Building a Prototype for Easy to Use Collaborative Immersive Analytics

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Abstract. The increase in the size and complexity of today's datasets creates a need to develop and experiment with novel data visualization methods. One of these innovations is immersive analytics, in which extended reality technologies such as virtual reality headsets are used to present and study data in virtual worlds. But while the use of immersive analytics dates back to the end of the 20th century, it wasn't until recently that collaboration in these data visualization environments was taken in consideration. One of the problems currently surrounding this field is the lack of availability of easy to use cooperative data visualization tools that take advantage of the modern, easily attainable head mounted display virtual reality solutions. This work proposes to create an accessible collaborative immersive analytics framework that users with low virtual reality background can master, and share, regardless of platform. With this in mind, a prototype of a visualization platform was developed in Unity3D that allows users to create their own visualizations and collaborate with other users from around the world. Additional features such as avatars, resizable visualizations and data highlighters were implemented to increase immersion and collaborative thinking. The end result shows promising qualities, as it is platform versatile, simple to setup and use and is capable of rapidly enabling groups to meet and analyse data in an immersive environment, even across the world.

Keywords: Immersive Analytics · Data Visualization · Virtual Reality · Immersive Environments· Immersive Collaboration

1 Introduction

With the establishment of the importance of data in today's world, which is increasing in size and complexity, it became necessary to create new ways to visualize and analyse it [9]. Immersive analytics is one of the areas that brings forward novel visualization and interaction models to the area of data visualization and analytics.

Immersive Analytics (IA), as defined by Dwyer *et al.*, is "the use of engaging, embodied analysis tools to support data understanding and decision making".

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Its goal is to allow the user to close the distance between himself and the data through the use of virtual environment technologies [15].

The increasing demands of large and multidimensional datasets are also making it unfeasible for a single expert to be able to tackle the analysis of large quantities of data. It has become necessary to create multidisciplinary teams with varying areas of expertise and even using different methodologies to solve problems when using these large datasets. This created new challenges in data visualization, such as determining how to present the data to different users, how to allow simultaneous data manipulation by multiple users, or how to let users socialize, among other challenges [22].

Research has proven that groups of people collaborating perform better in a variety of tasks than when alone, producing more accurate results [21]. Immersion also has a positive impact in user performance when used for collaboration [30]. Unsurprisingly, a collaborative immersive environment brings these benefits to the area of data analytics [3].

While immersive analytics is a research topic that is garnering interest, collaboration has yet to be well studied. Since there is a clear benefit in using collaboration to aid immersive data visualization, it should be easier for everyone to have access to this resource, in an easy-to-use package.

Furthermore, several immersive analytics experts (such as Chandler *et al.* [9], Hackatorn and Margolis [19], and Skarbez *et al.* [35], to cite a few) have pointed out that a huge research opportunity is the integration of collaboration in IA, creating Collaborative Immersive Analytics (CIA). Nowadays, with millions of people required to work from home, being able to "meet" with colleagues in an immersive environment to discuss, analyse and solve problems is welcoming.

To achieve this, an extension of an open-source immersive data visualization tool to include collaboration capabilities is proposed. The goal is to allow two or more users (immersed or not) to share a virtual environment where they can discuss a common data visualization of their choice. In addition, creating this visualization and setting up the virtual environment should be accessible to those not well versed in Virtual Reality (VR)/Data Visualization (DataViz).

This resulted in the implementation of a Unity3D framework that built upon the capabilities of the already existing DXR [34], by integrating it into a client-server room-based network handled by PHOTON PUN. User avatars were also implemented, alongside interaction tools that promote collaboration and data exploration. The expected contributions of this work are manifold. First off, the resulting research gap analysis from the state-of-the-art in CIA. Second, a proposed design for a CIA framework. And last, a prototype for easy to use CIA.

The remainder of this document is structured as follows: Section 2 explores some of the most recent related work in this field; Section 3 presents the proposed solution, the chosen technologies and the system architecture; Section 4 details the design choices and development of the prototype; Section 5 demonstrates how the platform can be used for collaborative immersive analytics and outlines the design of the user studies; and finally, Section 6 concludes the document and presents the plans for future work.

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2 Literature Review

The field of immersive collaboration is extensive, as it can be applied to many areas. This literature review starts with an overview of some of these areas, followed by a study of a collection of immersive analytics frameworks, and ending with a review of works related to this project.

2.1 Collaboration in Immersive Environments

The study of collaboration in immersive environments has been expanding in the past few years, with the number of areas taking advantage of this concept in virtual environments rising.

Education in one of such areas that fits perfectly to incorporate collaboration, as the act of teaching is in itself collaborative. This led to the creation of immersive worlds where students can see and experience things they wouldn't otherwise be able to, like the virtual Neurorobotics Lab created by Matthes *et al.* [29]. Zikky *et al.* were able to take students to a trip through the solar system. Their platform also opens the possibility for teachers and students to meet when far away and can accommodate larger class sizes [39].

Collaborative content creation is an area that faces a lot of challenges, especially not stepping on the work of other users. This is also true in immersive environments and is what Xia *et al.* worked on. They presented 3 new interaction concepts, which together give single users more powerful editing tools and groups of users less friction between them [37]. The work of Pereira *et al.* presents a generalized framework for collaboration in immersive environments [32].

Interestingly, another area gaining traction for immersive collaboration is human-robot interaction. Training robots to collaborate with human beings can be dangerous, and thus immersive simulations were created to allow humans and machines to collaborate safely during testing. The work by Matsas *et al.* [28] and de Giorgio *et al.* [18] are perfect examples of what immersive cooperation can achieve in this area.

2.2 Immersive Analytics Frameworks

Frameworks capable of generating many different types of 2D and 3D data visualizations for flat screens exist for quite some time. Sometimes mentioned as visualization authoring tools, these tools have evolved to become both easy to use and powerful, with Protovis [4], D3 [5] and Vega-Lite [33] being examples of notable ones. However, only recently frameworks made specifically for immersive analytics have emerged.

These frameworks facilitate the creation of this type of visualization by providing users with the tools required to present information efficiently and legibly, but without the necessary knowledge and effort associated with implementing them from the ground up.

Chronologically, the first example found of this kind of frameworks is Glance, from 2016 by Filonik *et al.*. It focused on providing dynamic representations of

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multidimensional data using geometric primitives and transformations. While pioneering in this area, this framework lacks the capability to easily be integrated in other works, something the more recent ones possess [17].

On the other hand, the first VR framework dedicated to data visualization and analysis was ImAxes in 2017 by Cordeil *et al.* [11]. It is based on the abstraction of data into physical axes that the user can grab and combine to create data visualizations. With this, the user can create 2D and 3D scatter plots as well as parallel coordinate plots, without interacting with any menus. The authors also noted that this level of physicality in the environment and interactions is advantageous for collaborative analysis, as physical cues like "gesticulation, passing, personal and shared spaces" facilitates collaboration, making it more instinctive. ImAxes was later used as the basis for a user study in 2020, in which participants were only asked to explore a dataset, and produced interesting results [2]. Of note, they found that legibility and fatigue weren't a problem, even for 60 minute sessions, and that users rarely moved, preferring to stay in place and work around them.

In 2019, three additional frameworks were presented that expanded on the concept of ImAxes, further simplifying the process of creating immersive data visualizations, even for those who are not proficient in the area. Once again, Cordeil *et al.* [10], and Sicat *et al.* [34] created toolkits for the Unity3D game engine called AITK (Immersive Analytics ToolKit) and DXR (Data visualization applications for eXtended Reality), respectively. Both were designed to work in virtual and mixed reality environments and accept common CSV (Comma-Separated Values) files as data input. The major difference between the two is that IATK is made specifically to visualize and analyse graphs, while DXR is more open to the type of data representation, but doesn't include the same interactive tools for data analysis that IATK has.

The last studied framework was developed upon the WebVR specification to run in web browsers. Like the previous two, VRIA utilizes a CSV file for input data and is restricted to 3D visualization of graphs like scatter plots and bar charts. User tests revealed that while subjects took longer to perform the given analysis tasks, they felt more engaged in the task at hand [7].

2.3 Related Work

The presented works focus on the collaborative immersive analytics projects that make use of Head Mounted Displays (HMD), since this is the technology that will be used for this work. The first example, authored by Donalek *et al.*, dates to 2014 and used the then recent Oculus Rift DK1. They started by using OpenSimulator, an open-source platform for sharing immersive environments. A data plot was then added through the platform's scripting language. This concept was then replicated in Unity3D to add more advanced features. This work showed it was possible to create good immersive visualizations that can be used with much cheaper hardware than the previously used CAVE systems [13].

Two year later, in 2016, Cordeil *et al.* presented a couple of immersive solutions for air traffic controllers. The first one situated the user in a virtual

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remote air traffic controller. The second one allowed air traffic experts located in distant sites to meet in a virtual environment where they can study flight trajectories together. The users' position is shared through the use of avatars, they can point and select paths as well as filter them, features that contribute to the collaboration between users [12].

A different approach to collaborative immersive analytics was presented by Butscher *et al.* in 2018. Instead of relying in a virtual environment, cameras in the front of the HMD capture the real world to create an augmented reality. This was used in conjunction with a touch-sensitive tabletop for user input. A 3D parallel coordinates visualization placed on top of the interactive table allowed the users to analyse multidimensional data [8].

A similar approach was presented by Ens *et al.* in 2020, in the form of the system called Uplift, which also uses a tabletop display in conjunction with augmented reality HMDs [16]. This project focused on accessibility and ease of use and targets scenarios of collaboration in quick bursts. Where this approach sets itself apart is in the interaction methods, provided by "tangible widgets". These are objects that are tracked in space, and which users can manipulate to modify the presented visualizations, thus increasing accessibility, engagement, as well as promoting collaboration through shared visualization controls.

A distinct solution for collaborative immersive analytics was researched by Sun *et al.* in 2019, by using a large, wall-sized display where various users can gather to collaborate while using OST-HMDs (Optical See-Through Head-Mounted Displays) [36]. While this implementation of CIA is similar to the two previous ones, the researchers introduced a new concept: giving different users distinct levels of access to information. Information displayed on the wall is open to all users, but it is supplemented with information each user can only see through his HMD. To promote collaboration, the users must verbally request information controlled by other users. The authors noted that in an initial phase, users tend to work alone, and progressively started collaborating as time went by, when they realised they required additional information.

The remainder of the reviewed literature dates from 2019, showing that a new interest in this topic has again emerged, probably due to the easy access to new generation, inexpensive HMDs. The first of these works was developed by Nguyen *et al.* and explores the visualization of multidimensional data using Star Coordinates and Star Plot graphs. The users can interact with the data simultaneously, and are represented by avatars to show what they are doing and improve social connectivity. Data analytics tools are also provided to the users to help them create decision trees as "a way to visualise the data in a top-down categorical approach", facilitating data analysis [31].

Another interesting project was the work of Bailey *et al.*. They developed a prototype to visualize microscopy data in virtual reality to which multiple users could join. While the main focus of the work is visualizing the microscopy data, they also spent some effort in implementing embodiment features such as full body avatars and personalized user faces. Interaction was handled through

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"physical" toggles (instead of a 2D Graphical User Interface (GUI)), such as switches and sliders, that the user can interact with his own hands [1].

The final reviewed work is FIESTA, a system for collaborative immersive analytics created by Lee *et al.*. It focuses on giving the users freedom to utilize the virtual space as they see fit, like creating visualizations and position them as they please. Several users can do this at the same time in the same room and then visually and verbally communicate their insights with each other. This system focuses on creating a shared, immersive data analysis environment for teams to present and discuss data through the use of several conventional 2D/3D visualizations like scatter plots [26].

A year later, in 2020, the authors conducted a user test based on the framework to ascertain collaborative performance with different visualization types [25]. One of the conclusions was that users usually start by creating individual work zones and only later join together to share their thoughts and findings. During this initial phase users engaged in "territorial" behaviour, by isolating in their zones and not using visualizations that were not created by them.

In conclusion, the works by Donalek *et al.*, Nguyen *et al.*, Butscher *et al.* and Ens *et al.* present platforms which take advantage of 3D space and immersion to present data in a novel way to groups of people collaborating. This means that with these systems, the user has a limited choice of type and number of visualizations. This is especially true for the systems presented by Cordeil *et al.* and Bailey *et al.*, which were designed to visualize a specific type of data (flight trajectories and microscopy images, respectively). The FIESTA project by Lee *et al.* gives the users freedom to create as many visualization as they wants and arrange them afterwards in a collaborative, shared environment. It also simplifies the data input process, since the visualizations are generated by IATK [10]. However, it is currently limited to 2D and 3D scatterplots and the authors have not made it open-surce, like many of the other similar frameworks such as DXR, IATK and ImAxes.

3 Proposed Solution

As mentioned in Section 1, the objective is to create a CIA framework more approachable to users such as researchers and scientists. The analysed state of the art shows that a solution that combines freedom of visualization choice and ease of use is not available. The proposed solution is to create an immersive environment for modern VR HMDs that allows the user to input his data and visualization styling and collaborate with other users in the same virtual space.

3.1 Technology Choices

As the majority of the mentioned projects in Section 2, this solution will be build on top of the Unity3D game engine. Other alternatives such as Unreal Engine don't offer the same quantity and variety of community developed tools useful for this project. Unity3D enables the use of existing tools made specifically for

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VR that suit this implementation, as detailed below. It will also allow authoring the project for a plethora of client devices' hardware and software combinations.

Before implementation, it is necessary to choose the tools that will give shape to the solution. The first decision is what framework to use to create the visualizations. Several options presented in Section 2.2 are suitable, although only three of them are open-source and ready to integrate in Unity3D: ImAxes [11], DXR [34] and IATK [10]. ImAxes was first rejected, as it provided poor customization support and visualization type variety. As mentioned previously, IATK and DXR are very similar in approach, but thanks to its superior visualization style diversity, better documentation and additional support for both AR and VR HMDs, DXR was chosen. Additionally, it was designed to strike a good balance between the ease of use for inexperienced users and the flexibility in creating data visualizations, akin to Vega-Lite [33].

To interface with VR in Unity3D the VRTK[1] toolkit was used. It provides seamless integration and runtime switching of the most popular VR Software Development Kits (SDKs), and many premade scripts for locomotion and interaction. It also includes VRSimulator, making it possible for users without a VR headset to also join the immersive environment through the desktop and interact with other users. A potential alternative would be OpenVR, although it's lack of desktop emulator and closed-source nature contradict the ethos of this solution. Additionally, VRTK is activly supported by the community.

Lastly, a network framework capable of making two or more users share a virtual location and interact with each other synchronously was necessary. Two popular networking Unity3D free add-ons are currently widely regarded: Mirror and PHOTON PUN[2]. Mirror is based on UNET, the stock Unity3D networking solution, and is designed to accommodate large scale networks with several clients connected to one host (server). On the other hand, PHOTON PUN is designed around smaller lobbies that the users find through a central server hosted by PHOTON. Subsequent traffic is also handled by the central PHOTON server. While Mirror is regarded to be more scalable, the simplicity of PHOTON PUN lobby centered design and in the cloud central server simplifies between user remote connection and lobby sharing. For these reasons PHOTON was chosen as the network backbone of this solution.

3.2 System Architecture

PHOTON PUN works in a client-server model, with a central server hosted by PHOTON to which different Unity3D instances can connect via an AppID. Users can join different rooms, but for the purpose of this prototype they will all connect to the same one, as seen in Fig. 1. The first user to connect is the one to instantiate the visualization, becoming its master.

When it comes to the individual instances, VRTK is the glue that connects all the other modules together. It is responsible for handling the virtual reality hardware SDKs, which in turn are responsible for presenting the user with

[1] More information available online at `https://vrtoolkit.readme.io/v3.3.0`

[2] More information available online at: `https://www.photonengine.com/pun`

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the visualization and gathering the required user data such as the headset and controllers' position. This information is then used to update the user's avatar position. VRTK also manages the interactions with the data visualization, which is externally created by DXR. PHOTON's client is responsible for updating the data visualization and user avatars in the server, and receiving the updates from the other users. This architecture can be visualize in Fig. 2.

4 Implementation

Margery *et al.* set the base level of cooperation in virtual environments at the ability of being able to see other users and communicate with them [27]. Subsequently, the first development step was to create a virtual scene that two or more users can share simultaneously and be able to visualize each other's presence.

To achieve this, PHOTON PUN was used to create the necessary network infrastructure, which consists of a client-server architecture hosted in PHOTON's cloud, allowing users to join the visualization. When a user joins, a representation of the headset and hand controllers is created. This simplified avatar follows the movements of the user in the 3D space, which are then shared with the other connected users via the PHOTON connection with the *Photon View* and *Photon Transform View* scripts.

When it came to integrating the data visualization component into the developed system, a couple of design considerations had to be weighted, based on the state-of-the-art work presented before, in Section 2. The first one was related to the amount of visualizations available for the users to share. All but one of the referenced contributions focus on presenting only one. FIESTA, the collaborative immersive analytics framework developed by Lee *et al.*, is the only one that enables multiple visualizations, with specific features for tracking visualization ownership. While a departure from previous contributions, it encourages

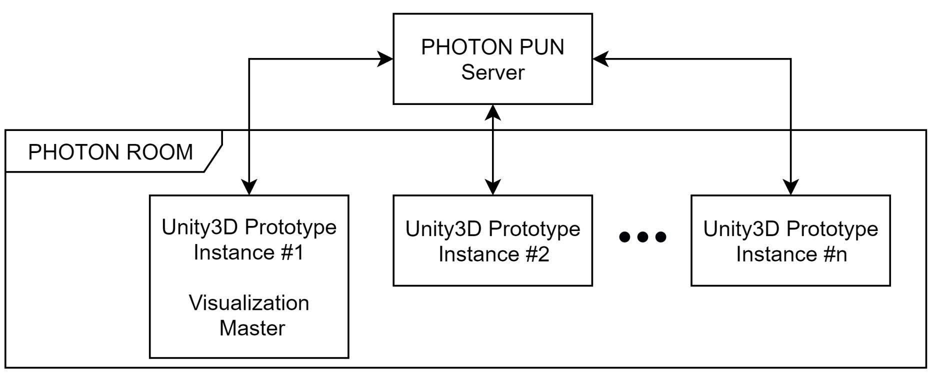

Fig. 1: Integration of PHOTON PUN client server architecture to enable collaboration between users.

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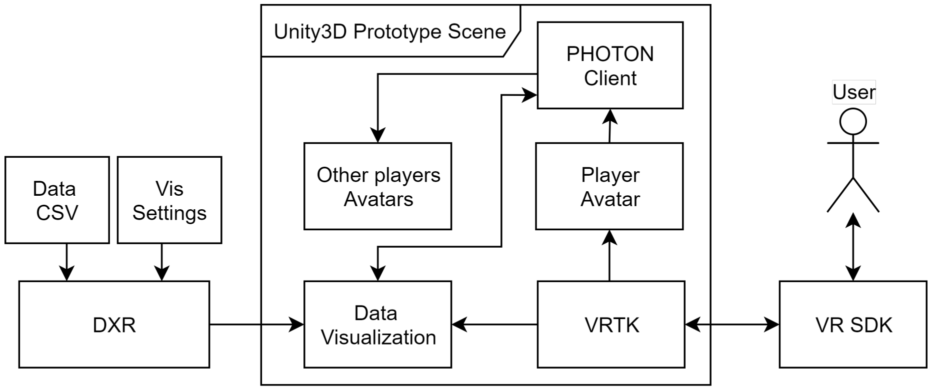

Fig. 2: Architecture of the proposed visualization scene.

the users to seclude from each other and work alone, defeating the purpose of enabling collaboration.

The second consideration was the size of the visualization. All the presented papers use visualizations with small sizes, that can be seen as a whole by the user without moving his head. As explored by Yang *et al.* [38] and Kraus *et al.* [24], this size of visualization is more often advantageous when compared to room scale ones. However, both authors agree that this style of visualization is regarded by the users as the most immersive and engaging. Since both visualization sizes have different strong points, it is up to user to decide which one to use.

One of the example visualization in DXR was then imported to the scene as a prefab. The visualization is instantiated by the first user to join the room, which at this point becomes the visualization master. In the current prototype iteration only the visualization master of an object can manipulate it, to avoid having to deal with synchronization problems. Despite this limitation, the master can grab the visualization and position it in any orientation and scale it up or down by grabbing with both hands.

In the context of collaborative analytics, simply sharing the visualizations and presenting them to other users is not enough. One of the most important aspects of visualization collaboration is guaranteeing that all users share a common ground, i.e., the shared information is perceived the same way by all the participants, eliminating any possible ambiguities [20]. Through PHOTON, it is already guaranteed that the visualization is viewed equally by all, but when discussing individual data points it might become hard to convey which one is being referenced. To prevent this and help the users indicate which part of the visualization is being discussed, a pointer and highlighter interaction was developed and added to the prototype. The user can use the HMD hand controller to point a laser that selects the intersected data point on the visualization, highlighting it and showing its information to that user. To the other users sharing the visualization, this selected data point will be highlighted, preventing uncertainties when discussing specific data points.

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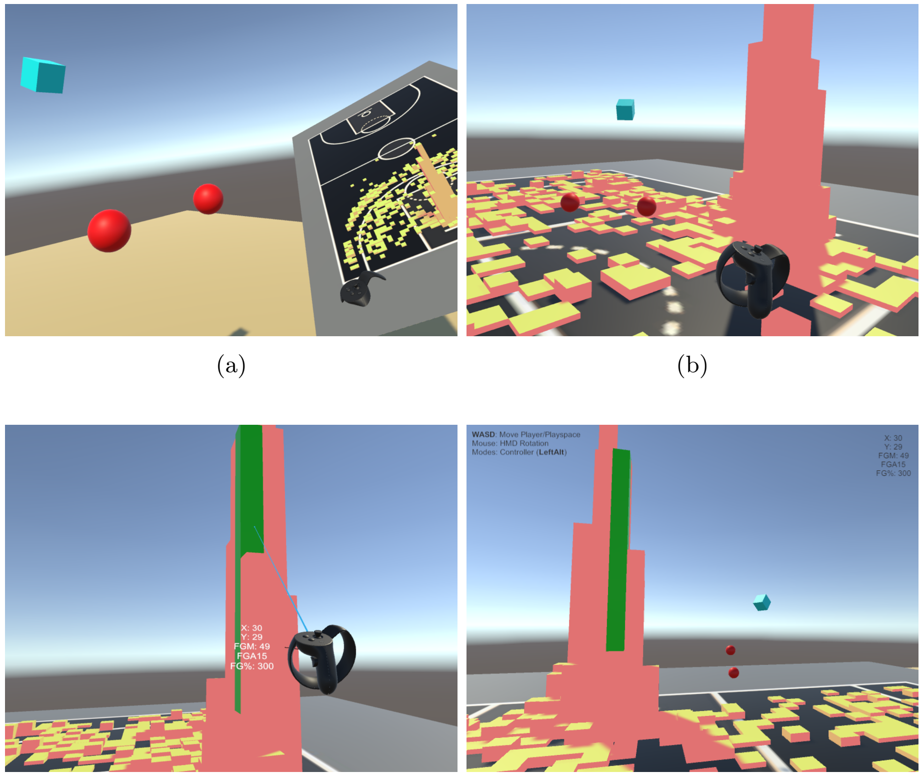

(a) (b)

(c) (d)

Fig. 3: Two users sharing an immersive environment and analysing data. Figure (a) shows one user grabbing the visualization and orienting it towards the other user; In Fig. (b) the users share the same visualization, but scaled up; In Fig. (c) the user is highlighting a specific data point, which the other user in Fig. (d) can also see as being highlighted.

5 Prototype Testing

To test the developed functionalities, a virtual environment was created with a simplified version of an example visualization created with DXR. For this test, two instances of the prototype were executed side by side in the same machine. The first instance (the master of the visualization) used an Oculus Rift CV1 with Oculus controllers while the second instance used the keyboard and mouse to control a virtual VR system through the built-in VR Simulator in VRTK, with similar functionality to the real HMD.

As can be seen in Fig. 3a, both users can see each other's avatar, allowing them to know where they are and where their hands are pointing to. The participants can then gather around the visualization and the master can manipulate it to provide a better view. To obtain a more immersive data visualization, it can be scaled up, turning the play area into the visualization itself, as shown in Fig. 3b. Using the controllers, the users can point to a specific data element, highlighting it to the other viewer, as depicted in Figs. 3c and 3d.

Being in a immersive environment with nothing but the data and other users increases attention and engagement. Additionally, a big difference in immersion is felt when using an enlarged visualization rather than a small one. Having the data surrounding the users creates a feeling of being inside or part of the visualization. It is also much easier for users to have a meaningful discussion about the data, thanks to the ability to ”travel” to the area of interest. Aiming the pointer to highlight specific data points also becomes easier due to the increased size of the data points.

The following test scenarios have been projected to evaluate the implemented features in this prototype:

a) *Immersive Collaboration with Interactions*: Immerse a team of people in the visualization and task them with finding specific insight from it. The users have access to all the developed tools, such as avatars and highlighter.
b) *Immersive Collaboration without Interactions*: The same as the previous one, but the users don't have access to the developed tools.
c) *Regular Collaboration*: The same as scenario a), but using conventional data analytics visualization tools.
d) *Single User*: The same as scenario a), but with a team of only one person.

For all these tests the teams will be evaluated by the same performance metrics. These include time to complete tasks, correctness of the answers and number of interactions by type. To evaluate the amount of collaboration both verbal communication time and amount of shared focus time can be used.

In the end, questionnaires will be handed out to the participants to gather their opinions on the prototype, their preferences and perceived immersion and level of collaboration. This includes the Simulator Sickness Questionnaire (SSQ) [23] and System Usability Scale (SUS) [6], which are commonly used in this field. A less acknowledged questionnaire, developed by Dupont *et al.*, will also be used. It was especially designed to evaluate immersive and collaborative performance in applications using Immersive Collaborative Environments [14].

6 Conclusion and Future Work

An immersive data analytic environment was created that allows users to collaborate in analysing information using modern virtual reality HMD technology. By showing a representation of the position of the other participants a greater sense of immersion and cooperation is given to the users. The inclusion of a data highlighting system also aids the collaborative discussion process. Furthermore, the use of DXR and PHOTON PUN to create the visualization and shared virtual space, respectively, contributes to the main objective of creating an immersive collaborative workspace in which it is simple to input data, change visualization

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styles and setup the necessary networking, even for remote scenarios. This work also helps further extend the state-of-the-art of this growing field.

The developed work stands as a prototype that can now be expanded into a fully fledged visualization tool. Before implementing other features, the user tests detailed above will be carried out. Afterwards, it is crucial to add a verbal communication system to complement the already implemented positional communication through the avatars. Subsequently, more data interaction tools must be added, such as filtering, creation of clusters and providing statistical analysis tools on those clusters. Furthermore, a new networking architecture could be integrated to bypass the restrictions of ownership and manipulation of the visualization, to further increase cooperation. Finally, implementing an asynchronous collaboration system is worthy of consideration, as it is currently even more under-researched than synchronous CIA.

References

1. Bailey, B.J., Lilja, A., Strong, C., Moline, K., Kavallaris, M., Hughes, R.T., McGhee, J.: Multi-user immersive virtual reality prototype for collaborative visualization of microscopy image data. In: The 17th International Conference on Virtual-Reality Continuum and Its Applications in Industry. VRCAI '19, Association for Computing Machinery, New York, NY, USA (2019)
2. Batch, A., Cunningham, A., Cordeil, M., Elmqvist, N., Dwyer, T., Thomas, B.H., Marriott, K.: There is no spoon: Evaluating performance, space use, and presence with expert domain users in immersive analytics. IEEE Transactions on Visualization and Computer Graphics **26**(1), 536–546 (2020)
3. Billinghurst, M., Cordeil, M., Bezerianos, A., Margolis, T.: Collaborative immersive analytics. In: Immersive Analytics, chap. 8, pp. 221–257. Springer International Publishing (2018)
4. Bostock, M., Heer, J.: Protovis: A graphical toolkit for visualization. IEEE Transactions on Visualization and Computer Graphics **15**(6), 1121–1128 (Nov 2009)
5. Bostock, M., Ogievetsky, V., Heer, J.: D^3 data-driven documents. IEEE Transactions on Visualization and Computer Graphics **17**(12), 2301–2309 (Dec 2011)
6. Brooke, J.: Sus: A 'quick and dirty' usability scale. In: Usability Evaluation In Industry, pp. 189–194. Taylor & Francis, first edn. (1996)
7. Butcher, P.W.S., John, N.W., Ritsos, P.D.: Vria - a framework for immersive analytics on the web. In: Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems. CHI EA '19, Association for Computing Machinery, New York, NY, USA (2019)
8. Butscher, S., Hubenschmid, S., Müller, J., Fuchs, J., Reiterer, H.: Clusters, trends, and outliers: How immersive technologies can facilitate the collaborative analysis of multidimensional data. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems. CHI '18, Association for Computing Machinery, New York, NY, USA (2018)
9. Chandler, T., Cordeil, M., Czauderna, T., Dwyer, T., Glowacki, J., Goncu, C., Klapperstueck, M., Klein, K., Marriott, K., Schreiber, F., Wilson, E.: Immersive analytics. In: 2015 Big Data Visual Analytics (BDVA). pp. 1–8 (Sep 2015)
10. Cordeil, M., Cunningham, A., Bach, B., Hurter, C., Thomas, B.H., Marriott, K., Dwyer, T.: Iatk: An immersive analytics toolkit. In: 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR). pp. 200–209 (March 2019)

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77961-0_50

11. Cordeil, M., Cunningham, A., Dwyer, T., Thomas, B.H., Marriott, K.: Imaxes: Immersive axes as embodied affordances for interactive multivariate data visualisation. In: Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology. pp. 71–83. UIST '17, ACM, New York, NY, USA (2017)
12. Cordeil, M., Dwyer, T., Hurter, C.: Immersive solutions for future air traffic control and management. In: Proceedings of the 2016 ACM Companion on Interactive Surfaces and Spaces. p. 25–31. ISS '16 Companion, Association for Computing Machinery, New York, NY, USA (2016)
13. Donalek, C., Djorgovski, S.G., Cioc, A., Wang, A., Zhang, J., Lawler, E., Yeh, S., Mahabal, A., Graham, M., Drake, A., et al.: Immersive and collaborative data visualization using virtual reality platforms. 2014 IEEE International Conference on Big Data (Big Data) (Oct 2014)
14. Dupont, L., Pallot, M., Christmann, O., Richir, S.: A Universal Framework For Systemizing the Evaluation of Immersive And Collaborative Performance. In: ACM (ed.) VRIC '18: Virtual Reality International Conference - Laval Virtual. Laval, France (Apr 2018)
15. Dwyer, T., Marriott, K., Isenberg, T., Klein, K., Riche, N., Schreiber, F., Stuerzlinger, W., Thomas, B.H.: Immersive analytics: An introduction. In: Immersive Analytics, chap. 1, pp. 1–23. Springer International Publishing (2018)
16. Ens, B., Goodwin, S., Prouzeau, A., Anderson, F., Wang, F.Y., Gratzl, S., Lucarelli, Z., Moyle, B., Smiley, J., Dwyer, T.: Uplift: A tangible and immersive tabletop system for casual collaborative visual analytics. IEEE Transactions on Visualization and Computer Graphics (2020)
17. Filonik, D., Bednarz, T., Rittenbruch, M., Foth, M.: Glance: Generalized geometric primitives and transformations for information visualization in ar/vr environments. In: Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry - Volume 1. p. 461–468. VRCAI '16, Association for Computing Machinery, New York, NY, USA (2016)
18. de Giorgio, A., Romero, M., Onori, M., Wang, L.: Human-machine collaboration in virtual reality for adaptive production engineering. Procedia Manufacturing **11**, 1279 – 1287 (2017), 27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017, 27-30 June 2017, Modena, Italy
19. Hackathorn, R., Margolis, T.: Immersive analytics: Building virtual data worlds for collaborative decision support. In: 2016 Workshop on Immersive Analytics (IA). pp. 44–47 (March 2016)
20. Heer, J., Agrawala, M.: Design considerations for collaborative visual analytics. Information Visualization **7**(1), 49–62 (2008)
21. Hill, G.W.: Group versus individual performance: Are n+1 heads better than one? Psychological Bulletin **91**(3), 517–539 (1982)
22. Isenberg, P., Elmqvist, N., Scholtz, J., Cernea, D., Ma, K.L., Hagen, H.: Collaborative visualization: Definition, challenges, and research agenda. Information Visualization **10**(4), 310–326 (2011)
23. Kennedy, R.S., Lane, N.E., Berbaum, K.S., Lilienthal, M.G.: Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. The International Journal of Aviation Psychology **3**(3), 203–220 (1993)
24. Kraus, M., Weiler, N., Oelke, D., Kehrer, J., Keim, D.A., Fuchs, J.: The impact of immersion on cluster identification tasks. IEEE Transactions on Visualization and Computer Graphics **26**(1), 525–535 (2020)
25. Lee, B., Hu, X., Cordeil, M., Prouzeau, A., Jenny, B., Dwyer, T.: Shared surfaces and spaces: Collaborative data visualisation in a co-located immersive environment. IEEE Transactions on Visualization and Computer Graphics pp. 1–1 (2020)

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26. Lee, B., Cordeil, M., Prouzeau, A., Dwyer, T.: Fiesta: A free roaming collaborative immersive analytics system. In: Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces. p. 335–338. ISS '19, Association for Computing Machinery, New York, NY, USA (2019)
27. Margery, D., Arnaldi, B., Plouzeau, N.: A general framework for cooperative manipulation in virtual environments. In: Gervautz, M., Schmalstieg, D., Hildebrand, A. (eds.) Virtual Environments '99. pp. 169–178. Springer Vienna, Vienna (1999)
28. Matsas, E., Vosniakos, G.C., Batras, D.: Prototyping proactive and adaptive techniques for human-robot collaboration in manufacturing using virtual reality. Robot. Comput.-Integr. Manuf. **50**(C), 168–180 (Apr 2018)
29. Matthes, C., Weissker, T., Angelidis, E., Kulik, A., Beck, S., Kunert, A., Frolov, A., Weber, S., Kreskowski, A., Froehlich, B.: The collaborative virtual reality neurorobotics lab. In: 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR). pp. 1671–1674 (March 2019)
30. Narayan, M., Waugh, L., Zhang, X., Bafna, P., Bowman, D.: Quantifying the benefits of immersion for collaboration in virtual environments. In: Proceedings of the ACM Symposium on Virtual Reality Software and Technology. p. 78–81. VRST '05, Association for Computing Machinery, New York, NY, USA (2005)
31. Nguyen, H., Ward, B., Engelke, U., Thomas, B., Bednarz, T.: Collaborative data analytics using virtual reality. In: 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR). pp. 1098–1099 (March 2019)
32. Pereira, V., Matos, T., Rodrigues, R., Nóbrega, R., Jacob, J.: Extended reality framework for remote collaborative interactions in virtual environments. In: 2019 International Conference on Graphics and Interaction (ICGI). pp. 17–24 (2019)
33. Satyanarayan, A., Moritz, D., Wongsuphasawat, K., Heer, J.: Vega-lite: A grammar of interactive graphics. IEEE Transactions on Visualization and Computer Graphics **23**(1), 341–350 (2017)
34. Sicat, R., Li, J., Choi, J., Cordeil, M., Jeong, W., Bach, B., Pfister, H.: DXR: A toolkit for building immersive data visualizations. IEEE Transactions on Visualization and Computer Graphics **25**(1), 715–725 (Jan 2019)
35. Skarbez, R., Polys, N.F., Ogle, J.T., North, C., Bowman, D.A.: Immersive analytics: Theory and research agenda. Frontiers in Robotics and AI **6**, 82 (2019)
36. Sun, T., Ye, Y., Fujishiro, I., Ma, K.: Collaborative visual analysis with multi-level information sharing using a wall-size display and see-through hmds. In: 2019 IEEE Pacific Visualization Symposium (PacificVis). pp. 11–20 (2019)
37. Xia, H., Herscher, S., Perlin, K., Wigdor, D.: Spacetime: Enabling fluid individual and collaborative editing in virtual reality. In: Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology. p. 853–866. UIST '18, Association for Computing Machinery, New York, NY, USA (2018)
38. Yang, Y., Cordeil, M., Beyer, J., Dwyer, T., Marriott, K., Pfister, H.: Embodied navigation in immersive abstract data visualization: Is overview+detail or zooming better for 3d scatterplots? IEEE Transactions on Visualization and Computer Graphics (2020)
39. Zikky, M., Fathoni, K., Firdaus, M.: Interactive distance media learning collaborative based on virtual reality with solar system subject. In: 2018 19th IEEE/ACIS International Conference on Software Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing (SNPD). pp. 4–9 (June 2018)

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