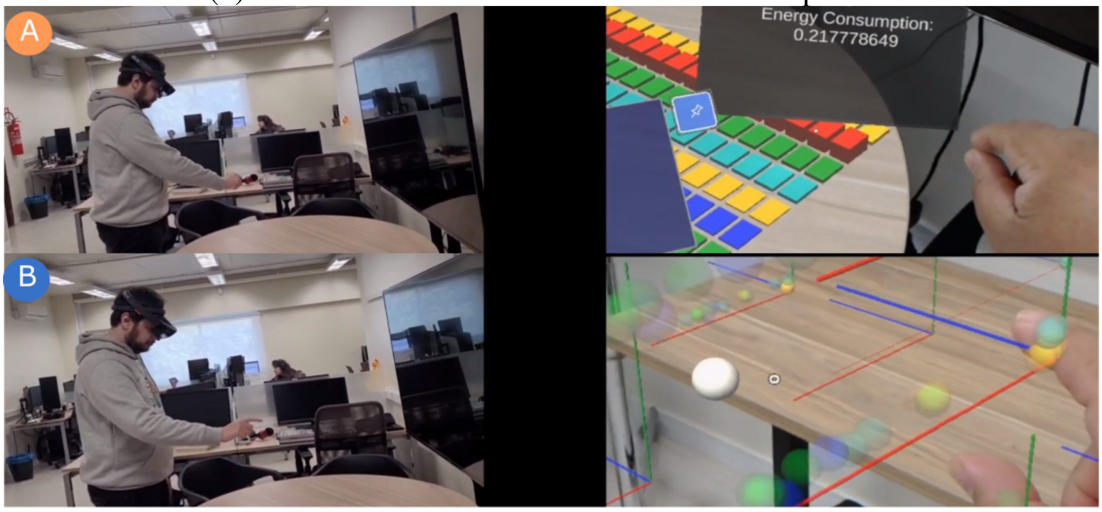


Figure 4.3: The user is interacting with the 3D bar chart with the Hololens (a); the user selects an object from the display, and when he performs the interaction the object changes its color to white (b). The user then interacts with the 3D scatterplot.



4.3 Dataset Used

The data used to conduct our use cases is available from World Bank Open Data[3] and Gapminder[4]. The data includes metrics such as Population, Arable Area, Energy Consumption, GDP per Capita, Life Expectancy (for both women and men), Infant Mortality, and Number of Personal Computers. These data has also been utilized by Robertson et al. (2008), who proposed two alternatives for visualizing trends: one approach overlays all trends simultaneously in a single display, while the other uses a small multiples display to present the trend traces side-by-side. The results of this study indicated that animation is the least effective method for analysis, whereas the small multiples display yields more accurate insights.

These visualizations are presented in 2D and are employed for data analysis. Brehmer et al. (2020) compared the efficacy of animated and small multiples variants of Scatterplots on mobile phones for analyzing trends in multivariate datasets. They identified scenarios that favor either animation or small multiples, raising new questions for further experimental research and implications for visualization design on mobile devices. The tasks in this study are similar to those in previous works; however, the key difference is that this research focuses on mobile devices, where the screen size is significantly smaller, specifically comparing the effectiveness of animated versus small multiples variants of scatterplots on mobile platforms.

[3]https://data.worldbank.org/
[4]https://www.gapminder.org/data/

The two previous works focused on 2D visualizations, while the following two studies explored 3D spaces within the context of Immersive Analytics (IA). Liu et al. (2020) explored the adaptation of 2D small multiples visualization on flat screens to 3D immersive environments. Their results suggest that, when using fewer multiples, a flat layout performs better, despite requiring participants to walk further. In contrast, Quijano-Chavez, Nedel and Freitas (2023) investigated how to best facilitate analysts in exploring and performing temporal trend tasks using similar techniques in immersive virtual environments. This study involved designing and conducting user tests based on approaches from previous works concerning visualization and interaction techniques, as well as tasks for comparisons in three-dimensional settings.

All the previously cited works utilize various parameters such as Population, GDP per Capita, and others, as these metrics are essential for their respective tasks. In the case of DeAR, we specifically selected Energy Consumption and GDP per Capita, as the visualizations (Bar Chart and Scatterplot) chosen for our experiments require only two parameters.

4.4 Summary

In this chapter, we described a use case for DeAR in which a fictional user interacts with two visualizations: a Bar Chart (discussed in Section 4.1) and a Scatterplot (covered in Section 4.2). Our hypothetical user can transition between 2D and 3D visualizations or attempt to combine both formats simultaneously.

5 USER STUDY PROPOSAL

In this chapter, we outline the procedures for conducting user experiments with DeAR prototype. The primary aim of these two experiments is to evaluate the effectiveness of our interface in both Solo and Collaborative modes. These experiments will allow us to gather data and feedback for validating our interface in each mode.

5.1 Standard Protocol

Participants for our experiments will be recruited via email or from our personal network, specifically targeting individuals with some background in data analysis. This protocol will be applied uniformly across both modes of interaction. We will record audio from all participants during the experiment and capture their entire session through strategically positioned cameras. However, video footage from the Hololens will not be recorded due to delays that can interfere with interaction with 3D objects. Instead, we will save logs from the Desktop Environment (e.g., mouse interactions), the AR Environment (e.g., gestures and movement), and the server (e.g., interactions with both interfaces and user positioning within the experimental space). Additionally, participants will complete a demographic questionnaire (Appendices A and B) prior to the experiment and a user experience questionnaire (Appendix E) afterward. To enrich our qualitative data, we will encourage participants to verbalize their thoughts using the "Think-Aloud" technique throughout the experiment, followed by a brief interview upon completion of the tasks.

5.1.1 Consent and Confidentiality Term

At the start of the experiment, we will present the Consent and Confidentiality Terms (see Appendix F). During this presentation, we will address important questions, such as how the participant will interact with devices like the Hololens and whether they experience any discomfort while using the device. Participants will be allowed to proceed with the experiment only if they confirm their agreement with the term. If a participant disagrees with any of the points presented, they will not be permitted to participate in the experiment.

5.1.2 Testing Protocol

The Testing Protocol (see Appendix G) outlines the steps to follow from the beginning to the end of our experiment. After the participant accepts the terms, we will explain the interactions they will need to perform, the devices they will use, and how these devices function. Once this initial explanation is complete, we will provide an overview of our research and present several questionnaires, assuring participants that all collected data will remain confidential. At the end of this section, we will address any questions the users may have.

We will clearly explain each task so that participants understand how to complete them. After finishing the tasks, participants will need to fill out another questionnaire. Once all tasks and questionnaires are completed, we will be available to answer any remaining questions from the participants.

In the next sections (Section 5.3 and Section 5.4), we will explore the different modes and the questionnaires that need to be completed for each of the visualizations.

5.2 Tasks

In this work, our primary goals are to assess the interactions of DeAR as a system and to evaluate the overall usability of the workflow during the experiments. To ensure valid results, participants should not have previously engaged in experiments similar to the ones we are conducting. The tasks assigned in this study closely resemble the use case presented in Chapter 4.

We will use the same public dataset from previous studies (ROBERTSON et al., 2008; BREHMER et al., 2020; QUIJANO-CHAVEZ; NEDEL; FREITAS, 2023), which can be accessed for free online[1,2]. This dataset includes information on *Energy Consumption, Population,* and *GDP per Capita* for each of the 16 countries from 1975 to 2000. To minimize any economic biases, we assigned each country a letter designation from A to P, presenting them in a randomized order. This approach was taken to prevent any preconceived notions from influencing the participants' responses.

Participants will be required to complete *selection and exploration tasks* for each visualization. For instance, in the Bar Chart, they might be asked to *"Find the country*

[1]https://data.worldbank.org/
[2]https://www.gapminder.org/data/

with the highest Energy Consumption between the years 1975 to 2000". Similarly, in the Scatterplot, they will be tasked with *"Identify the outlier in the relationship between GDP Per Capita and Energy Consumption"*. Clear instructions need to be provided to guide users through these tasks, followed by a questionnaire to capture their responses.

While there is no strict time limit for completing the tasks, we aim for the sessions to last between 30 to 45 minutes. This duration is chosen because interactions involving mid-gestures may become tiring (HARRISON; RAMAMURTHY; HUDSON, 2012; FILHO; FREITAS; NEDEL, 2019), leading to unreliable (CAVALLO et al., 2019) and inaccurate (CHAN et al., 2010) results if prolonged.

5.3 DeAR Solo Mode

The Solo Mode was designed for individual users, allowing them to interact with both environments based on the interface they choose to complete their tasks. Users are required to engage with the visualizations (Bar Chart and Scatterplot) and their variants (2D and 3D). If they wish to utilize both environments, users must walk to the designated table for interaction. As detailed in previous chapters (Chapter 3 and Chapter 4), any interaction with elements in one visualization is reflected in the other. Therefore, users need to move between environments to observe any color changes in the elements.

5.3.1 Solo Mode with Bar Chart and Scatterplot

In this experiment, we present a scenario that showcases DeAR as a Data Analysis Tool within a Hybrid Environment. The user can utilize two visualizations, each with its variants (2D and 3D): the Bar Chart and the Scatterplot, both rendering the same data. Each element within the visualizations can be interacted with independently, regardless of the environment, as demonstrated in Chapter 3.

5.3.2 Solo Mode Questionnaires

In this subsection, we outline all the questionnaires that we propose to apply during the experiment. The list of questionnaires is as follows:

- **Questionnaire (Q1)** (see Appendix A): This questionnaire collects demographic data and assesses any prior experience participants may have with Virtual Reality or Augmented Reality.
- **Questionnaire (Q2)** (see Appendix C): This questionnaire is administered before and after each experiment to identify any discomfort or symptoms experienced during the tasks involving interactions with virtual environments.
- **Questionnaire (Q3)** (see Appendix D): This questionnaire is conducted after each experiment to evaluate any mental load resulting from the activities performed.
- **Questionnaire (Q4)** (see Appendix E): This questionnaire is completed at the end of the session to assess the effectiveness, efficiency, and satisfaction associated with using our prototype.

5.4 DeAR Collaborative Mode

Our prototype supports a collaborative mode, which differs from the SOLO mode by allowing multiple participants to interact simultaneously. In this scenario, we will consider two users engaging within our hybrid environment. Both participants must have the same setup, with each user connected to the same network, enabling data sharing through our server. Users can interact with one another and the hybrid environment, facilitating conversation, idea exchange, and task discussion. The primary goal of the collaborative mode is to encourage decision-making and collaborative problem-solving while navigating the tasks within the hybrid space.

5.4.1 Collaborative Mode with Bart Chart and Scatterplot

The design of the collaborative mode closely resembles that of the solo mode, with the primary difference being the number of users interacting simultaneously. This mode is designed to facilitate the exchange of information, decision-making, and discussions based on the actions performed by each participant. Users can interact with the spheres in the scatterplot or with the bars in the bar chart, whether in the same or different environments (desktop or AR). Whenever one user interacts with an element in a visualization, that element changes color to indicate the action. Participants can undertake different tasks or complete questionnaires, and their responses are recorded each time they answer the tasks.

5.4.2 Collaborative Mode Questionnaires

In this subsection, we outline the questionnaires proposed for this experiment, which include:

- **Questionnaire (Q1)** (see Appendix B): This questionnaire gathers demographic data and assesses whether participants have prior experience with Virtual Reality or Augmented Reality.
- **Questionnaire (Q2)** (see Appendix C): Administered before and after each experiment, this questionnaire aims to identify any uncomfortable symptoms experienced during interactions or within virtual environments.
- **Questionnaire (Q3)** (see Appendix D): This questionnaire is completed after each experiment to evaluate the mental load caused by the activities performed.
- **Questionnaire (Q4)** (see Appendix E): Conducted at the end of the session, this questionnaire assesses the effectiveness, efficiency, and satisfaction of participants when using our prototype.

5.5 Summary

In this chapter, we examined the design of each use case, detailing the tasks to be performed. The use cases are divided into two modes: SOLO and COLLABORATIVE. While the tasks remain the same in both modes, the key difference lies in the number of participants allowed to interact. Additionally, questionnaires are administered at various stages – before, during, and after each use case – to gather valuable feedback and insights.

6 CONCLUSION

Our primary contribution with this work was the design of the DeAR (Combining Desktop and Augmented Reality for Visual Data Analysis) prototype, which enables interaction across different interfaces and displays, each operating independently and effectively within hybrid environments. We developed two distinct use cases for conducting selection and exploration tasks to validate our DeAR prototype. During the execution of these use cases, we successfully completed all proposed tasks.

Additionally, we established an experimental design that facilitates interaction among one or more users in hybrid environments by integrating heterogeneous interfaces. Following the completion of each use case and the validation of our interface, we gained insights into new methods for designing hybrid interfaces tailored for visual data analytics.

Lastly, we proposed a protocol detailing how to execute tasks and develop use cases for each visualization. Upon task completion, we proposed some questionnaires aimed at qualitatively measuring the effectiveness of each use case.

6.1 Limitations and Future Works

In the DeAR project, until now we worked with a small amount of data, which eliminated the need for a load balancer between the messages, devices, and server. However, for better data management and when handling larger datasets, it's essential to implement balancing techniques and utilize tools like Kafka[1] or RabbitMQ[2] to ensure data consistency and prevent information loss. While Node.js is suitable for managing small data volumes, its performance significantly declines as the data volume increases. To enhance the system's efficiency, migrating the server to a more performant language such as Rust or Go would be beneficial.

The visualizations used for interaction are straightforward and user-friendly. However, an improvement would be to introduce more complex visualizations for participants, along with designing intricate tasks that extend beyond merely validating our interface. This would also allow us to compare our work with other prototypes discussed in Chapter 2.

[1]https://kafka.apache.org/
[2]https://www.rabbitmq.com/

For future work, we aim to integrate additional devices, such as tablets, smartphones, and virtual reality head-mounted displays (HMDs). We also plan to implement various collaboration modes, not just synchronous and co-located interactions, but to expand upon the other forms outlined in Section 2.3. Additionally, we seek to create an environment where all devices can operate cohesively and simultaneously for enhanced interaction and perception.

6.2 Other contributions

During my master's degree, I collaborated on various publications and projects, some of which contributed directly or indirectly to my dissertation. Through each of these publications, I gained insights that aided my research, such as:

3DUI and the Phantom Limb: Multisensory Experience for Embodiment of Amputation

In this work, I explored the use of haptic devices and their interaction with virtual objects through two distinct cases. In the first case, users engage with virtual reality controllers and virtual objects, receiving haptic feedback in the form of vibrations when the two elements interact. In the second case, users interact with their elbow and virtual objects, with vibrations being transmitted when the haptic device interacts with the virtual elements.

E-mpathy and the Phantom Limb Sensation: A Multisensory Experience for Embodiment of Amputation

This work builds on previous research but focuses on fostering empathy for individuals with phantom limb disorder. In this study, we compared users' feelings when interacting without using a hand, examining their emotional responses during the experience.

Cooking in the Dark: Exploring Spatial Audio as MR Assistive Technology for the Visually Impaired

In this project, we established a connection between a virtual assistant and voice commands using Hololens. I developed various voice rules tailored to specific tasks. The communication was asynchronous and occurred within the same environment. The sound emitted by an object (such as a pot or kitchen appliance) varied depending on its distance from the user; if the object was nearby, the sound was loud, and if it was farther away, the sound was softer.

Cooking in the dark: a mixed reality empathy experience for the embodiment of blindness

In this project, we built upon our previous work but shifted our focus to creating an experience that fosters empathy for individuals who are blind. Unlike the earlier study, which measured the number of tasks users could complete, this time we aimed to gather feedback from users about their feelings and experiences while performing these tasks.

Vibrotactile Data Physicalization: Exploratory Insights for Haptization of Low-resolution Images

In this project, I worked with the data. These data was about death and vaccinated people due to coronavirus between 2020 and 2021. I filtered just South America countries. Depending on the amount of data (death and vaccination), while the amount is higher the vibration feedback is stronger, if the amount is lower the vibration feedback is weaker.

DeAR: Combining Desktop and Augmented Reality for Visual Data Analysis

This was our latest publication submitted to the Symposium on Virtual and Augmented Reality 2023. In this work, we presented two different visualizations (Scatterplot and Bar Chart) and outlined their respective uses. We submitted a condensed version of DeAR, which was accepted as a short paper with only a few corrections.

REFERENCES

BILLINGHURST, M. et al. Collaborative immersive analytics. In: ____. **Immersive Analytics**. Cham: Springer International Publishing, 2018. p. 221–257. ISBN 978-3-030-01388-2. Available from Internet: <https://doi.org/10.1007/978-3-030-01388-2_8>.

BREHMER, M. et al. A comparative evaluation of animation and small multiples for trend visualization on mobile phones. **IEEE Transactions on Visualization and Computer Graphics**, v. 26, n. 1, p. 364–374, 2020.

CAVALLO, M. et al. Immersive insights: A hybrid analytics system forcollaborative exploratory data analysis. In: **Proceedings of the 25th ACM Symposium on Virtual Reality Software and Technology**. New York, NY, USA: Association for Computing Machinery, 2019. (VRST ’19). ISBN 9781450370011. Available from Internet: <https://doi.org/10.1145/3359996.3364242>.

CHAN, L.-W. et al. Touching the void: Direct-touch interaction for intangible displays. In: **Proceedings of the SIGCHI Conference on Human Factors in Computing Systems**. New York, NY, USA: Association for Computing Machinery, 2010. (CHI ’10), p. 2625–2634. ISBN 9781605589299. Available from Internet: <https://doi.org/10.1145/1753326.1753725>.

CORDEIL, M. et al. Iatk: An immersive analytics toolkit. In: **2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)**. [S.l.: s.n.], 2019. p. 200–209.

CUYA, F. G. B. et al. Vibrotactile data physicalization: Exploratory insights for haptization of low-resolution images. In: **Symposium on Virtual and Augmented Reality**. New York, NY, USA: Association for Computing Machinery, 2022. (SVR’21), p. 84–91. ISBN 9781450395526. Available from Internet: <https://doi.org/10.1145/3488162.3488171>.

DWYER, T. et al. Immersive analytics: An introduction. In: ____. **Immersive Analytics**. Cham: Springer International Publishing, 2018. p. 1–23. ISBN 978-3-030-01388-2. Available from Internet: <https://doi.org/10.1007/978-3-030-01388-2_1>.

ENS, B. et al. Grand challenges in immersive analytics. In: **Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems**. New York, NY, USA: Association for Computing Machinery, 2021. (CHI ’21). ISBN 9781450380966. Available from Internet: <https://doi.org/10.1145/3411764.3446866>.

FEINER, S.; SHAMASH, A. Hybrid user interfaces: Breeding virtually bigger interfaces for physically smaller computers. In: **Proceedings of the 4th Annual ACM Symposium on User Interface Software and Technology**. New York, NY, USA: Association for Computing Machinery, 1991. (UIST ’91), p. 9–17. ISBN 0897914511. Available from Internet: <https://doi.org/10.1145/120782.120783>.

FILHO, J. A. W.; FREITAS, C. M. D. S.; NEDEL, L. Comfortable immersive analytics with the virtualdesk metaphor. **IEEE Computer Graphics and Applications**, v. 39, n. 3, p. 41–53, 2019.

GRANDI, J. G.; DEBARBA, H. G.; MACIEL, A. Characterizing asymmetric collaborative interactions in virtual and augmented realities. In: **2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)**. [S.l.: s.n.], 2019. p. 127–135.

HACKATHORN, R.; MARGOLIS, T. Immersive analytics: Building virtual data worlds for collaborative decision support. In: **2016 Workshop on Immersive Analytics (IA)**. [S.l.: s.n.], 2016. p. 44–47.

HARRISON, C.; RAMAMURTHY, S.; HUDSON, S. E. On-body interaction: Armed and dangerous. In: **Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction**. New York, NY, USA: Association for Computing Machinery, 2012. (TEI '12), p. 69–76. ISBN 9781450311748. Available from Internet: <https://doi.org/10.1145/2148131.2148148>.

HUBENSCHMID, S. et al. Stream: Exploring the combination of spatially-aware tablets with augmented reality head-mounted displays for immersive analytics. In: **Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems**. New York, NY, USA: Association for Computing Machinery, 2021. (CHI '21). ISBN 9781450380966. Available from Internet: <https://doi.org/10.1145/3411764.3445298>.

HUBENSCHMID, S. et al. Towards asynchronous hybrid user interfaces for cross-reality interaction. In: JETTER, H.-C. et al. (Ed.). **ISS'21 Workshop Proceedings: "Transitional Interfaces in Mixed and Cross-Reality: A new frontier?"**. [S.l.: s.n.], 2021.

ISENBERG, P. et al. Collaborative visualization: Definition, challenges, and research agenda. **Information Visualization**, v. 10, n. 4, p. 310–326, 2011. Available from Internet: <https://doi.org/10.1177/1473871611412817>.

JAMES, R. et al. Personal+context navigation: combining AR and shared displays in network path-following. **CoRR**, abs/2005.10612, 2020. Available from Internet: <https://arxiv.org/abs/2005.10612>.

JANSEN, Y. et al. Opportunities and challenges for data physicalization. In: **Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems**. New York, NY, USA: Association for Computing Machinery, 2015. (CHI '15), p. 3227–3236. ISBN 9781450331456. Available from Internet: <https://doi.org/10.1145/2702123.2702180>.

LANGNER, R. et al. Marvis: Combining mobile devices and augmented reality for visual data analysis. In: **Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems**. New York, NY, USA: Association for Computing Machinery, 2021. (CHI '21). ISBN 9781450380966. Available from Internet: <https://doi.org/10.1145/3411764.3445593>.

LEE, B. et al. Shared surfaces and spaces: Collaborative data visualisation in a co-located immersive environment. **IEEE Transactions on Visualization and Computer Graphics**, v. 27, n. 2, p. 1171–1181, 2021.

LIU, J. et al. Design and evaluation of interactive small multiples data visualisation in immersive spaces. In: **2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)**. [S.l.: s.n.], 2020. p. 588–597.

LU, F.; BOWMAN, D. A. Evaluating the potential of glanceable ar interfaces for authentic everyday uses. In: **2021 IEEE Virtual Reality and 3D User Interfaces (VR)**. [S.l.: s.n.], 2021. p. 768–777.

MARK, G.; CARPENTER, K.; KOBSA, A. Are there benefits in seeing double? a study of collaborative information visualization. In: **CHI '03 Extended Abstracts on Human Factors in Computing Systems**. New York, NY, USA: Association for Computing Machinery, 2003. (CHI EA '03), p. 840–841. ISBN 1581136374. Available from Internet: <https://doi.org/10.1145/765891.766023>.

MARRIOTT, K. et al. Immersive analytics: Time to reconsider the value of 3d for information visualisation. In: ____. **Immersive Analytics**. Cham: Springer International Publishing, 2018. p. 25–55. ISBN 978-3-030-01388-2. Available from Internet: <https://doi.org/10.1007/978-3-030-01388-2_2>.

MUNZNER, T. **Visualization Analysis and Design**. CRC Press, 2015. (AK Peters Visualization Series). ISBN 9781498759717. Available from Internet: <https://books.google.de/books?id=NfkYCwAAQBAJ>.

PAVANATTO, L. et al. Do we still need physical monitors? an evaluation of the usability of ar virtual monitors for productivity work. In: **2021 IEEE Virtual Reality and 3D User Interfaces (VR)**. [S.l.: s.n.], 2021. p. 759–767.

PLASSON, C.; BLANCH, R.; NIGAY, L. Selection techniques for 3d extended desktop workstation with ar hmd. In: **2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)**. [S.l.: s.n.], 2022. p. 460–469. ISSN 1554-7868.

QUADRI, G. J.; ROSEN, P. A survey of perception-based visualization studies by task. **IEEE Transactions on Visualization and Computer Graphics**, IEEE Educational Activities Department, USA, v. 28, n. 12, p. 5026–5048, dec 2022. ISSN 1077-2626. Available from Internet: <https://doi.org/10.1109/TVCG.2021.3098240>.

QUIJANO-CHAVEZ, C.; NEDEL, L.; FREITAS, C. M. D. S. Comparing scatterplot variants for temporal trends visualization in immersive virtual environments. In: **2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR)**. [S.l.: s.n.], 2023. p. 669–679.

RASKAR, R. et al. The office of the future: A unified approach to image-based modeling and spatially immersive displays. In: **Proceedings of the 25th Annual Conference on Computer Graphics and Interactive Techniques**. New York, NY, USA: Association for Computing Machinery, 1998. (SIGGRAPH '98), p. 179–188. ISBN 0897919998. Available from Internet: <https://doi.org/10.1145/280814.280861>.

REIPSCHLAGER, P.; FLEMISCH, T.; DACHSELT, R. Personal augmented reality for information visualization on large interactive displays. **IEEE Transactions on Visualization and Computer Graphics**, v. 27, n. 2, p. 1182–1192, 2021.

ROBERTSON, G. et al. Effectiveness of animation in trend visualization. **IEEE Transactions on Visualization and Computer Graphics**, v. 14, n. 6, p. 1325–1332, 2008.

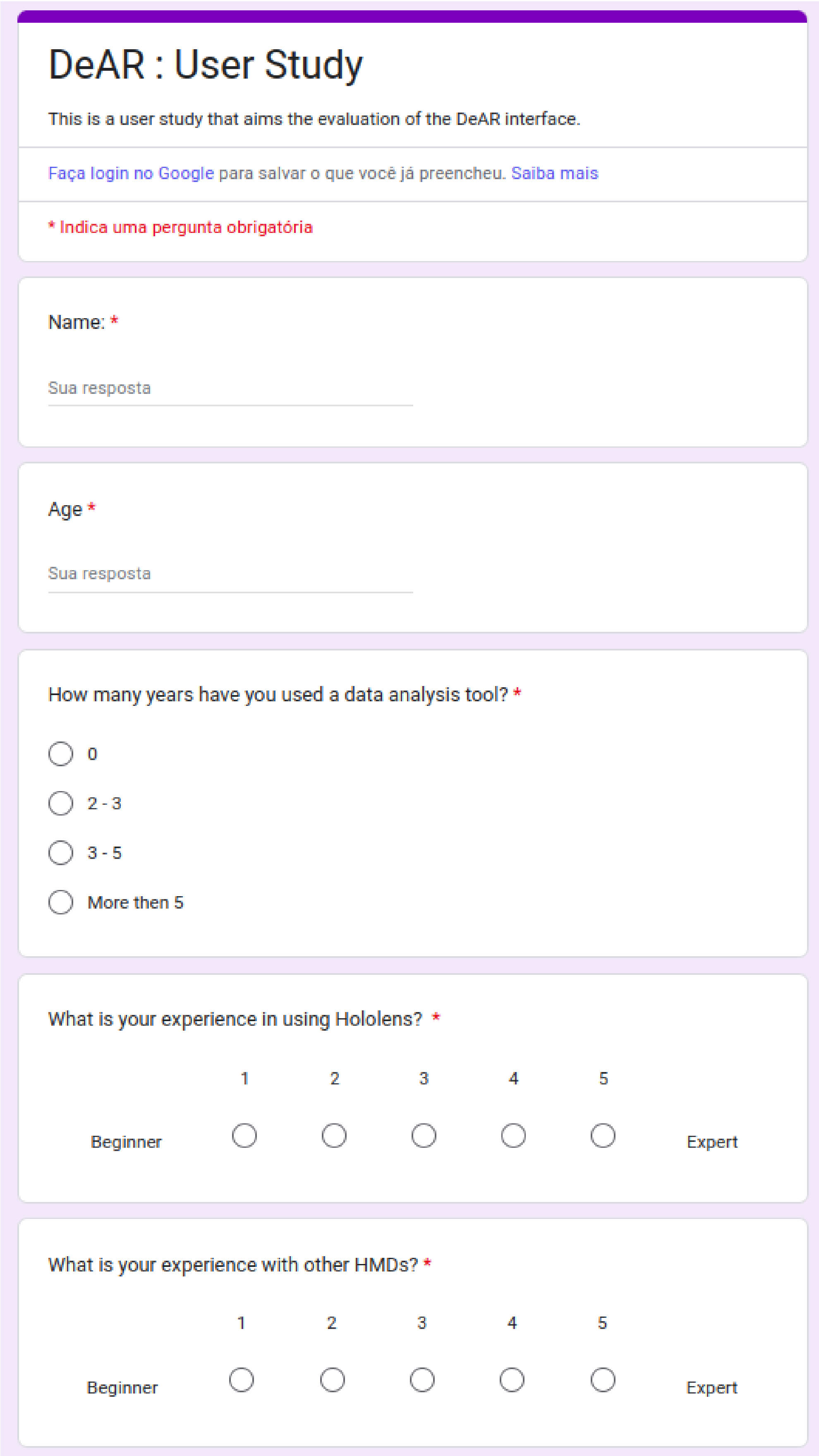
SAKET, B.; ENDERT, A.; DEMIRALP. Task-based effectiveness of basic visualizations. **IEEE Transactions on Visualization and Computer Graphics**, v. 25, n. 7, p. 2505–2512, 2019.

SICAT, R. et al. Dxr: A toolkit for building immersive data visualizations. **IEEE Transactions on Visualization and Computer Graphics**, v. 25, n. 1, p. 715–725, 2019.

WANG, X. et al. Towards an understanding of augmented reality extensions for existing 3d data analysis tools. In: **Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems**. New York, NY, USA: Association for Computing Machinery, 2020. (CHI '20), p. 1–13. ISBN 9781450367080. Available from Internet: <https://doi.org/10.1145/3313831.3376657>.

WILLETT, W. et al. Perception! immersion! empowerment! superpowers as inspiration for visualization. **IEEE Transactions on Visualization and Computer Graphics**, v. 28, n. 1, p. 22–32, 2022.

APPENDIX A — USER STUDY - SOLO MODE: PRE-QUESTIONNAIRE



DeAR : User Study

This is a user study that aims the evaluation of the DeAR interface.

Faça login no Google para salvar o que você já preencheu. Saiba mais

* Indica uma pergunta obrigatória

Name: *

Sua resposta

Age *

Sua resposta

How many years have you used a data analysis tool? *

- ◯ 0
- ◯ 2 - 3
- ◯ 3 - 5
- ◯ More then 5

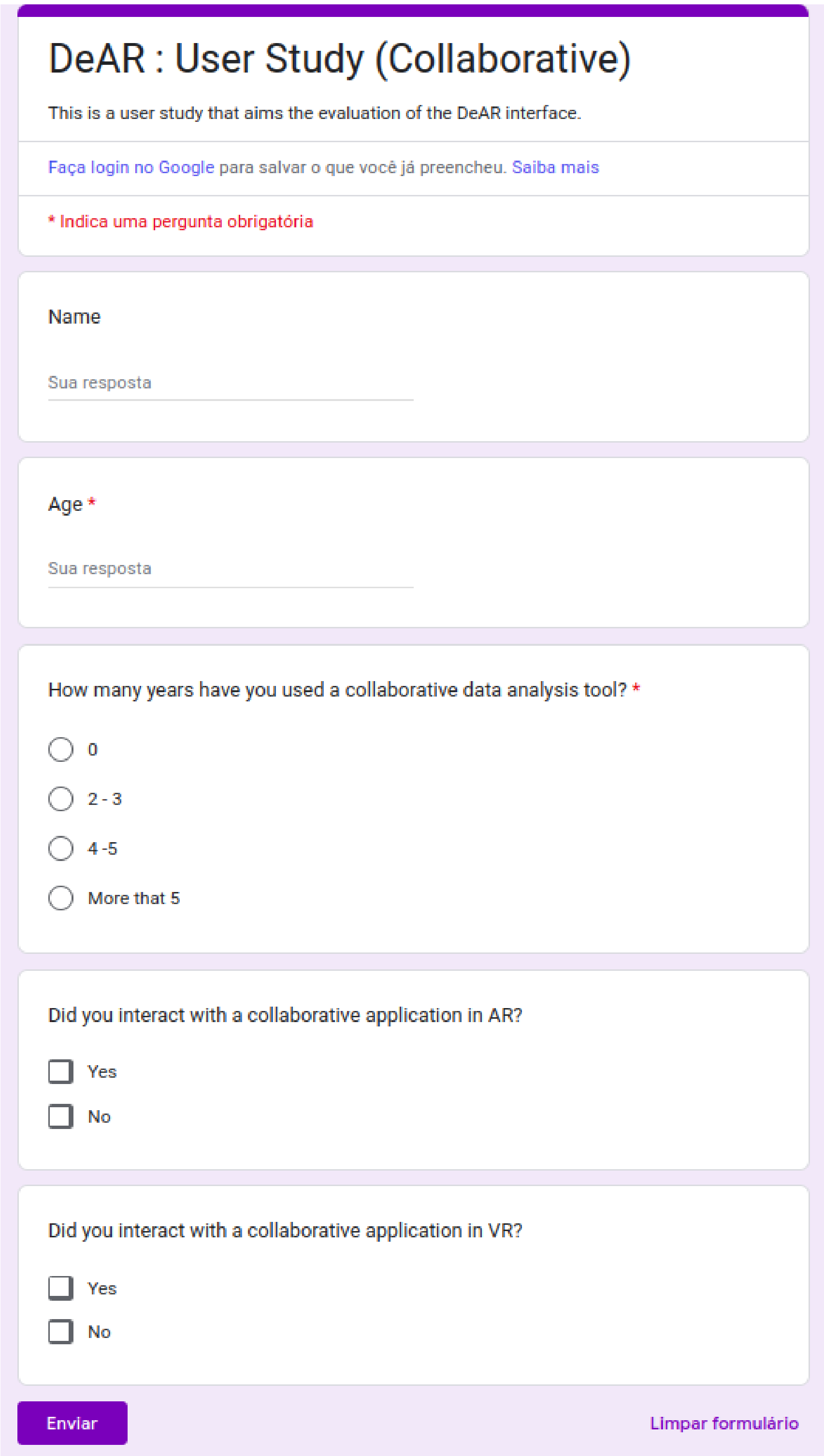
What is your experience in using Hololens? *

	1	2	3	4	5	
Beginner	◯	◯	◯	◯	◯	Expert

What is your experience with other HMDs? *

	1	2	3	4	5	
Beginner	◯	◯	◯	◯	◯	Expert

APPENDIX B — USER STUDY - COLLABORATIVE MODE: PRE-QUESTIONNAIRE



DeAR : User Study (Collaborative)

This is a user study that aims the evaluation of the DeAR interface.

Faça login no Google para salvar o que você já preencheu. Saiba mais

* Indica uma pergunta obrigatória

Name

Sua resposta

Age *

Sua resposta

How many years have you used a collaborative data analysis tool? *

- 0
- 2 - 3
- 4 -5
- More that 5

Did you interact with a collaborative application in AR?

- Yes
- No

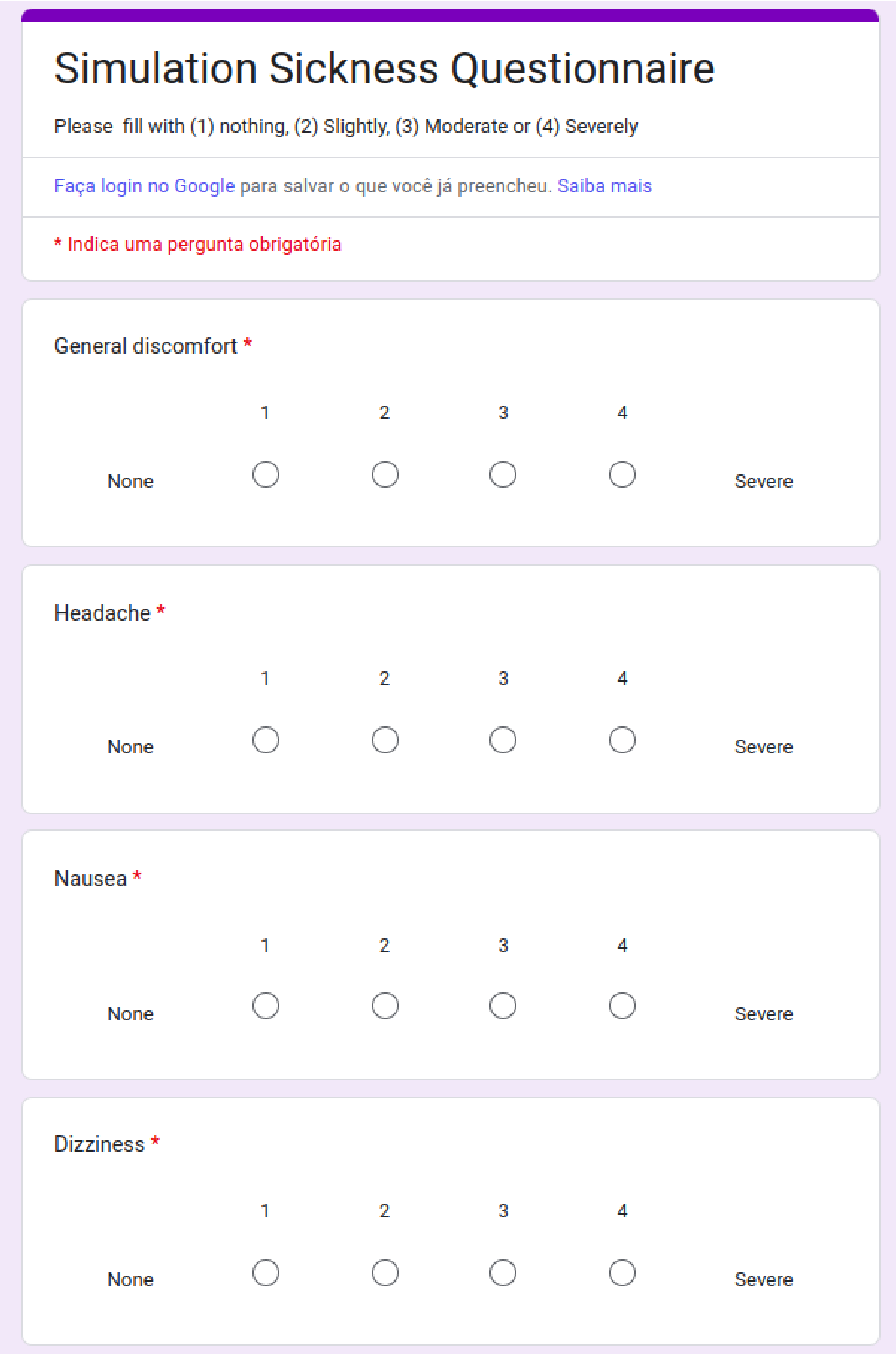
Did you interact with a collaborative application in VR?

- Yes
- No

Enviar

Limpar formulário

APPENDIX C — USER STUDY - SIMULATION SICKNESS QUESTIONNAIRE



Simulation Sickness Questionnaire

Please fill with (1) nothing, (2) Slightly, (3) Moderate or (4) Severely

Faça login no Google para salvar o que você já preencheu. Saiba mais

* Indica uma pergunta obrigatória

General discomfort *

	1	2	3	4	
None	◯	◯	◯	◯	Severe

Headache *

	1	2	3	4	
None	◯	◯	◯	◯	Severe

Nausea *

	1	2	3	4	
None	◯	◯	◯	◯	Severe

Dizziness *

	1	2	3	4	
None	◯	◯	◯	◯	Severe

APPENDIX D — USER STUDY - NASA TLX QUESTIONNAIRE

NASA TLX Questionnaire

Answer according to your experience with the task have just performed

Faça login no Google para salvar o que você já preencheu. Saiba mais

* Indica uma pergunta obrigatória

Mental Demand *

How much mental and percentual activity was required? Was the ask easy or demanding, simple or complex?

	1	2	3	4	5	
Low	○	○	○	○	○	Higth

Physical Demand *

How much physical activity was required? Was the task easy or demanding, slack or strenuous?

	1	2	3	4	5	
Low	○	○	○	○	○	Higth

Performance *

How successful were you in performing the task? How satisfied were you with your performance?

	1	2	3	4	5	
Low	○	○	○	○	○	Higth

Low ○ ○ ○ ○ ○ Higth

Temporal Demand *

How much time pressure did you feel due to the place at witch the tasks or task element ocurrend? Was the pace slow or rapid?

	1	2	3	4	5	
Low	○	○	○	○	○	Higth

Effort *

How hard did you have to work (mentally or physically) to accomplish you level of performance?

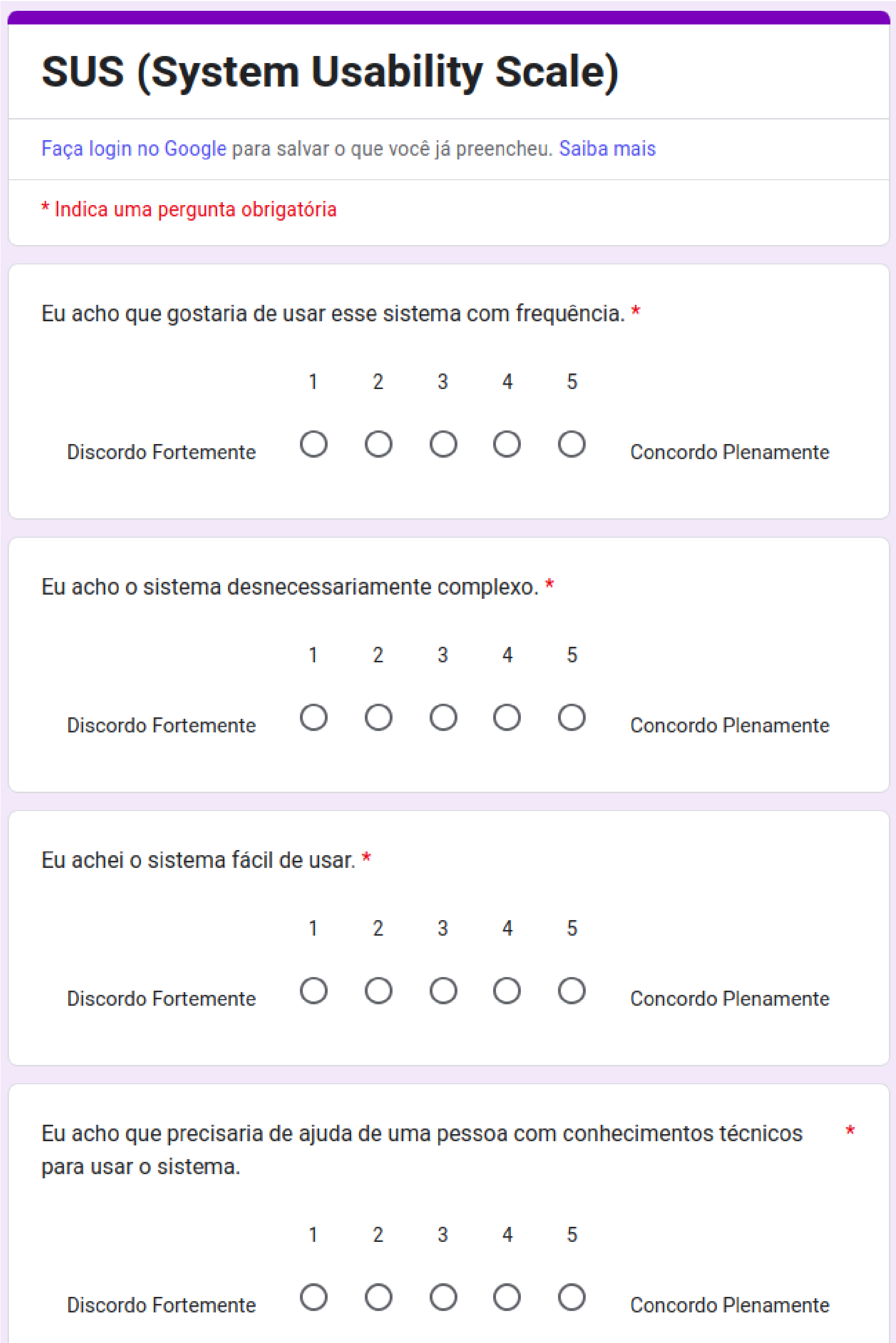
	1	2	3	4	5	
Low	○	○	○	○	○	Higth

Frustration *

How irritated, stresse, and anoyed versus content, relaxed, and complacent did you feel during the task?

	1	2	3	4	5	
Low	○	○	○	○	○	Higth

APPENDIX E — USER STUDY - SYSTEM USABILITY SCALE QUESTIONNAIRE



SUS (System Usability Scale)

Faça login no Google para salvar o que você já preencheu. Saiba mais

* Indica uma pergunta obrigatória

Eu acho que gostaria de usar esse sistema com frequência. *

	1	2	3	4	5	
Discordo Fortemente	○	○	○	○	○	Concordo Plenamente

Eu acho o sistema desnecessariamente complexo. *

	1	2	3	4	5	
Discordo Fortemente	○	○	○	○	○	Concordo Plenamente

Eu achei o sistema fácil de usar. *

	1	2	3	4	5	
Discordo Fortemente	○	○	○	○	○	Concordo Plenamente

Eu acho que precisaria de ajuda de uma pessoa com conhecimentos técnicos para usar o sistema. *

	1	2	3	4	5	
Discordo Fortemente	○	○	○	○	○	Concordo Plenamente

Eu acho que as várias funções do sistema estão muito bem integradas. *

	1	2	3	4	5	
Discordo Fortemente	○	○	○	○	○	Concordo Plenamente

Eu acho que gostaria de usar esse sistema com frequência. *

	1	2	3	4	5	
Discordo Fortemente	○	○	○	○	○	Concordo Plenamente

Eu acho que o sistema apresenta muita inconsistência. *

	1	2	3	4	5	
Discordo Fortemente	○	○	○	○	○	Concordo Plenamente

Eu imagino que as pessoas aprenderão como usar esse sistema rapidamente. *

	1	2	3	4	5	
Discordo Fortemente	○	○	○	○	○	Concordo Plenamente

Eu achei o sistema atrapalhado de usar. *

	1	2	3	4	5	
Discordo Fortemente	○	○	○	○	○	Concordo Plenamente

Eu me senti confiante ao usar o sistema. *

	1	2	3	4	5	
Discordo Fortemente	○	○	○	○	○	Concordo Plenamente

Eu precisei aprender várias coisas novas antes de conseguir usar o sistema. *

	1	2	3	4	5	
Discordo Fortemente	○	○	○	○	○	Concordo Plenamente

Enviar

Limpar formulário

APPENDIX F — USER STUDY PROPOSAL - CONSENT AND CONFIDENTIALITY TERMS

TERMO DE CONSENTIMENTO E CONFIDENCIALIDADE
isso no formulário do Google Forms

Pesquisadores responsáveis: Yhonatan Jesus Iquiapaza Ccama
Instituição: Universidade Federal do Rio Grande do Sul - UFRGS

Você está sendo convidado para participar, como voluntário, de um experimento com usuário para comparação da realização de atividades em realidade física e realidade aumentada.

Você pode a qualquer momento pedir esclarecimentos sobre a pesquisa, os métodos utilizados e os procedimentos do experimento (informações coletadas, armazenamento e uso das informações, pessoas responsáveis pela pesquisa, etc.).

Você também poderá parar de participar a qualquer momento apenas avisando o pesquisador sem sofrer qualquer tipo de penalidade ou prejuízo.

Após ler e tirar suas dúvidas sobre as informações a seguir, se aceitar participar da pesquisa, assine no final deste documento, que tem duas cópias. Uma delas é sua e a outra será arquivada pelo pesquisador responsável.

O que você precisará fazer nos testes:

1. Ouvir as instruções do pesquisador.
2. Realizar as tarefas de organização de informações.
3. Usar os óculos de realidade aumentada Microsoft HoloLens.
4. Evitar distrações durante a realização de cada tarefa.
5. Preencher questionários no final das tarefas.

Riscos que você corre ao participar da pesquisa:

1. Se irrita por ter que realizar tarefas que não gosta.
2. Se sentir desconfortável pelo uso dos óculos de realidade aumentada.

Participar dessa pesquisa não gera nenhum custo. Você também não receberá qualquer vantagem financeira.

Seu nome e outros dados serão mantidos em sigilo, e as informações coletadas na pesquisa serão guardadas pelos pesquisadores responsáveis. Os resultados poderão ser divulgados no texto do trabalho final da disciplina, em publicações ou outras formas de divulgação respeitando sempre o sigilo.

APPENDIX G — USER STUDY PROPOSAL - TESTING PROTOCOL

PROTOCOLO DE TESTES

1) (boas-vindas)

Obrigado, ______, por aceitar participar dessa pesquisa. Eu sou ______ , pesquisador responsável, e serei o facilitador desse teste que faremos agora.

Não há muitas pesquisas que relacionem o esforço para realizar uma tarefa usando materiais físicos e materiais digitais. Assim, nós queremos investigar qual dessas alternativas é melhor para realizar certas tarefas. Os testes dessa pesquisa envolvem realizar tarefas de organização de dados com materiais físicos e com óculos de realidade aumentada, e devem durar até xx minutos.

É necessário deixar claro: embora eu esteja chamando de teste, essa é uma avaliação do nosso sistema e não uma avaliação sua. Não há respostas certas ou erradas, então não precisa se preocupar. É o sistema que está sendo testado aqui, e não você.

2) (pesquisa)

O que eu vou falar agora não faz parte do teste. Eu vou apenas explicar como o teste vai funcionar. Você pode escolher não participar do teste e, mesmo que aceite, pode escolher parar de participar em qualquer momento. Você tem alguma dúvida?

Você precisará responder algumas questões no final de cada teste. Aqui estão os materiais que usaremos **[mostrar QUESTIONÁRIOS].**

Aqui também está o termo indicando que você aceita participar dessa pesquisa e que seus dados não serão revelados para ninguém. Apenas os pesquisadores terão acesso a eles. Você pode lê-lo se aceitar participar do teste. **[mostrar termos]**

Nós temos um ambiente de desktop **[mostrar o computador]** e um dispositivo de realidade aumentada **[mostrar o HoloLens]**. Ele é um produto comercial da Microsoft que pode ser comprado pela internet e que geralmente é usado em pesquisas e indústrias. Você conseguirá ver através dessas lentes e, ao mesmo tempo, verá objetos virtuais. Há alguns gestos que você pode usar para interagir com ele, mas falaremos disso em seguida.

Você tem alguma dúvida até agora?

Você aceita participar do teste?

3) (termo de consentimento e confidencialidade)

(aceita participar)

Ótimo! Você pode ler o termo de consentimento e de confidencialidade. Se estiver de acordo, pode assinar no final de duas cópias do termo. Uma dessas cópias ficará com você e outra conosco. **[aguardar assinatura e entregar termos]**

(se nega a participar)

Bem... obrigado pelo seu tempo. Estaremos à disposição se mudar de ideia ou se tiver qualquer dúvida sobre a pesquisa.

4) (tarefas em diferentes ambientes)

5) (exploração)

6) (questionários)

Lembra que eu mostrei a você alguns questionários? **[mostrar novamente QUESTIONÁRIOS]**

No final da realização das tarefas com os objetos físicos e com os objetos em realidade aumentada, você vai respondê-los em relação à experiência que acabou de ter. Certo?

7) (teste)

(ambientes desktop)

(ambientes AR com hololens)

(ambientes com os dois, desktop e AR)

(HoloLens)

8) (todos os testes terminados)

Terminado!

Agradeço muito sua ajuda nessa pesquisa! Esses dados irão nos ajudar a entender melhor a qualidade das tarefas realizadas em realidade física e realidade aumentada. Você ficou com alguma dúvida?

Estaremos à disposição se tiver qualquer dúvida sobre a pesquisa.

APPENDIX H — RESUMO EXPANDIDO

A maioria das ferramentas de Análise Visual de Dados na literatura foca em ambientes convencionais Desktop, onde interações via mouse e teclado são tipicamente usadas. Embora tais ferramentas possam ser extremamente eficientes para muitas tarefas analíticas, a natureza exclusivamente bidimensional tanto das interações quanto das exibições em ambientes Desktop pode, em alguns casos, dificultar a percepção de detalhes ou correlações que poderiam ser mais evidentes em uma visualização tridimensional dos dados. Hipotetizamos que o uso combinado de exibições convencionais e visualizações holográficas em Realidade Aumentada (RA) pode, portanto, ser útil em tais circunstâncias. Neste trabalho, propomos um novo protótipo para Análise Visual de Dados em Ambientes Híbridos, chamado *DeAR* (*Desktop + RA*, ou seja, combinando Desktop e Realidade Aumentada para Análise Visual de Dados).

O protótipo[1] desenvolvido para validar nossa Interface de Usuário Híbrida – DeAR (Combining Desktop and Augmented Reality) – é dividido em três componentes: o Ambiente Desktop, o Ambiente AR e o Servidor. O objetivo deste protótipo é facilitar tarefas de Análise Visual de Dados, que podem ser realizadas utilizando a interface desktop ou a interface AR através do Hololens. Ambas as interfaces podem ser utilizadas separada ou simultaneamente. Nosso protótipo foi implementado combinando diferentes tecnologias para aproveitar as vantagens de cada uma e compensar suas limitações individuais (HUBENSCHMID et al., 2021b).

No ambiente desktop, os participantes podem interagir exclusivamente com a tela do computador, utilizando teclado e mouse de maneira tradicional, com as visualizações disponíveis exclusivamente em 2D. Em contraste, o ambiente AR permite a interação exclusivamente através do Hololens, onde são apresentadas visualizações em 3D. O Ambiente Desktop e o Ambiente AR podem se comunicar através de um servidor via WiFi, utilizando o protocolo HTTP.

O DeAR é composto por diversos componentes, dois dos quais – o Ambiente Desktop e o Ambiente AR – foram desenvolvidos utilizando a engine de jogos Unity[2]. A Unity suporta nativamente o C#, uma linguagem de programação desenvolvida pela Microsoft e amplamente utilizada para o desenvolvimento de jogos, Realidade Virtual e Realidade Aumentada. O Ambiente Desktop foi criado sem o uso de bibliotecas ou frameworks adicionais, enquanto o Ambiente de Realidade Aumentada foi desenvolvido

[1] https://youtu.be/eOjx9yhL_Uk
[2] https://www.unity.com

com o auxílio do MRTK[3] (Mixed Reality Toolkit) v2.8. O MRTK facilita as interações com objetos 3D utilizando o Hololens.

Já o servidor foi implementado utilizando JavaScript com Node.js[4] e a biblioteca Express. Cada cliente pode renderizar gráficos de barras e diagramas de dispersão, juntamente com outras informações relevantes, desde que estejam em conformidade com o formato especificado e a extensão de arquivo (JSON) que utilizamos.

Os usuários interagem com vários tipos de visualizações e em diferentes ambientes. Para o **Gráfico de Barras**, os participantes podem engajar-se com as visualizações tanto no computador quanto com objetos 3D utilizando o Hololens. O mesmo se aplica ao **Diagrama de Dispersão**, onde os participantes têm a opção de interagir através da interface Desktop ou do ambiente de Realidade Aumentada.

Os dados utilizados em nosso protótipo são originários do Gapminder[5]. Esse conjunto de dados foi empregado anteriormente em outros trabalhos significativos relacionados à Visualização da Informação (e.g., ROBERTSON et al. e BREHMER et al.). A extração dos dados foi realizada por meio dos logs gerados no ambiente Desktop e dos logs do ambiente de Realidade Aumentada utilizando o Hololens. Além disso, registramos o desempenho de todo o experimento utilizando o Hololens e coletamos feedbacks por meio de questionários administrados ao final do experimento.

Implementamos as técnicas de interação mais comuns para os usuários, conforme explorado em diversos trabalhos anteriores. Por exemplo, no ambiente Desktop, os participantes utilizam o teclado e o mouse, de maneira similar à maioria das ferramentas de Análise de Dados. No ambiente de Realidade Aumentada, focamos exclusivamente em interações por gestos manuais, que são a forma mais natural de engajamento. Ao interagir com ambos os ambientes, os participantes não estão restritos a uma localização fixa; eles podem se movimentar livremente para explorar todo o espaço (WANG et al., 2020).

Para uma validação inicial de nosso protótipo, discutimos dois cenários de uso que demonstram como nosso design apoiaria tarefas comuns de visualização integrando visualizações 2D e 3D dos dados. No primeiro cenário, um analista usa o *DeAR* para interagir com duas visualizações diferentes (gráfico de barras e de dispersão), uma em uma tela convencional e a outra vista como um holograma tridimensional. No segundo cenário, dois participantes trabalham juntos, realizando tarefas similares, mas colaborando de forma assimétrica, cada um interagindo com um paradigma de visualização

[3]https://github.com/microsoft/MixedRealityToolkit-Unity
[4]https://nodejs.org/en
[5]https://www.gapminder.org/

diferente.

Também apresentamos um design de experimento que permitirá uma avaliação controlada de nossa interface em um futuro estudo com usuários. Propusemos uma série de tarefas para tal avaliação e apresentamos os questionários mais adequados a serem usados.

Nossa principal contribuição neste trabalho foi o design e a implementação de um protótipo de prova de conceito para interação com dados em ambientes híbridos (*DeAR*) combinando interfaces/exibições heterogêneas. Uma contribuição adicional foi o design do experimento para um estudo com usuários avaliando o desempenho de ambientes híbridos usados por um único participante ou por múltiplos participantes colaborativamente.