Immersion in Virtual Reality: CAVE Automatic Virtual Environments vs. Head-Mounted Displays

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Abstract

The paper describes immersive capabilities of CAVE Automatic Virtual Environment and Head-Mounted Display. An important aspect of this research was to develop a method for quantifying user immersion in both systems. Two virtual reality applications, "Flat of Negative Emotions" and "Arachnophobia Treatment Support" were used to observe and analyze user reactions and engagement levels. Participants were exposed to these applications in both environments, allowing for a comparative analysis of the technologies. The methodology incorporated surveys, observation forms, and direct interaction analysis, combining qualitative and quantitative data for a comprehensive evaluation of both systems. The study involved 124 participants from varied backgrounds. The paper presents the objectives, methodology, and findings, with a focus on comparing the immersion levels in CAVE and HMD settings. The results contribute to the academic discourse in virtual reality and human-computer interaction, offering methodological advancements in measuring immersion and guiding future research in immersive technology.

Keywords: virtual reality, immersion in virtual reality, CAVE, HMD.

1. Introduction

Virtual reality (VR) technologies have rapidly evolved recently, becoming integral tools in various fields, from entertainment to education. Numerous technologically diverse devices have been created to facilitate the use of virtual reality. Despite their differences, each aims to render reality as vividly as possible, immersing the user in the virtual world. This study was conducted to answer whether it is possible to compare the creation of VR through different technological devices. It was decided to limit the investigation to two devices: CAVE Automatic Virtual Environments (CAVE) and Head-Mounted Displays (HMD). The experiment was carried out using two applications for both environments.

The mentioned simulation potential was decided to be examined through measuring the level of user immersion. Immersion is the perception of physical presence in a non-physical, virtual reality world. The basic objective of the study was to verify whether measuring immersion is possible and how it can be achieved. A systematic review of the literature (next section) revealed that there are few research studies where immersion was measured, and there are no clearly defined ways of measuring it. The main challenge identified was that the feeling of immersion is subjective and depends on many factors.

2. Related work

The primary goal of a systematic literature review was to review existing studies in the field of CAVEs and HMDs. Additional objectives included finding information on the concept of "immersion in VR" and identifying methods used in similar research.

Three academic publication databases were utilized: IEEE Xplore, Scopus, and Springer. Searches in each database were conducted using the search string ("virtual reality" AND "cave automatic virtual environment" AND "immersion"). There were set inclusion criteria for articles and conference papers from 2015-2023 related to computer science, VR, computer-aided instruction, human-computer interaction, augmented reality, psychology, and cognition. The first phase resulted in 144 publications. Based on a vote regarding the adequacy of titles and abstracts, 17 publications were selected for the second phase of the literature review. A similar voting process concerning content led to the selection of 12 publications [1-12] for the third phase. For them, extraction was performed, and the snowballing method was applied, identifying 30 new noteworthy items. After a similar process 6 additional publications [13-18] were selected for analysis.

Among the publications, there were several thematically similar works found. For instance, one study investigated the ease of evacuation and the legibility of signs in a car tunnel using HMD and CAVE devices [10]. There were also several studies measuring the level of immersion on a single device without making comparisons [2, 4, 8]. Some studies compared a three-wall CAVE to HMD but only in terms of the perception [12]. Another study compared a four-wall CAVE with HMD in terms of ship simulation quality, but two different applications were used [7]. There were publications addressing the issue of immersion only theoretically [5, 6]. Studies were found investigating the issue of orientation or cybernetic disease on two different devices [9]. None of the found studies compared the level of immersion between HMD and a six-wall CAVE.

The literature review uncovered various methods for measuring immersion, such as surveys and subject observation. Details were also discovered about how studies using CAVEs were conducted. Examples of surveys designed to measure immersion were identified, gathering 224 questions and challenges encountered in previous research were recognized, including distinction between immersion and presence. The systematic literature analysis further provided information on procedures used in other experiments, such as the sequence of tasks performed by subjects and the duration of breaks.

In summary, the analysis of prior work on the topic concluded that such a study had not been conducted before and that it could contribute to the development of the field and bring a lot of new insights. Additionally, the analysis of prior work allowed for learning from mistakes and utilizing the achievements of already conducted research.

3. Research method

Two devices were used for the study. A full immersive six-wall cube-shaped CAVE is located at the Immersive 3D Visualization Lab at the Gdańsk University of Technology. This CAVE utilizes 12 projectors to display images on 6 walls. Position tracking was done using infrared (3D glasses with infrared reflective markers). Subjects' movement tracking was done using two infrared Flystick controllers. Sound was emitted through speakers. The second device used by participants was the HMD Valve Index. Subjects' position tracking was done using two torches and movement tracking was done using two Valve Index controllers. Sound was emitted through headphones in the HMD.

Two applications were selected for the study, both prepared for HMD and CAVE. The "Rooms" application depicted a flat consisting of 6 dark, negative emotion-evoking, interactive rooms. The subject‘s goal was to use the controllers to explore all the rooms within 10 minutes. The "Spiders" application created to arachnophobia treatment support, aimed for the subject to watch different densities of spiders, manually switched by the researcher. Users did not use controllers. This study lasted a maximum of 4 minutes.

Since the feeling of immersion is highly subjective, it was decided to use two research methods to obtain the most reliable results. The first chosen method was quantitative in the form of surveys. During the study, each participant filled out three surveys, marking, among other things, their subjective feelings. The second method applied was qualitative in the form of observing the subjects. For this purpose, the participants were recorded. During the analysis, observation sheets were filled out.

The subject filled out three surveys in total. The preliminary survey collected information such as the subject's age, gender, occupation, VR experience, suffering from arachnophobia, etc. Additionally, subjects filled out two "post" surveys after using the HMD and the CAVE. Both contained practically identical questions that subjects provided answers using a Likert scale. The questions concerned the subjects' feelings.

During the examination of each participant, two observation forms were filled out for both applications. These forms captured various metrics, including the time spent in each application. For the "Spiders" application, the form queried about participant's reactions to spiders, emotions, and whether the task was successfully completed. The form for the "Rooms" application contained more comprehensive inquiries due to the application's larger scope and the study's longer duration. Questions included whether the participant avoided virtual obstacles and reacted to events that they would react to in reality.

Each user used two applications once. Two persons were simultaneously invited to the lab, where each of them completed an initial survey. Then, they both tested the same application, but one in the CAVE and the other with the HMD. Researchers monitored them both and documented their observations on designated forms, and recorded supplementary notes. Upon completing the application, participants filled out a brief survey. The devices were then swapped between users to use the alternate application. Observations continued as before, with researchers completing the relevant observation forms. A final brief survey was filled out by participants after they finished the second application. The entire process for each participant lasted approximately 30 minutes.

4. Results

During the research conducted at the Gdańsk University of Technology, 124 individuals were examined over a period of 9 days. As a result, the team gathered 124 preliminary surveys, 248 observation sheets, and 248 "post" surveys. The participants included 31 women and 93 men (Fig. 1a). Out of these, 111 were students, while 13 were not (Fig. 1b). The use order of devices and applications is presented in Fig. 1c and Fig. 1d.

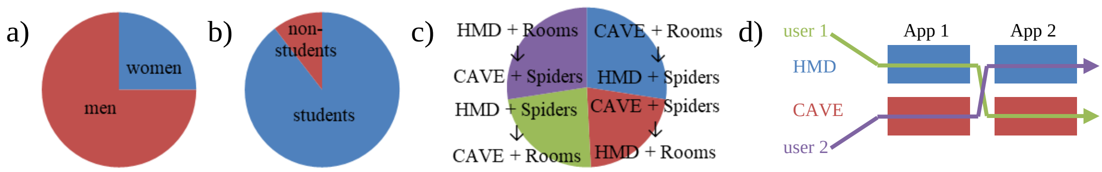

Fig. 1. Research group: women/men (a), occupation (b), experiment order (c); experiment scheme (d).

For the "post" surveys, which were based on the Likert scale, it was decided to count the number of each type of response for all questions and calculate the weighted average. The following weights were assigned: -2 (*strongly disagree*), -1 (*disagree*), 0 (*don't know*), 1 (*agree*), 2 (*strongly agree*). This was done for both "post" surveys (Fig. 2).

The results seem to show a deeper immersion in the HMD. It outweighs CAVE in most cases. But it turns out that the results are significantly influenced by differing technical parameters of analogous subsystems in both tested VR environments, especially for tracking. In CAVE, there were problems with participants interacting with the virtual objects. This was due to the use of old versions of ART Flysticks with tracking cameras placed only in the upper corners of the CAVE. The design of the Flystick itself, with targets only at the front, means that when reaching down, the rear part of the Flystick obscures the target from tracking cameras placed at the top. During the study, there were regular problems, such as losing track of the controllers in the lower corners of the CAVE. Unfortunately, these problems were reflected in the surveys. On the other hand, during the HMD study, modern Valve Index controllers didn't cause any problems. If contemporary controllers were used in CAVE, the results might have been different.

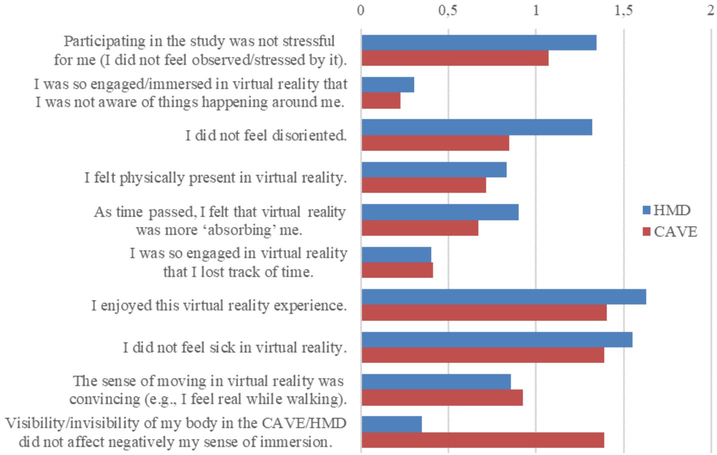

Fig. 2. Post study survey results.

The last question about the impact of body visibility on the sense of immersion draws attention. CAVE definitely "wins" here, showing the advantage of body visibility. This feeling is not distorted by the stuttering tracking in CAVE. It is possible that this also influenced the sense of realism of moving in the virtual environment.

Unfortunately, the study compares not so much environments but the technologies used to build two specific devices. Therefore, we have concluded that the study that used tracking is inadequate and its results are doubtful. It should be repeated after unifying the subsystems of tracking in both environments. Fortunately, only the "Rooms" application used tracking, so the results of the "Spiders" application are suitable for further analysis.

For the observation, the analysis concerned subjects' behavior in the scale: 0 (*lack of activity*) and 1 (*activity*). Three behaviors were analyzed for the "Spiders" application. Then it was decided to count the percentage of activities for every analyzed behavior in a given VR environment and calculate the average for the HMD and the CAVE (Fig. 3a).

The level of immersion was determined by averaging the normalized results obtained from surveys for both devices with both applications and observation sheets for both devices, but only with the "Spiders" application. We assumed that each device should achieve a score ranging from 0 to 1 from post-study survey and observation sheets. The immersion value calculated in this way could range from 0 to 1. The CAVE achieved 17.3% higher level of immersion 0.46 compared to the HMD 0.39 (Fig. 3b).

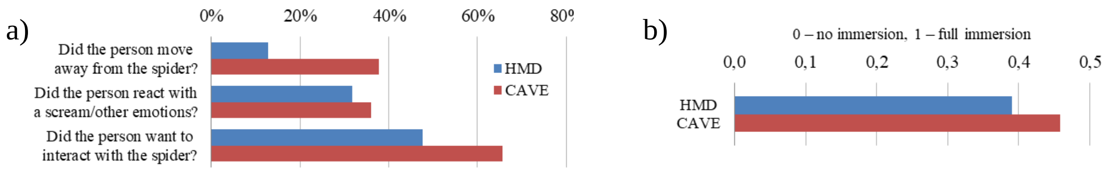

Fig. 3. Percentage of reactions in the "Spiders" application (a), designated level of immersion (b).

Based on the results obtained, it can be stated that CAVE is more immersive than HMD. However, the observed difference is not great (17.3%), although it would probably be greater if there were no problems with tracking the controller in the CAVE.

It must be honestly admitted that for the "Rooms" application, the immersion for the HMD achieved a higher level than in the CAVE. This is likely because the level of immersion in the CAVE "Rooms" application could have been lowered by problems related to interaction (discussed above). In the CAVE, nine people had problems using Flysticks, whereas in the HMD, not a single person had issues with controllers. HMD users more often reached all rooms and collected more pickups. It must be admitted that despite these issues the sense of moving in VR was more convincing in the CAVE.

The way the study was conducted, the difference between the devices used, and the encountered technical and organizational issues indicate the following threats to validity:

controllers of various quality, different levels of external interference (other laboratory users in the case of HMD tests), various methods used to signal the boundaries of the operating area, different complexities of preparing the user to the device. Additionally, the group of subjects was unbalanced. There were significantly more people of student age than other age groups, and more men than women. This caused the research group to not be very representative. Quantifying these effects with precision poses a challenge.

5. Conclusions

This research aimed to measure the immersion of CAVE- and HMD-type VR simulation. It was shown that in the case of passive scenarios (without the use of hand-held controllers), the level of immersion in CAVE is undoubtedly higher than in HMD. However, hardware imperfections prevented this from being tested for full interaction.

Future research directions should focus on addressing the identified validity threats, exploring the impact of updated CAVE systems on user immersion, and extending the demographic diversity of participants to improve the external validity of findings.

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