10 Years of Operating a Center with Large-Scale Virtual-Reality Installations - Developments and Learnings

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Abstract

Virtual Reality (VR) can be found in many fields including art history, education, research, and industry 4.0. Next to lightweight Head-Mounted Displays there are also VR installations, such as immersive 3D screens, large-scale displays, and CAVE systems, that are used in research, scientific visualization, and also the automotive industry. These systems offer high visual quality and collaborative VR experiences for researchers and have long been used in research. We present learnings and insights from ten years of operating and maintaining a visualization center with large-scale immersive displays and installations. Our report aims to answer questions on the benefits and challenges of such a location-based VR center. We broke down the ten years into three

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This is the author's final version, which has been accepted for publication in Massachusetts Institute of Technology PRESENCE: Virtual and Augmented Reality (2024) 33: 405–423, https://doi.org/10.1162/pres_a_00431

phases and discuss the installations themselves, software, and other various developments of the center over time, illustrated with exemplary use cases. Finally, we cover our experiences at the beginning of phase four with the installation of a (novel) LED CAVE and the future (forward-looking) developments we expect for location-based VR centers.

1 Introduction

Virtual Reality (VR) has found application in many different fields (Komianos, 2022; Mantovani et al., 2003; Martín-Gutiérrez et al., 2017) and has proven to be a useful tool in research (Bryson, 1996). It has also been adopted in Scientific Visualizations (SciVis), as it offers numerous opportunities for viewing data (Bryson, 1996) and helps viewers understand the results of simulations (Danyluk et al., 2020; Theart et al., 2017; Walton et al., 2021).

Bryson et al. defined VR in SciVis as a system that needs to be head-tracked and usually stereoscopic (Bryson, 1996); it needs a high-performance computer graphics system to deliver images and an option for user interaction. This applies not only to lightweight Head-Mounted Displays (HMDs) but also to large immersive display systems such as the CAVE (Cruz-Neira et al., 1992). Immersive systems offer a different viewing experience to an HMD and their advantages include the ability to collaborate with other researchers in the same room, high-quality displays and immersive as well as interactive experiences. Their limitations however are that they are fixed to one location and typically are cost-intensive.

We present findings and report on our experiences of supervising a visualization center with large-scale immersive displays for ten years. The center was created to offer researchers access to such VR installations. The goal of this paper is to examine the long-term use of the visualization center for virtual reality and present our learnings, thus providing empirical knowledge to research teams who are about to establish a similar facility as well as the centers using other types of large-scale immersive displays. This report illustrates the typical use cases and the operational aspects, advantages, and disadvantages of the long-term use of our center, and aims to fill a gap in the existing VR literature. Augmented Reality devices or topics will not be covered in this paper. We address the following questions:

- **Q1:** What are the benefits and challenges of using a location-based visualization center (with large-scale immersive displays) for research?
- **Q2:** What are the lessons learnt from operating such a center for ten years?
- **Q3:** What is the future of such a center?

The paper is structured as follows: We first lay the groundwork on VR in science and research with a focus on large-scale immersive displays and different use cases. We present learnings from ten years of operating a visualization center with large-scale visual displays, including benefits, structure, hardware, software, usage, team composition, and responsibilities. Following this we discuss the benefits and challenges of such a center as well as the limitations. Finally, we conclude with a reflection and an outlook into the future of location-based VR centers.

2 Related Work

In this section, we outline the fundamentals of VR in research and present an overview of large-scale immersive displays. We subsequently examine use cases and detail a typical VR workflow.

2.1 Virtual Reality in Science

VR has found many areas of application, including art history (Komianos, 2022), education (Martín-Gutiérrez et al., 2017), medicine (Claudio & Maddalena, 2014), and research and scientific visualization (SciVis) (Bryson, 1996). VR refers to an immersive, interactive, multi-sensory, viewer-centered, 3D computer-generated environment (Onyesolu & Eze, 2011). Here not only hardware, like HMDs are used but also other immersive devices like large-scale 3D projection installations (Anthes et al., 2016).

Researchers were initially wary of using immersive displays and VR (Chen, 1999; Duval et al., 2014; Laramee et al., 2014). However, e.g., Duval et al. concluded that an immersive 3D display helps gain better insight into the data due to "the innate human capability to recognize and reason with 3D information" (Duval et al., 2014). Researchers discovered that VR provided unique and effective ways to learn and that it proved to be highly motivating to learners (Mantovani et al., 2003). Specifically the interactive aspect of VR overcame the boundaries between viewers and computer displays (Onyesolu & Eze, 2011). VR in SciVis can be defined by a few components (Bryson, 1996):

- A head-tracked, usually stereoscopic display
- A computer system that delivers images
- The option for user interaction through an input device that allows the users to provide input into the system

Both HMDs and immersive displays with their respective input devices fulfill these conditions. Visualization and especially SciVis is the art of interpreting data for many scientific problems (Van Dam et al., 2000) and various fields have accepted it as a key to insight and understanding of complex data. VR lets researchers analyze data even more efficiently. Laha et al. performed a study examining performing a task in different VR environments and SciVis: they found that stereoscopic and high quality of the visualization had the strongest effects on task performance (Laha et al., 2014). When directly comparing data exploration in VR to traditional 2D data visualization, Millais et al. found that the increased feeling of immersion with VR reduced the perceived workload and increased satisfaction of participants (Millais et al., 2018).

2.2 A Snapshot of Large-Scale Immersive Displays

With the current developments of HMDs by large tech companies e.g., Meta (Meta, 2023), the devices have become more user friendly and affordable and they have become a popular tool for

VR (Anthes et al., 2016). And while HMDs can offer individual VR experiences and provide advantages as being affordable and transportable, this paper focuses on large-scale immersive displays. The original CAVE that was built and designed by Cruz-Neira et al. can be described as one of the most iconic (Cruz-Neira et al., 1992): it is a room-scale cube that uses rear projection onto the walls to display a virtual world and a top projection for the floor. A major advantage of this system was the ability to collaborate in person, since a small group of people could be in the installation at a time. A majority of modern CAVEs use back-projection to generate the immersive space.

Already in 1993 there were many use cases for CAVE systems in research, as these offered a “strong sense of immersion and participation in the environment” (Cruz-Neira et al., 1993). Use cases included, but were not limited to, visualizations of galaxies, human anatomy, molecular dynamics, and weather phenomena. What defines a CAVE or CAVE-like-system is a room-scale area (not necessarily a cube), many use projection, that offers users an immersive experience with head-tracking for at least one user. However there are different types of CAVEs too (Muhanna, 2015). Muhanna defined the difference between different large-scale immersive systems as follows: CAVEs are fully immersive room-based systems, whereas Powerwalls encompass non-room-based, partially immersive installations (Muhanna, 2015). There have been developments to the CAVE system concept, such as the StarCAVE (DeFanti et al., 2009), which was comprised of five walls with floor projection using 15 rear-projected wall displays.

Cruz-Neira et al. also created an “affordable surround-screen virtual reality display” to combat the high costs of a standard CAVE system (Cruz-Neira et al., 2010). This system only had three walls and used low-cost commercial systems but had an omni-directional treadmill at the center of the installation. However, this system required frequent recalibration of the projectors due to the structure holding up the walls. There are also large-scale immersive displays such as Powerwalls or InfinityWalls (Czernuszenko et al., 1997). These walls are a combination of multiple displays with stereo options and optionally tracking of six degrees of freedom. Currently, there are a few visualization centers using immersive display systems. As of writing this paper, these systems generally have four walls and are rear-projected[1,2,3].

2.3 Use Cases and Effects of CAVE Systems

Large-scale immersive experiences can not only be found in the field of research but also in entertainment (Mine, 2003). This report on ten years of using large-scale immersive theatre by Mine showed the advantages it offered for teamwork when creating entertainment experiences (Mine, 2003). In 1993, Cruz-Neira et al. reported on fields such as architecture, astrophysical, fractal, molecular, and weather visualizations using the CAVE (Cruz-Neira et al., 1993). They state that these are only a few of the science areas that could benefit from a CAVE, but such a system requires a simple input device for user navigation and interaction with the visualizations. In a study conducted in 2004, it was indicated that using a CAVE with head tracking and four sides deepened the feeling of immersion compared to using just one wall (with or without head tracking) (Raja et al., 2004). In 2014 Laha et al. performed a study comparing HMDs and CAVE systems, however there were no significant differences in the level of immersion. Here, the CAVE users could see their own bodies, whereas with HMDs they had no bodies and no reference to the outside world (Laha et al., 2013). Harvig et al. looked at CAVEs and HMDs more critically and examined their advantages and disadvantages (Havig et al., 2011). While HMDs were smaller, portable, and inexpensive, they isolated users and users could become tangled with the cabling. On the other hand, CAVEs are much larger, offer high resolution and a physical room where multiple users can enjoy the experience, however their cost and scale are demanding, as well as them being location-based.

There have also been approaches to CAVE visualizations in other fields like geophysics (Billen et al., 2008) and medicine (Jadhav, Shreeraj and Kaufman, Arie E., 2022). Tcha-Tokey et al. examined the user experiences in a CAVE compared to an HMD using an edutainment application (Tcha-Tokey et al., 2017): In the CAVE participants felt more presence, more user engage-

[1] CAES's CAVE-like system
[2] HLRS's CAVE
[3] Villanova's CAVE

ment, more state of flow, higher perceived skill, better user judgment, and fewer negative consequences like cybersickness. In 2017, Cordeil et al. examined a collaborative experience with Powerwall compared to an HMD (Cordeil et al., 2017). Here two participants per installation (where one participant in the Powerwall didn‘t have head tracking) were examined in speed and user experience. They found that the HMD was faster compared to the Powerwall team and user experience was felt similarly in both. In a further study comparing a (four-sided) CAVE and an HMD (Juan & Pérez, 2009), the CAVE raised the users' feeling of presence.

3 The Visualization Center

This section will focus on the visualization center and its development over time. We will provide a description of the requirements for the center, the installations, and how the operation of the center has changed over the years.

The center was intended to provide access to immersive VR installations to researchers from various universities. As the center was planned and built between 2010 and 2012, at this time HMDs were not as widespread and commercially available for individual consumers as today. Therefore, the visualization center was built around the idea of providing large-scale immersive installations for various scientific use cases.

In essence, two requirements had to be met in the form of two installations, that needed to support stereoscopic displays and user tracking:

- A system designed for medium-sized groups similar to a 3D cinema
- A CAVE-like system for high immersion but mainly focused on a single tracked user with the option of further untracked users

In order to accommodate these installations an interior space with a size of 11 $m \times 11$ $m \times 12$ m was provided. The building is equipped with air conditioning to provide a stable temperature and a controlled environment. The two installations are situated next to one another (see Figure 1).

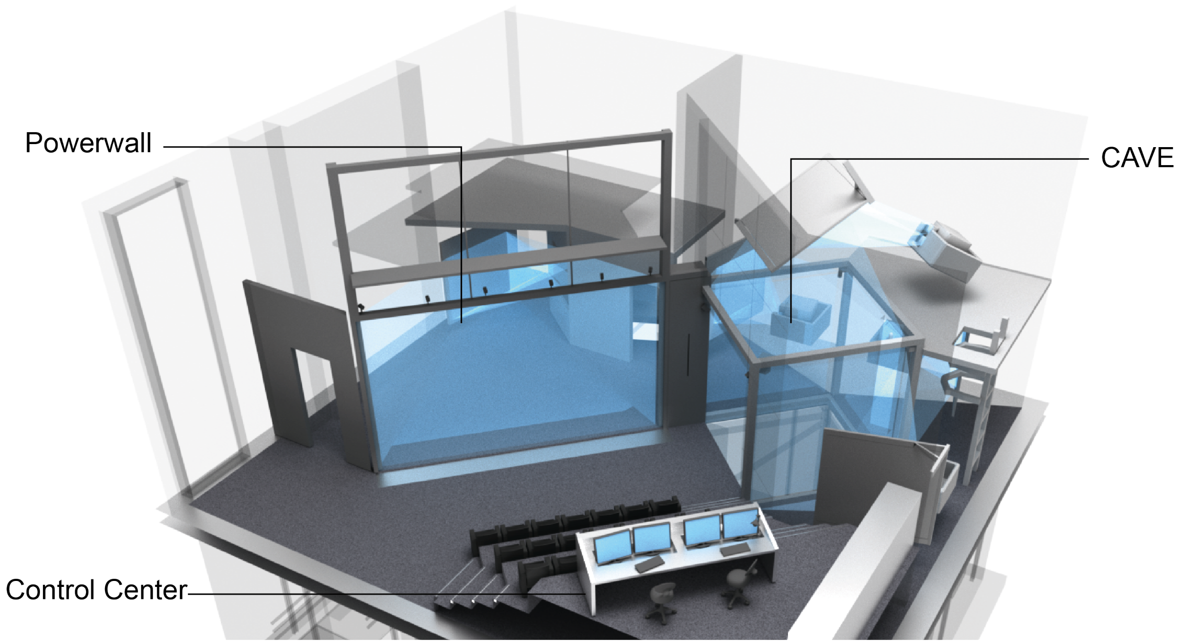

Figure 1: Layout of the visualization center with the Powerwall (left) and the CAVE (right).

The first requirement, an immersive installation for medium-sized groups, was covered by the installation of a *Powerwall*. The planar projection surface has a size of 6 $m \times 3.15$ m and the projectors have a resolution of 4096×2160 $pixels$. Due to the constraints of transmission rate, the Powerwall is divided into four quadrants, each driven by a separate input. Stereoscopy is achieved via polarization filters and passive stereo-glasses. For seating, 21 cinema-style seats are provided and the Powerwall is equipped with an optical tracking system.

The *CAVE* is comprised of five walls with a size of 2.7 $m \times 2.7$ m each, forming a cube with one side open. Each wall is projected onto by two active stereo projectors, achieving an overall resolution of 1920×1920 $pixels$ per wall. For each wall one projector covers the top half and a second projector the lower half of the wall and a seamless blending zone is created between the projectors as well as a crossfade on hardware side. Tracking is done similarly to the Powerwall with an optical system and four cameras located in the corners near the ceiling of the CAVE. Even though the perspective in the CAVE is only tracked for a single user, the construction allows for up to five people to enter the CAVE at once to support a collaborative experience.

Table 1: Overview of the different phases during our ten years of operating a visualization center.

	Phase 1	**Phase 2**	**Phase 3**
Duration	2012-2014	2014-2017	2017-
Hardware	CAVE, Powerwall	CAVE, Powerwall	CAVE, Powerwall, LED-Powerwall
Software	RTT Deltagen, Amira, OpenSG, Drishti	Equalizer, OpenSG, In-house libraries, Magnum Engine, ParaView, Amira, COVISE	In-house library, Open Source Game Engine, COVISE
Example Project	Prototyping tool for Geoscience fields Science Domain: Multiple	Visualizing Convection Streams Science Domain: Geophysics	Visualizing Rainfall in Bavaria Science Domain: Climatology, Hydrology

Due to the size of the projections for both installations and the size of the room, we worked with mirrors to shorten the projection path (see Figure 1).

The installations are supported by a compute cluster for image generation, as well as a media control system, both being located in the basement below the visualization center with rack servers with Nvidia Quadro GPUs and 100GBit/s network for communication within the cluster as well as the externally. The installations themselves can be controlled via the control panel situated opposite the installations (see Figure 1 bottom left corner). For the majority of the applications both installations use a 6DOF input device called a wand. However, it is possible to use other input devices additionally.

Our report covers the ten years of operations, starting from 2012 until 2022. We have broken this decade down into three phases (see Table 1). In our description of each individual phase, we cover a hardware and software snapshot as well as our default workflow for the timeframe outlined with an exemplary project of the phase. Lastly, there is a summary of the phase and changes that were made during the transition to the next phase.

3.1 Phase 1

Phase 1 took place from 2012 to 2014 and marked the beginning of the visualization center. In order to keep maintenance and development times low and to provide a stable service from the beginning, the focus during this phase was less on software development and more on operating commercial software solutions. Two proprietary, commercial products were mainly used: RTT

Deltagen[4] (now: 3DExcite Deltagen), and Amira[5]. At that time most users were not familiar with the intricacies of VR methods, so the team was only involved in the data visualization process in an advanced stage of the projects. Either data were pre-processed with specialized software by the domain scientists providing the data and then imported as a geometric model into RTT Deltagen for immersive display or datasets could be converted into a visual representation with the standard visualization methods provided by Amira. While, in both cases, the team had to accept the restrictions the proprietary software imposed, these applications allowed to support a number of visualizations, some of which also served as presentation material to advertise our VR services amongst the local scientific community.

In parallel, the scene graph library OpenSG (Reiners et al., 2002a) - with an additional tool to manage distributed rendering, the CAVE Scene Manager[6], developed by Adrian Haffegee (Haffegee et al., 2005) - was installed and adapted as a base for custom application development. At this early stage a few VR projects already used the installations as a platform for displaying their visualizations but research in the field of VR was not a focus of the team of the visualization center during this phase.

3.1.1 Phase 1 Hardware and Software Snapshot

During this phase, the workstations were run as dual boot systems providing Windows (Windows 7) and Linux (SLES). The Windows OS was necessary for the following reasons:

- RTT Deltagen, which was the preferred viewer in phase 1, was only available for Windows.
- The Linux stereo display setup for the Powerwall caused problems for some applications, reducing the software portfolio.

Due to the less restrictive licensing and the cost of commercial software solutions, open-source software like OpenSG was considered for further development (see Table 1). The use of open-source software was the driving factor behind the installation of a Linux OS.

[4]https://www.3ds.com
[5]https://www.thermofisher.com/
[6]http://dev.invrs.org/documents/14

3.1.2 Phase 1 Example Project: Prototyping Project for Geo-Sciences

Phase 1 Project From 2011 to 2015, we collaborated with a prototyping project aimed at creating a prototype e-Science environment to give meteorologists, hydrologists, and earth science experts access to data and models in order to facilitate collaboration and provide data management, High-Performance Computing (HPC) and postprocessing services. As visualization is crucial for understanding and communicating HPC simulation results, an immersive visualization of an extreme weather event that had been successfully modeled was developed. Here a multi-model approach under the Meteorological Model Bridge (MMB) was prepared for the CAVE: the 2011 flash flood that hit Genova and the surrounding region (Hally et al., 2015). The result was presented at an informal workshop in 2014 in order to familiarize the group with the possibilities of immersive visualization.

Phase 1 Workflow The datasets provided consisted of climate data on a 1 km and 5 km grid covering 24 hours in 48 timesteps, with each timestep containing $475 \times 475 \times 83$ data points. Rain, snow, sleet, and accumulated precipitation on the ground were chosen for visualization. The format was WRF NetCDF which is a variant of NetCDF with special conventions. AmiraVR was chosen as a software tool, as it provided standard visualization tools like isosurface generation. But due to its focus on Life Science applications it showed some deficits when handling geospatial data. In addition to problems reading the provided WRF files there was no built-in support to provide coordinates for the grid points (that WRF logically organizes as a rectilinear grid) following the earth's curvature. IDL therefore was chosen for preprocessing, i.e., calculating elevation as geopotential height, determining coordinates on the basis of a Bessel reference ellipsoid, and converting the datasets to AmiraVR format. This was only due to the fact that the WRF NetCDF files of this project could instantaneously be imported into IDL, which saved time. In AmiraVR isosurfaces of three levels were prepared for the values of rain, snow, and sleet for every timestep and presented as an animation. Isosurfaces for other values could have been created on demand during the session, which is one of the advantages of scientific visualization software over a presentation software or game engine. Nevertheless it is advisable to prepare an extract of the most interesting parts of user data for a fluent presentation.

3.1.3 Phase 1 Summary

During phase 1 it was vital to gather experiences concerning different aspects of running a visualization center. Up until that point the team had run a smaller projection device - a so-called "Holobench" (Van Treeck et al., 2009) - for VR applications before, but the large number of components in the new center resulted in a high complexity of the system. Problems included the occasional hardware failures, which were often enough even difficult to diagnose for the technical personnel of the vendor, but also the time it took handling the CAVE or Powerwall.

As to software, this phase was dominated by commercial products. More than 50% of our projects were realized with RTT Deltagen in phase 1, followed by AmiraVR. At that time a number of vendors offered a VR add-on to their packages, but as large projection installations typically are custom-built products, VR software cannot be regarded as "off-the-shelf" and even on-site amendment by the vendor was sometimes necessary. After having overcome the initial obstacles, quite a number of models could be transferred into VR presentations successfully. Especially for RTT Deltagen we provided a template for the import of user models to simplify positioning and adapt proportions. With commercial software however, the user is always restricted to the available range of functions, limiting especially how interaction with and navigation in the model can be achieved. It was clear that customized applications were desired but could only be achieved by in-house development, which led to a change in the approach in phase 2.

Another lesson learnt was that being involved in a project from an early stage as it allows influence on the choice of data formats and pre-processing steps. This is why in this phase it was especially important to popularize our service among local researchers. As a consequence a number of group events with demonstrations of applications took place, where we learnt to handle medium-sized groups. For example, we prepared walk-through camera paths with a time limit per person and used scripts to automatize preparation steps for the installations.

3.2 Phase 2

By 2014 the user base had grown and expanded into additional science domains, which caused the commercial software systems to become a limiting factor. Amira and RTT Deltagen could no longer provide the flexibility, support the variety of data formats, and handle the size of datasets demanded by the users. ParaView and COVISE[7] were too limited in their functionality and could not satisfy the needs for our users. As such, with the beginning of phase 2 the visualization team moved away from commercial software solutions and towards developing custom visualizations to meet the users' demands.

At first these applications were mainly based on third-party libraries like OpenSG and Equalizer (Eilemann, 2013) to handle the multi-display installations and the size of the datasets. In addition, a member of the visualization team started developing custom libraries to provide the flexibility required for the visualization projects. Two libraries were created to cover two functionalities: One library was created to provide a simple synchronization mechanism for the multi-display installations, the other was responsible for loading, managing, and rendering of large-scale datasets. These two libraries allowed us to tailor the visualizations to the users' datasets and their visualization needs. As these libraries were extended and adapted depending on various project requirements, they eventually became the software predominantly used for visualization and the use of other third-party libraries was phased out.

The workflows during phase 2 started out similar to phase 1: Datasets were preprocessed and, if necessary, simplified to a format that could be used for a VR visualization. Contrary to phase 1, the visualization was then not loaded into some commercial software, but rather integrated into a custom software application tailored to the domain scientists' requirements. During this phase the added software development and the tailoring of software solutions meant a larger time investment, which was offset by the quality and usability of the resulting visualizations. The close communication with the domain scientists often proved challenging, as their custom terminology and specialized expectations as well as datasets required not only additional time investment but

[7] https://www.hlrs.de/de/loesungen/rechentypen/visualisierung/covise

also research and development to solve the specialized issues. This resulted in the staff members of the visualization center transitioning from being service providers to conducting their own research into VR, visualization, and user interaction.

The project that initially sparked the move towards custom development was the visualization of convection streams for geophysics (see Phase 2 Example Project: Visualization of Convection Streams), but the workflow was subsequently adapted for a number of other projects (e.g., a project in the materials science field, see Phase 2 Additional Projects).

3.2.1 Phase 2 Hardware and Software Snapshot

In this phase, development was done on the Linux operating system, with Windows considered legacy for continued support of phase 1 projects. As for the software, the visualization team had developed some custom in-house libraries (see Table 1) and used some additional external software, e.g., COVISE.

3.2.2 Phase 2 Example Project: Visualization of Convection Streams

Phase 2 Project This project stems from the domain of geophysics and visualizes the temperature distribution within Earth's mantle over the course of about 200 million years (see Figure 2). A large-scale dataset had been produced by running a simulation on a supercomputer that contains the time-varying data. The geophysicists required a VR visualization that would allow them to interactively explore their data in detail and in real-time as well as smoothly play the entire duration contained in the simulation data as an animation sequence. The established workflows and software could not fulfill these requirements. Therefore, this was the project that triggered the exploration of new workflows and custom application development (Wiedemann et al., 2015).

Phase 2 Workflow The workflow started out similarly to phase 1 with a preprocessing step of the data. As the raw simulation dataset was a large, complex volumetric dataset that wasn't suitable for real-time visualization due to its size, we pre-computed simplified isosurfaces from the

Figure 2: A user in the CAVE interacting with the visualization of convection streams within the Earth's mantle for a project of geophysics.

dataset. While this visualization initially used OpenSG, this was changed due to the requirements and size of the data. Contrary to phase 1, however, we started developing a custom binary data format and software library, that allowed us to optimize the data storage and implement efficient streaming of the data to graphics memory. Implementing the loading and managing of the data ourselves allowed us to create more complex 3D data for each timestep without compromising performance. The result is a highly detailed, interactive visualization of the data.

With the widespread and affordable availability of HMDs in 2016 (Anthes et al., 2016), we also started to port our libraries to support the newly surfacing ecosystem. The long-term goal was to not limit ourselves to the large-scale installations in the visualization center, but to be able to easily port our visualizations to the HMDs.

3.2.3 Phase 2 Additional Projects

As for the use of external software is the MrSymBioMath project (Krieger et al., 2017), in the genomics field (2013-2017). This explored the use of cloud and HPC resources to study genomic data. The project took place during the transition between phases 1 and 2, and used Eyescale Equalizer[8] to drive the multi-display visualization. As part of the project, three commonly-used 2D visualizations in the genomics community (dot plot, gradient view, and linear representation) were combined into free-floating 3D objects in the CAVE. At the time of the project it was considered a novel idea to simulaneously use the CAVE walls as 2D screens and project data in the CAVE space. This allowed for 2D views and the 3D object to co-exist.

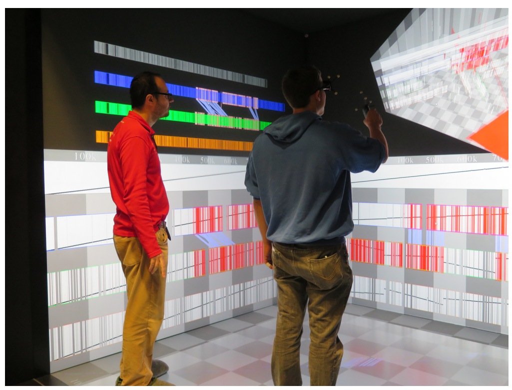

Figure 3: Users experimenting with software in the genomics field in the CAVE: 2D projection and 3DScover (García-Hernández et al., 2016; Krieger et al., 2017)

For the workflow: The input data from the domain expert are FASTA files, which describe genomes. These files were pre-processed using domain-specific software to find correspondences between genome pairs. The first step to study the correspondences was the development of a non-VR, 3D visualization software, Multiple Genome Visualization Tool to explore the 3D object and projections mentioned above. Afterwards, the visualization was ported to the CAVE (Figure 3) and HMDs with a 6DOF input device. For this project, the equalizer libraries and their supporting ecosystem (Lunchbox[9], Pression[10]) provided a convenient way to drive the large-scale systems.

[8]https://github.com/Eyescale/Equalizer
[9]https://github.com/Eyescale/Lunchbox
[10]https://github.com/Eyescale/Pression

3.2.4 Phase 2 Summary

Phase 2 saw the center moving away from commercial software solutions and towards custom-developed visualizations. This change was caused by the highly specialized requirements of the growing user base, e.g., extremely large datasets, custom data formats, and various data types. The maintenance of the developed software, however, requires low-level computer graphics and network programming knowledge. During this phase the team had become familiar with developing custom software as well as using the in-house libraries. The visualization team was involved in earlier project stages than during phase 1, as the desire for high-quality visuals grew, where previously VR visualizations were often considered an afterthought. Additionally, the team had started conducting their own research into VR, visualization, and user interaction.

At this point, game engines had already been used for scientific applications (Friese et al., 2008) and developing and maintaining our libraries ourselves was time intensive and required a high amount of low-level know-how. We decided to explore game engines for use in multi-display applications for easier workflows, higher-quality visuals, and faster development times.

3.3 Phase 3

By 2017 HMDs gained popularity with the releases of the HTC Vive and Oculus Rift (Anthes et al., 2016). With these, game engines surged in the field of VR, even though they had been used for scientific visualizations previously (Friese et al., 2008). Commercial HMDs also facilitated exhibiting scientific VR visualizations at conferences and educational institutions like museums. However, this necessitated cross-platform support due to the diversity of provided systems; a readily available feature of many commercial game engines. Further advantages include state-of-the-art rendering algorithms, benefiting from developments and maintenance of the code base by numerous other programmers, and the reusability of significant portions of prior visualizations for future projects. Especially the use of previously developed project templates for the use with the center's custom-made VR displays helped streamline the visualization workflows and contributed to considerably shorter development times. At the same time, the workflow retained flexibility to create purpose-built visualizations for specific data.

Phase 3 is marked by the introduction of Unreal Engine 4 (UE4) to the visualization center's systems as well as a dedicated focus on the scientific evaluation of implemented VR visualizations. Game engines had previously been used in CAVE systems (Jacobson & Lewis, 2005), in that case, however, the CAVE did not support stereoscopy and was not equipped with a tracking system.

With the release of the nDisplay plugin[11], it was possible to use UE4 for a CAVE and a Powerwall display setup, which only required the addition of tracking via VRPN (Reiners et al., 2002b). This not only facilitated a more flexible workflow in regards to lighting, visualizations, target systems, and interactions, but also higher visual quality and faster development times, although we had to customize the plugin to be able to run on Linux.

While domain scientists now had the means to create VR visualizations on their own without the support from VR facilities, during phase 3, most resorted to having their applications implemented largely by members of the VR center.

3.3.1 Phase 3 Hardware and Software Snapshot

To reduce considerable overhead in maintenance, phase 3 limited the operating system to Linux and discontinued support of previous Windows projects. Instead, several visualizations were recreated and rebuilt with the new Game-Engine-based workflow from various fields, including art history and zoology. Nearing six years of continued use, the rendering cluster was upgraded with up-to-date hardware. During phase 3, we acquired an additional Powerwall based on LED technology (see Table 1). Due to its functional similarity to our projection-based Powerwall, we can export for all three installations with our current workflow.

[11] https://docs.unrealengine.com/4.27/en-US/WorkingWithMedia/IntegratingMedia/nDisplay/QuickStart/

3.3.2 Phase 3 Example Project: Visualization of Extreme Rainfall Events

Phase 3 Project The ClimEx project is an international collaboration which investigates the effects of climate change on meteorological and hydrological events. This includes the transient climate simulation of a 50-member ensemble for the years 1950-2099, using the Canadian Regional Climate Model (CRCM5) and the RCP8.5 scenario (Leduc et al., 2019). The corresponding VR visualization (Kolb et al., 2018) compares three extreme rainfall events in Bavaria: one historical, which preceded the 1999 Pentecost flood, and two simulated future events. Each rainfall event is extracted from the project dataset and consists of 200 timesteps spanning 60 hours of aggregated precipitation. The magnitude of the aggregated rainfall is displayed using vertical height as well as colored isosurfaces. A 3D representation of geographical Bavaria provides further context and orientation (see Figure 4).

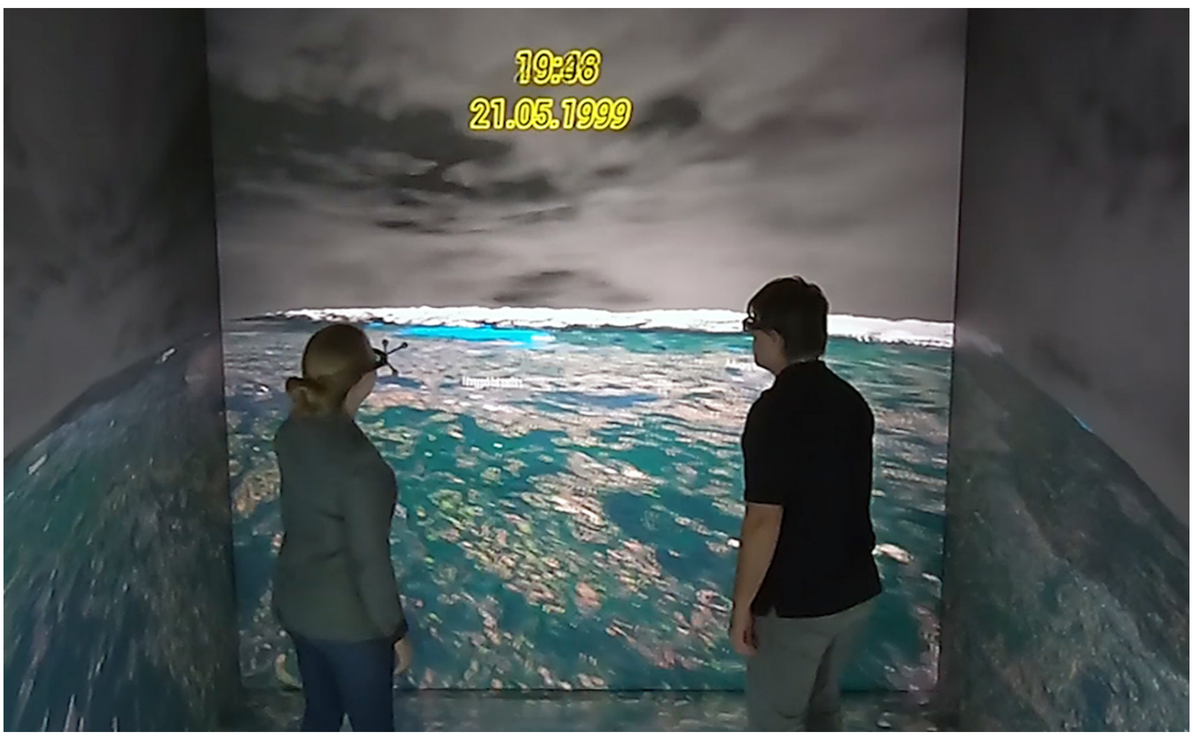

Figure 4: Users exploring extreme rainfall events in VR.

Phase 3 Workflow With Unreal Engine 4.22 providing the necessary rendering quality and performance for CAVE visualizations, pre-processing and preparing the raw input data was the most laborious and time-consuming step of the workflow. The application uses three sets of data: A digital elevation model of Bavaria (EU-DEM v1.1), high-res satellite images by SENTINEL-2 serving as textures, and rainfall data originating from a scientific simulation executed on an HPC system. All three datasets were not provided in graphics data formats. The free software R[12] was used to extract and convert the numerical elevation data as well as the rainfall data to Wavefront OBJ files. The likewise free Geospatial Data Abstraction Library (GDAL)[13] turned the satellite images into Tag Image File Formats. Both, the digital elevation model and its corresponding texture data, could then be loaded, composed, and improved for 3D rendering with the commercial program Autodesk 3ds Max[14]. Its free alternative Blender[15] was used to optimize and polish the converted rainfall data files. This extensive preparation enabled compatibility with Unreal Engine, which facilitated the final data composition, performance improvements like mipmaps, and rapid design iterations of visual aspects and user interaction.

3.3.3 Phase 3 Summary

While game engines managed to reduce workload by streamlining the visualization process, one bottleneck remained: converting raw data into uniform data for VR. A major issue of phase three was the diverse nature of scientific data, with every science domain relying on its own data types, e.g., CSV, ASC, NetCDF, or even custom-developed data format for specialized, cutting-edge research. The visualization team was now also involved in the project from the beginning. Further, the advantage of using a customized plugin to display experiences in the CAVE and Powerwall lets the team focus more on the visualizations themselves than the process of bringing them into the installations. One disadvantage was to create a dependency on external software, especially as a few years after introducing UE4 and the plugin, support for OpenGL was removed from UE4 in favor of Vulkan, which caused issues with the display setup of the CAVE, effectively forcing us to rely on an older engine version.

[12] https://www.r-project.org/
[13] https://gdal.org/
[14] https://www.autodesk.com/products/3ds-max/
[15] https://www.blender.org/

4 Discussion

We discuss the advantages and challenges of running a visualization center from our experience. Following this are our learnings as well as the limitations of our report.

4.1 Benefits and Challenges

The center has been used consistently over the years. From phase 3 on we started tracking the visitor count (see Figure 5). We averaged ≈ 152 users a month between January 2017 and December 2023. In early 2020 the center was closed due to the COVID-19 pandemic. Even after

Figure 5: Left: This graphic depicts the number of users at the center per Day. Right: This graphic depicts the hours the center was in use. Both images depict data from the visualization center over the course of five years. The impact of the COVID-19 pandemic can be seen between March 2020 and June 2022.

it was made accessible again during the summer of 2020, restrictions due to sanitary and health concerns severely limited the number of simultaneous users. During the years of the pandemic, access to the center was restricted. We compared the average monthly users of the years 2017-2018 (258) with the average monthly users of two years affected by the pandemic 2020-2021 (39) and found an 85% reduction in use due to sanitary and health concerns. However, user numbers are recovering with an average of 126 monthly users during the year of 2022 as opposed to an average of 31 monthly users during the year of 2021.

Benefits Over the course of its ten years in operation, the visualization center has proved to provide a number of advantages for users. One of the biggest benefits is to have the hardware as well as a team of visualization experts in the same place. This allowed the center to expand from simply providing hardware to also offering consulting and being included in the workflows: while during phase 1 visualization was not integral in many projects and users were often left to their own devices, the workflows changed over the years resulting in the visualization team being included early on in projects during phase 3. This change not only allowed a streamlining of processes, but also improved the quality of the visualizations. Additionally, the team of the visualization center could adapt their workflows and tools to better suit the users' needs.

Having a team of visualization experts be part of projects from various science domains also offers another benefit: reusability. Often, different science domains are confronted with similar challenges when it comes to visualizations. A single team supporting many projects is able to reuse existing code, workflows, or tools and cut down development times. This enables domain scientists to focus on their scientific goals and less on visualizing their data.

When the center was first opened in 2012, users could benefit from access to professional VR installations without having to take care of maintenance or having to provide the know-how for the operation of the hardware and software. To some extent this has changed over time, as VR has become a lot cheaper and more accessible with the introduction of relatively cheap commercial HMDs in 2016 and the subsequent rise in software support for VR. As indicated by the number of users (Figure 5), however, the popularity of the large-scale installations has not been impacted negatively by the availability of HMDs. Many users report, that they consider systems like the CAVE or Powerwall to be beneficial to their work due to their large-scale and their ease of accessibility, since they consider the isolation from the environment, that comes with the use of HMDs, to negatively impact the experience.

Another advantage has been a close collaboration with HPC facilities, which allows close contact with scientists responsible for simulations. This way they have been able to learn or are inspired by existing visualizations before running their simulations, which in turn makes the visualization process easier and faster.

Challenges The main disadvantages of installations like the CAVE or Powerwall are their space requirements, complexity, cost, and the effort required to maintain them. The monetary and time investment upfront is high, especially for high-quality equipment. Projector-based installations can sometimes span over multiple floors and may require air conditioning or even specialized cooling solutions. When using multiple projectors for a single display, as with the CAVE in the visualization center, the alignment of the projectors must be readjusted regularly to maintain image quality.

In addition, the lack of mobility of such installations can be a deterring factor to users. Requiring physical travel to use the installations may be justified for events or longer sessions but is often seen as too time-consuming for short sessions or during day-to-day work. With regards to the scientific community, the use of stationary installations is also disadvantageous as it prevents visualizations from being demonstrated at conferences, gatherings or other events. The inconvenience of requiring travel to the installations can therefore lower visibility to potential users or collaborators.

Another challenge is the complex setup of the installations due to them being multi-display. Using multiple projectors to form a single display and using multiple workstations or compute nodes to render images requires complex synchronization, so that the stereoscopic effect is displayed correctly. As a result, software support is significantly more limited compared to HMDs and the overall system is prone to failures due to the amount of different hardware components required to work together.

On the software side, we have learnt from phase 1 on that the complexity of the hardware and the variety in projection facility design also makes the development of applications more difficult. During phase 1, we moved away from commercial software due to their support for multi-display systems being retracted. And while game engines like UE4 enable creating applications for the

CAVE or Powerwall, they require additional plugins and configuration. With multi-display installations not being as common as commercial HMDs, their support is not guaranteed and may be removed in the future, which is much less likely for widespread systems.

4.2 Learnings

Creating visualizations for different science domains gave the team experience in handling various types and sizes of data. This makes it possible for us to be able to create visualizations for many different fields. Two of the visualizations, where the center's team played a significant role have been honored at conferences specializing in visualizing extremely large datasets (Cielo et al., 2021; Mayer et al., 2021). However as a visualization center that offers public presentations, a challenge has been to negotiate with domain scientists if they want to show their data to the public. A majority of the time these presentations are in the spirit of science communication to show results of research to the public.

Another major learning, as discussed in the different phases of the center, is that the VR team should be incorporated in the early steps of a VR visualization. Where previously, visualization and VR experts were only introduced late in the visualization process, now they are involved from the start. This gives them the ability to guide the visualization process for an ideal and high-quality outcome.

As for the visualizations and user experiences, we discovered that CAVEs are not suited for rendering small text due to the limited resolution of the displays. This is also true for VR in general (Kojić et al., 2020). The same is partially true for menu-based or button-based interfaces. For use cases requiring this, we have augmented the CAVE with additional IO devices, such as hand-held tablets or mobile phones. Sending text and high-resolution graphics from the VR environment to the tablet and controlling the environment via buttons and menus on the tablet provides a significantly faster and easier interaction environment, combining the benefits of both devices. While 3D UI has been examined and many methods discovered (Bowman et al., 2004), there is no standardization of creating interactions for large-scale immersive displays.

The introduction of game engines showed immediate effects. We are now able to focus mainly on the user experience as well as the visual quality of the visualizations. Further, compared to phase 1, the visualization process has been sped up significantly. It is now possible to simultaneously create experiences for CAVE, Powerwall, and HMDs with little rework.

4.3 Limitations

As of the writing of this paper, we only found little research on location-based visualization centers. There had also been debates on if CAVE systems are still relevant (de Vasconcelos et al., 2019).

Further, we can only report on what we have maintained, observed, and learnt over the years. Our visitor numbers show there is an interest and active audience for such a center. Here, we are also interested in tracking the purpose why visitors are using the center e.g., if it is for development or simply for viewing. We have not found an existing established scientific methodology to evaluate the added value of dedicated visualization centers. However, with the many science domains that have profited from our support, we hope many more can profit from our report on the long-term use of such a center. As a research center we are also looking for how the center could be used in the future.

5 Conclusions and Future Work

In this paper we presented learnings from ten years of operating a visualization center with large-scale immersive displays. We aimed to answer the following questions, which we shall answer directly:

Q1: What are the benefits and challenges of using a location-based VR center (with large-scale visual displays) for research?

The center has faced many challenges as the tasks of the team were not clearly defined at the beginning and the center was only included in projects at late stages of scientific projects. Only during phase 2, did the team get a more active role and were able to support researchers actively with custom in-house libraries. Phase 3 showed that even with a workflow including game engines being much faster than at the start of the center, there are still many challenges to overcome: bottleneck of the data, exposure of the center, and dependency on external programs.

Q2: What are the lessons learnt from operating such a center for ten years?

There are many advantages and disadvantages as discussed in Section 4, our main lessons learnt were:

- The necessary collaboration between visualization and VR experts and domain scientists.
- The role of the visualization center: creation/support in the visualization process and communicating the findings of the visualization to a broader audience.
- The use of mainstream tools, e.g., game engines to avoid long-term issues with the software. Our new CAVE is now designed to accept side-by-side input as opposed to the old system which required an active stereo signal limiting us in further development.

Q3: What is the future of such a center?

As an outlook on what we consider the next phase: With regard to display technologies, we have been working for ten years with projector-based systems with our CAVE and Powerwall. Our LED-based display was installed in 2018. We saw several advantages of the LED technology which makes us follow developments with this technology closely and consider it for the next iteration of the installations in our center. The advantages include reduced maintenance, easier serviceability, favorable brightness, and good color reproduction among other things. On the downside, however, there are issues like dissipation of heat, which could lead to high temperatures in an enclosed space like a CAVE and smaller defects like dead pixels being common. As of the beginning of 2023 we installed a new CAVE system based on LED technology (see Figure 6); the construction can also be seen in the drop of our user numbers from February 2023 (see Figure 5). The LED CAVE has a scale of $3\ m \times 3\ m \times 3\ m$ with 5 sides, 225 LED cabinets, for a total

Figure 6: User in the LED CAVE interacting with an arthistoric visualization of a baroque room.

of 1.620 LED panels. The pixel pitch is 1.25 *mm* and the CAVE offers stereoscopy and tracking. Visitors of the new LED CAVE have provided positive feedback, especially in regards to the colors being more saturated, much-improved brightness as well as the 3D effect being more convincing. The team and some users also discovered that the physical walls and edges of the LED CAVE disappear, leading to some close encounters of users almost walking into them.

On the software side, we currently base the majority of our developments on Unreal Engine. While this helps us to reduce development time and we can fully benefit from any developments to the multi-display plugin of UE4, the removal of OpenGL from UE4 has proven to be a severe limitation. As such, we are looking to expand our software portfolio to include other applications or libraries.

The future of location-based visualization centers with large-scale immersive displays will be in close collaboration with prevalent, transportable VR hardware like HMDs. These centers offer a unique opportunity for researchers as well as a broader audience and play an important role for research and science communication.

Acknowledgements

We wish to thank the following people for data/visualizations related to this paper: Prof. Peter Bunge (LMU Munich Geophysics), Dr. Markus Wiedemann, Prof. Ralf Ludwig (LMU Munich Geography), and the ClimEx project. We would also like to thank all our former colleagues who made the center what it is today, especially FH-Prof. Christoph Anthes for his leading role during phases 1 and 2. Additionally, we wish to thank our partners at the Corpus of Baroque Ceiling Painting in Germany Prof. Hoppe and Dr. Burioni, the Bayerische Schlösserverwaltung and Dr. Karin Guminski and Dr. Ute Engel from the LMU Munich for supporting us and providing the dataset shown in the CAVE in Figure 6.

References

Anthes, C., García-Hernández, R. J., Wiedemann, M., & Kranzlmüller, D. (2016). State of the Art of Virtual Reality Technology. *2016 IEEE Aerospace Conference*, 1–19. https://doi.org/10.1109/AERO.2016.7500674

Billen, M. I., Kreylos, O., Hamann, B., Jadamec, M. A., Kellogg, L. H., Staadt, O., & Sumner, D. Y. (2008). A geoscience perspective on immersive 3D gridded data visualization. *Computers & Geosciences*, *34*(9), 1056–1072. https://doi.org/10.1016/j.cageo.2007.11.009

Bowman, D. A., Kruijff, E., LaViola Jr, J. J., & Poupyrev, I. (2004). *3D User Interfaces: Theory and Practice*. Addison-Wesley. https://doi.org/10.1162/pres.2005.14.1.117

Bryson, S. (1996). Virtual reality in Scientific Visualization. *Communications of the ACM*, *39*(5), 62–71. https://doi.org/10.1145/229459.229467

Chen, C. (1999). *Information Visualisation and Virtual Environments* (C. Chen, Ed.). Springer. http://www.inf.u-szeged.hu/~dombi/visualization/Chen_InfVis.pdf

Cielo, S., Iapichino, L., Günther, J., Federrath, C., Mayer, E., & Wiedemann, M. (2021). Visualizing the world's largest turbulence simulation. *Parallel Computing*, *102*, 102758. https://doi.org/10.1016/j.parco.2021.102758

Claudio, P., & Maddalena, P. (2014). Overview: Virtual Reality in Medicine. *Journal of Virtual Worlds Research*, *7*(1). https://doi.org/10.4101/jvwr.v7i1.6364

Cordeil, M., Dwyer, T., Klein, K., Laha, B., Marriott, K., & Thomas, B. H. (2017). Immersive Collaborative Analysis of Network Connectivity: CAVE-style or Head-Mounted Display? *IEEE Transactions on Visualization and Computer Graphics*, *23*(1), 441–450. https://doi.org/10.1109/tvcg.2016.2599107

Cruz-Neira, C., Leigh, J., Papka, M., Barnes, C., Cohen, S. M., Das, S., Engelmann, R., Hudson, R., Roy, T., Siegel, L., et al. (1993). Scientists in Wonderland: A Report on Visualization Applications in the CAVE Virtual Reality Environment. *Proceedings of 1993 IEEE Research Properties in Virtual Reality Symposium*, 59–66. https://doi.org/10.1109/VRAIS.1993.378262

Cruz-Neira, C., Reiners, D., & Springer, J. P. (2010). An Affordable Surround-Screen Virtual Reality Display. *Journal of the Society for Information Display*, *18*(10), 836–843. https://doi.org/10.1889/JSID18.10.836

Cruz-Neira, C., Sandin, D. J., DeFanti, T. A., Kenyon, R. V., & Hart, J. C. (1992). The CAVE: Audio Visual Experience Automatic Virtual Environment. *Communications of the ACM*, *35*(6), 64–73. https://doi.org/10.1145/129888.129892

Czernuszenko, M., Pape, D., Sandin, D., DeFanti, T., Dawe, G. L., & Brown, M. D. (1997). The ImmersaDesk and Infinity Wall Projection-based Virtual Reality Displays. *ACM SIGGRAPH Computer Graphics*, *31*(2), 46–49. https://doi.org/10.1145/271283.271303

Danyluk, K., Ulusoy, T. T., Wei, W., & Willett, W. (2020). Touch and Beyond: Comparing Physical and Virtual Reality Visualizations. *IEEE Transactions on Visualization and Computer Graphics*, *28*(4), 1930–1940. https://doi.org/10.1109/TVCG.2020.3023336

DeFanti, T. A., Dawe, G., Sandin, D. J., Schulze, J. P., Otto, P., Girado, J., Kuester, F., Smarr, L., & Rao, R. (2009). The StarCAVE, a third-generation CAVE and virtual reality OptIPortal. *Future Generation Computer Systems*, *25*(2), 169–178. https://doi.org/https://doi.org/10.1016/j.future.2008.07.015

de Vasconcelos, G. N., Malard, M. L., Van Stralen, M. d. S., Campomori, M. J. L., de Abreu, S. C., Lobosco, T., Gomes, I. F., & Lima, L. D. C. (2019). Do we still need CAVEs? *Architecture in the Age of the 4th Industrial Revolution – Proceedings of the 37th International Conference on Education and Research in Computer Aided Architectural Design in Europe*. https://doi.org/10.5151/proceedings-ecaadesigradi2019_474

Duval, T., Kuntz, P., Royan, J., Stuerzlinger, W., & Venturini, G. (Eds.). (2014). *2014 IEEE VIS International Workshop on 3DVis: Does 3D really make sense for Data Visualization?* IEEE.

Eilemann, S. (2013). *Equalizer Programming and User Guide: The official reference for developing and deploying parallel, scalable OpenGL applications using the Equalizer parallel rendering framework*. Eyescale Software GmbH.

Friese, K.-I., Herrlich, M., & Wolter, F.-E. (2008). Using Game Engines for Visualization in Scientific Applications. *Entertainment Computing Symposium*, 11–22. https://doi.org/10.1007/978-0-387-09701-5_2

García-Hernández, R. J., Anthes, C., Wiedemann, M., & Kranzlmüller, D. Perspectives for Using Virtual Reality to Extend Visual Data Mining in Information Visualization. In: *IEEE Aerospace Conference 2016*. 2016.

Haffegee, A., Jamieson, R., Anthes, C., & Alexandrov, V. (2005). Tools For Collaborative VR Application Development. In V. S. Sunderam, G. D. van Albada, P. M. A. Sloot, & J. Dongarra (Eds.), *Computational Science – ICCS 2005* (pp. 350–358). Springer Berlin Heidelberg. https://doi.org/10.1007/11428862_49

Hally, A., Caumont, O., Garrote, L., Richard, E., Weerts, A., Delogu, F., Fiori, E., Rebora, N., Parodi, A., Mihalović, A., Ivkovic, M., Dekic, L., Verseveld, W., Nuissier, O., Ducrocq, V., D'Agostino, D., Galizia, A., Danovaro, E., & Clematis, A. (2015). Hydrometeorological multi-model ensemble simulations of the 4 November 2011 flash flood event in Genoa, Italy, in the framework of the DRIHM Project. *Natural Hazards and Earth System Sciences*, *15*, 537–555. https://doi.org/10.5194/nhess-15-537-2015

Havig, P., McIntire, J., & Geiselman, E. (2011). Virtual reality in a cave: limitations and the need for HMDs? *SPIE Digital Library Proceedings* (pp. 58–63). https://doi.org/10.1117/12.883855

Jacobson, J., & Lewis, M. (2005). Game Engine Virtual Reality with CaveUT. *Computer*, *38*(4), 79–82. https://doi.org/10.1109/MC.2005.126

Jadhav, Shreeraj and Kaufman, Arie E. (2022). Md-cave: An immersive visualization workbench for radiologists. *IEEE Transactions on Visualization and Computer Graphics*, 1–12. https://doi.org/10.1109/TVCG.2022.3193672

Juan, M. C., & Pérez, D. (2009). Comparison of the Levels of Presence and Anxiety in an Acrophobic Environment Viewed via HMD or CAVE. *Presence: Teleoperators and Virtual Environments*, *18*(3), 232–248. https://doi.org/10.1162/pres.18.3.232

Kojić, T., Ali, D., Greinacher, R., Möller, S., & Voigt-Antons, J.-N. (2020). User Experience of Reading in Virtual Reality — Finding Values for Text Distance, Size and Contrast. *2020 Twelfth International Conference on Quality of Multimedia Experience (QoMEX)*, 1–6. https://doi.org/10.1109/QoMEX48832.2020.9123091

Kolb, D., Kurtz, W., Weismüller, J., von Ramm, A., Ludwig, R., & Kranzlmüller, D. (2018). Visualization of climate simulation data in virtual reality using commercial game engines. In H.-J. Bungartz, D. Kranzlmüller, V. Weinberg, J. Weismüller, V. Wohlgemutz, H.-J. Bungartz, D. Kranzlmüller, V. Weinberg, J. Weismüller, & V. Wohlgemutz (Eds.), *Adjunct Proceedings of the 32nd EnviroInfo Conference* (pp. 39–45). Shaker Verlag GmbH; Ludwig-Maximilians-Universität München. https://doi.org/10.5282/ubm/epub.71909

Komianos, V. (2022). Immersive Applications in Museums: An Analysis of the Use of XR Technologies and the Provided Functionality Based on Systematic Literature Review. *JOIV: International Journal on Informatics Visualization*, *6*(1), 60–73. https://doi.org/http://dx.doi.org/10.30630/joiv.6.1.708

Krieger, M. T., Torreno, O., Trelles, O., & Kranzlmüller, D. (2017). Building an open source cloud environment with auto-scaling resources for executing bioinformatics and biomedical workflows. *Future Generation Computer Systems*, *67*, 329–340. https://doi.org/10.1016/j.future.2016.02.008

Laha, B., Bowman, D. A., & Schiffbauer, J. D. (2013). Validation of the MR simulation approach for evaluating the effects of immersion on visual analysis of volume data. *IEEE Transactions on Visualization and Computer Graphics*, *19*(4), 529–538. https://doi.org/10.1109/tvcg.2013.43

Laha, B., Bowman, D. A., & Socha, J. J. (2014). Effects of VR system fidelity on analyzing isosurface visualization of volume datasets. *IEEE Transactions on Visualization and Computer Graphics*, *20*(4), 513–522. https://doi.org/10.1109/tvcg.2014.20

Laramee, R. S., Hansen, C., Miksch, S., Mueller, K., Preim, B., & Ware, C. (Eds.). (2014). *2D vs 3D IEEE VIS 2024 Panel Proposal*. IEEE.

Leduc, M., Mailhot, A., Frigon, A., Martel, J.-L., Ludwig, R., Brietzke, G. B., Giguère, M., Brissette, F., Turcotte, R., Braun, M., & Scinocca, J. (2019). The ClimEx Project: A 50-Member Ensemble of Climate Change Projections at 12-km Resolution over Europe and Northeastern North America with the Canadian Regional Climate Model (CRCM5). *Journal of Applied Meteorology and Climatology*, *58*(4), 663–693. https://doi.org/10.1175/JAMC-D-18-0021.1

Mantovani, F., Castelnuovo, G., Gaggioli, A., & Riva, G. (2003). Virtual reality training for healthcare professionals. *CyberPsychology & Behavior*, *6*(4), 389–395. https://doi.org/10.1089/109493103322278772

Martín-Gutiérrez, J., Mora, C. E., Añorbe-Díaz, B., & González-Marrero, A. (2017). Virtual Technologies Trends in Education. *Eurasia Journal of Mathematics, Science and Technology Education*, *13*(2), 469–486. https://doi.org/https://doi.org/10.12973/eurasia.2017.00626a

Mayer, E., McCullough, J., Günther, J., Cielo, S., & Coveney, P. (2021). Visualization of Human-scale Blood Flow Simulation using Intel® OSPRay Studio on SuperMUC-NG. *Proceed-*

ings of the SC '21: The International Conference for High Performance Computing, Networking, Storage and Analysis.

Meta. (2023). *Meta Quest 3 Launches Later This Year + Lower Prices & Improvements for Quest 2* [Accessed: 2023-06-28]. Retrieved June 1, 2023, from https://www.meta.com/de-de/blog/quest/vr-hardware-news-quest-3-sneak-peek-price-drop/

Millais, P., Jones, S. L., & Kelly, R. (2018). Exploring data in Virtual Reality: Comparisons with 2D Data Visualizations. *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, 1–6. https://doi.org/10.1145/3170427.3188537

Mine, M. (2003). Towards Virtual Reality for the Masses: 10 Years of Research at Disney's VR Studio. *Proceedings of the Workshop on Virtual Environments 2003*, 11–17. https://doi.org/10.1145/769953.769955

Muhanna, M. A. (2015). Virtual reality and the CAVE: Taxonomy, interaction challenges and research directions. *Journal of King Saud University-Computer and Information Sciences*, *27*(3), 344–361. https://doi.org/10.1016/j.jksuci.2014.03.023

Onyesolu, M. O., & Eze, F. U. (2011). Understanding virtual reality technology: advances and applications. *Advances in Computer Science and Engineering*, 53–70. https://doi.org/10.5772/15529

Raja, D., Bowman, D., Lucas, J., & North, C. (2004). Exploring the Benefits of Immersion in Abstract Information Visualization. *Proc. Immersive Projection Technology Workshop*, *61*, 69–75.

Reiners, D., Voß, G., & Behr, J. (2002a). Opensg: Basic Concepts. *1. OpenSG Symposium OpenSG 2002*.

Reiners, D., Voß, G., & Behr, J. (2002b). Vrpn: A device-independent, network-transparent vr peripheral system. *1. OpenSG Symposium OpenSG 2002*.

Tcha-Tokey, K., Loup-Escande, E., Christmann, O., & Richir, S. (2017). Effects on User Experience in an Edutainment Virtual Environment: Comparison Between CAVE and HMD.

Proceedings of the European conference on cognitive ergonomics, 1–8. https://doi.org/10.1145/3121283.3121284

Theart, R. P., Loos, B., & Niesler, T. R. (2017). Virtual reality assisted microscopy data visualization and colocalization analysis. *BMC Bioinformatics*, *18*(2), 1–16. https://doi.org/10.1186/s12859-016-1446-2

Van Dam, A., Forsberg, A. S., Laidlaw, D. H., LaViola, J. J., & Simpson, R. M. (2000). Immersive VR for Scientific Visualization: A Progress Report. *IEEE Computer Graphics and Applications*, *20*(6), 26–52. https://doi.org/10.1109/38.888006

Van Treeck, C., Frisch, J., Egger, M., & Rank, E. (2009). Model-adaptive analysis of indoor thermal comfort. *Building Simulation*, 1374–1381.

Walton, J., Adams, S., Hayek, W., Florek, P., & Dyson, H. (2021). Dynamic 3-D Visualization of Climate Model Development and Results. *IEEE Computer Graphics and Applications*, *41*(1), 17–25. https://doi.org/10.1109/mcg.2020.3042587

Wiedemann, M., Anthes, C., Bunge, H.-P., Schuberth, B. S., & Kranzlmulle, D. (2015). Transforming Geodata for Immersive Visualisation. *2015 IEEE 11th International Conference on eScience (eScience 2015)*, 249–254. https://doi.org/10.1109/eScience.2015.80