International Conference on Artificial Reality and Telexistence
Eurographics Symposium on Virtual Environments (2023)
J.-M. Normand, M. Sugimoto, and V. Sundstedt (Editors)

Don't denigrate the CAVE ! A comparative Examination of CAVE and HMD for navigation in virtual worlds

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Abstract

This paper conducts a comprehensive analysis of user experiences by comparing navigation and cybersickness between two distinct categories of immersive devices: CAVE and HMD. Using consistent methodology and analysis for both technologies in the same application to underscores disparities in user experiences, particularly in navigation and exploration tasks, addressing a gap in the existing literature. The study comprises two experiments with differing navigation paradigms. The first demanded active participant navigation in a complex virtual environment, focusing on distinctions like field of view and field of regard intrinsic to CAVE and HMD technologies. Physiological parameters (heart rate and skin conductance) and the Virtual Reality Sickness Questionnaire (VRSQ) were recorded to assess cybersickness levels. Results indicate no significant variations in self-rated cybersickness but a higher heart rate for HMD and longer completion time in the CAVE. Participants favored HMDs personally. In the second experiment, participants were guided through an automated virtual environment (VE) walk, recording similar physiological and psychological measurements. Although no significant inter-device variations emerged in psychological measurements, a notable influence of the HMD on physiological cybersickness data and postural stability was observed. Nevertheless, other measurements and participant feedback did not align with substantial cybersickness. Overall, our results provide a better understanding of the differences between these two VR displays.

CCS Concepts

• ***Human-centered computing*** → ***Virtual reality;*** *Graphical user interfaces; Interaction paradigms;*

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1 Introduction

Virtual reality (VR) technologies are experiencing growing use across various domains, including gaming, education, and healthcare. VR presents users with an immersive and interactive environment capable of simulating real-life scenarios, allowing them to engage in different activities and explore diverse environments. Nevertheless, VR encounters a notable challenge concerning cybersickness, a condition marked by symptoms including nausea, dizziness, and disorientation. Cybersickness can occur due to a mismatch between the visual and vestibular systems, causing the brain to perceive motion that is not physically happening [RO16].

Previous research aimed to understand the causes and impact of cybersickness and develop strategies for easing its effects. Numerous factors were pointed out as contributors to cybersickness: the field of view (FOV), field of regard (FOR), display resolution, frame rate, and navigation metaphor. For instance, a limited FOV and reduced display resolution are identified as potential catalysts for inducing disorientation and cybersickness [RO16, SHH*19]. Researchers have put forth several solutions to tackle cybersickness issue in VR, like fine-tuning display settings, applying motion-sickness reduction techniques, and designing more ergonomic VR devices [KCC20]. The goal is to enhance the user experience and expand the scope of applications for VR technology. Ongoing research and development initiatives focus on reducing cybersickness influence and facilitating more immersive and effective VR usage.

While most VR research uses head-mounted displays (HMDs) due to their widespread availability, it is important to recognize that immersive devices extend beyond HMDs. Larger devices like CAVE systems, particularly relevant in specialized applications such as collaborative scenarios, also warrant attention. Prior research has studied CAVEs to investigate navigation or interaction in the virtual environment (VE) and cybersickness. However, studies directly comparing user experiences across different devices, within the same VE and task context, remain relatively scarce, despite the significant impact that device characteristics can have on users' overall experience [GPK14, CKG16, GFC*18].

In this paper, we aim to bridge this gap by conducting a comparative study that centers on virtual navigation and the consequent effects

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DOI: 10.2312/egve.20231323

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on cybersickness, employing both CAVE systems and HMDs. We have designed two experiments with the specific aim of discerning how disparities in device characteristics, specifically FOV and FOR, can influence users' immersion and their overall experience.

2 Related Work

This paper aims to compare two fundamental VR display systems: HMDs and CAVEs. HMDs are known for their immersive qualities, while CAVEs offer a more expansive physical space for interaction. However, the choice between these systems is not always clear-cut. This comparative analysis encompasses several crucial factors, including FOV, FOR, navigation strategies, cybersickness, and user preferences. By investigating these areas, this paper aims to shed light on the advantages, limitations, and user-centric considerations associated with these distinct VR devices.

2.1 Field of view and field of regard

The FOV and FOR represent fundamental distinctions between HMDs and CAVEs, possibly having a substantial impact on the user's overall experience [FF16]. FOV refers to the extent of the user's visual perception, typically measured in degrees. In VR, the FOV is often constrained by the capabilities of the visualization technology, as the human FOV (approximately 210° for the horizontal FOV with two eyes) typically exceeds what VR systems can provide. Indeed, HMDs typically offer horizontal FOVs of around 110° (although some recent devices can offer more, e.g., Pimax 5k or StarVR one), while CAVE systems provide a considerably wider FOV [MRO*17]. Previous research has indicated that these disparities may prompt users to adopt alternative behaviors during exploratory tasks, such as an increased reliance on virtual rotation to survey their surroundings, potentially leading some users to opt for different pathways to avoid this potentially discomforting rotation [CVH15]. More broadly, this factor can influence distance estimation, perception, and navigation [KL04, MD05, RVH13]. On the other hand, the FOR is the visible area that can be assessed when moving the head. HMDs have a wider FOR than CAVEs, which can impact the user's ability to look around the virtual environment. In a typical CAVE system (four or five-sided systems), if users face the front screen and do not move their heads but only their eyes, they cannot see the system's borders and thus cannot leave the virtual immersion. Additionally, if participants look around (e.g., behind them), they are likely to see outside the virtual world as there may be a lack of a physical screen. It is worth noting that six-sided CAVEs exist but they are rare. On the contrary, with HMDs, if users look up with their eyes, they will see plain black as they will see around the screens. However, users can look all around without leaving the virtual environment. Figure 1 illustrates these distinctions between HMDs and CAVEs concerning FOV and FOR.

2.2 Virtual navigation and interactive tasks

The navigation experience in VEs differs significantly between HMDs and CAVE systems. In CAVE systems, users can see their own bodies, whereas with an HMD, users are shielded from reality. Additionally, variations in controller shape and the distinctions in FOV/FOR, as discussed earlier, also contribute to these differences. As previously stated, user experience might be affected by them, and new technological challenges appear, such as the need to implement users' virtual avatars for HMDs or to restrict actions and ensure comparable capabilities between both devices.

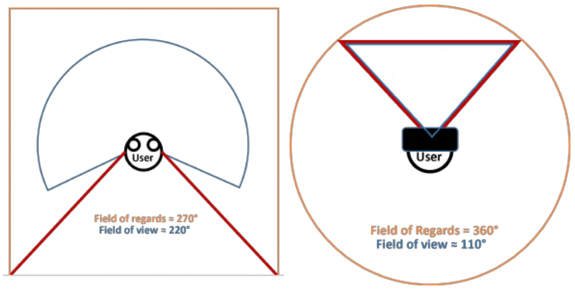

Figure 1: *FOV and FOR limitations with CAVE (Left) and HMD (right) systems. In red the devices limitation, in blue the human human FOV (220°) in orange the human FOR (360°).*

Navigation strategies also arise from intrinsic distinctions between HMDs and CAVE systems. CAVE systems restrict physical displacements to navigate in VEs, necessitating the development of strategies involving unnatural metaphors such as steering navigation, teleportation, or walk-in-place. These strategies can potentially impact the user experience [BC19, DCW*20]. Additionally, due to the limited FOR in CAVE systems, users cannot freely turn their heads in a 360-degree direction, thus requiring the use of navigation controllers to facilitate rotation if needed. In contrast, with HMDs, users can freely turn around naturally and physically move within a more extensive physical area. To address this device limit, techniques such as redirected walking are available and can be implemented with both types of devices. Redirected walking enables users to move physically, although it may require meticulous parameter adjustments to smoothly manipulate the virtual environment without the user's awareness [BRKD19].

Consequently, the choice of a suitable navigation technique may be device-specific. When designing and implementing virtual environments, it is imperative to account for the distinct characteristics of each device and their potential impact on navigation, ensuring the appropriate implementation of navigation techniques.

For interactive tasks, some comparative studies have revealed that participants were significantly faster to perform tasks when using HMDs [CDK*17]. However, these studies considered a specific collaborative task. Furthermore, users tend to make choices faster with HMDs when asked to cross a road or to board a train [SP05, GPK14]. Moreover, they are faster to perform selection tasks only with CAVE-like systems, though better results can be achieved when using HMDs for selection and interaction.

2.3 Cybersickness

New technologies often intrigue participants' interest, but their enthusiasm can be tempered by the onset of cybersickness [SHH*19]. This condition shares symptoms similar to motion sickness, including nausea, pale skin, cold sweats, vomiting, dizziness, headaches, salivation, and fatigue [RO16]. However, the severity of these symptoms can vary depending on the type of motion sickness experienced, such as sea-sickness, space-sickness, or cybersickness. The effects of cybersickness can manifest only a few minutes of use or hours later. A common cause of these symptoms is the sensory mismatch between the visual and the vestibular systems [RO16].

Kim et al. [KPCC18] identified three primary conflicts contributing to motion sickness: 1) what I felt but did not see, 2) what I

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saw but did not feel, and 3) what I felt but did not match what I saw. Simulator sickness, in particular, often originates from conflict two. Several methods exist for evaluating cybersickness during VR exposure. One approach involves physiological measurements. For example, heart rate (HR) can be considered a marker of the onset of cybersickness [MZBG15, BW11, DSS18]. It can be conveniently assessed using wearable devices like a watch or small sensors, and its interpretation is straightforward. An elevation in HR during a VR experiment suggests that the user may be prone to experiencing cybersickness or, at the very least, to feel discomfort. Another method to evaluate cybersickness is through Electrodermal Activity (EDA), commonly known as skin conductance, as established by previous studies [GGH*19, RO16, DSS18]. However, the hardware to measure EDA is more expensive and difficult to obtain than HR monitoring devices. Both devices have limitations and associated risks when it comes to acquiring and analyzing data. Indeed, several factors can influence physiological measurement, including stress, room temperature, and potential issues with the devices themselves. Apart from physiological measurements, behavior measurements can also characterize cybersickness. Postural instability (PI) can be used to predict a user's likelihood of experiencing sickness [OLY98], with specific features of postural sway serving as indicators of cybersickness occurrence [CMM17]. It is important to note that PI measurements should be conducted both before and after VR exposure. Indeed, recent studies [APAK19, SB20] have demonstrated a connection between postural instability and cybersickness, suggesting that pre-exposure PI measurements can gauge a user's susceptibility to cybersickness. Finally, another method to measure cybersickness, which is the most commonly used, is subjective assessment through questionnaires. The Simulator Sickness Questionnaire (SSQ) [KLBL93] is frequently employed in VR studies. However, concerns regarding its validity in VR setups have led to the development of more suitable questionnaires, such as the Virtual Reality Sickness Questionnaire (VRSQ) [KPCC18], which is derived from the SSQ by removing several items that were not significantly affected by VR exposure.

The difference in optic flow might occur between our devices as they do not provide the same FOV. The optic flow can be defined as the apparent motion of brightness patterns in an image sequence [JFS04]. This increase in information for the user can result in inappropriate spatial and temporal changes in light intensities. Consequently, this can lead to an underestimation of visual motion information [JFS04]. This phenomenon has been studied in relation to cybersickness, with some research proposing 3D deformation techniques to mitigate this optical flow issue [LC19, LSB22]. Past studies reveal a lower effect of optical flow in CAVEs [KCC20, PH15]. In the study of Polcar et al., the CAVE-like system employed was a one-wall CAVE, resulting in reduced optic flow compared to CAVEs with more walls, potentially mitigating the adverse effects of such displays [PH15]. Nevertheless, their findings revealed a higher overall occurrence of symptoms in CAVEs but with more severity observed in HMDs. Sharples et al. investigated the distinctions between various displays in inducing virtual cybersickness symptoms and effects [SCMW08]. Their study used HMDs, desktop screens, standard projection, and reality theaters (i.e., horizontally curved screens) across two different movement modalities: active and passive. Their results underscore that HMDs and reality theaters tend to induce more symptoms and effects compared to the other devices. In another study that compared CAVE-like systems and HMDs within a driving simulation context [KGMC17], no significant differences were observed between the two devices. However, it was noted that rotational motion induced more cybersickness effects than longitudinal motions.

In summary, there is no definitive conclusion that one device is superior to the other in preventing cybersickness effects. To address this uncertainty, we conducted a comparison of both devices without introducing additional variables or altering the devices to ensure a consistent user experience. Our decision to utilize both hardware options was driven by the recognition that each device is designed with its distinct features and capabilities.

2.4 Contribution

Comparative studies involving our two immersive devices are relatively scarce, primarily due to the limited availability of certain setups, such as CAVE systems. In this paper, we aim to contribute to addressing this gap by conducting an evaluation of the differences that can potentially influence the user experience in two fundamentally different VR configurations: CAVE systems and HMDs. Both setups are subjected to the same virtual environment and tasks, shedding light on virtual navigation and its repercussions on cybersickness effects and user preferences. To gain a deeper understanding of how disparities in device characteristics impact user immersion and experience, we have devised two experiments. The two experiments investigate the effects of FOV and FOR differences in each device on navigation and cybersickness.

3 VR Setups

To carry out our experiments, we used two distinct families of systems: two different CAVE systems and one HMD. At this point, we acknowledge that all subsequent findings will be strictly applicable to the specific devices used in our experiments. It's important to note that CAVE systems come in a multitude of forms, sizes, and specifications, such as some specific CAVE set up can present radically different settings and limitations. All the application where developed with Unity3D (LTS 2021.3.30f1) and the asset steamVR (Version 2.7.3) for interaction.

The first CAVE system (called here *C1*) is composed of five screens (front, left side, right side, top and bottom). Its dimensions are 3.40 m (W)×2.70 m (H)×3 m (D). On each screen, active stereoscopic retro-projection is performed through Mirage 4k25 projectors, achieving a resolution of 4096×2160 pixels at a 120 Hz framerate. An ART tracking system with eight infrared cameras placed on the corners of the CAVE is installed to track users and interaction devices. Six computers control the system via MPI. Here, an ART Flystick device was used to interact (navigate and manipulate) within virtual environments. The second CAVE system (called here *C2*) is composed of three vertical screens and a floor. The vertical screens are 4 meters high, and the floor surface is 3x3 meters, also equipped with stereoscopic projection and a motion capture system. Thus it has no ceiling/top screen. Despite the absence of a top screen, the height of the side screens allows users to have a full field of vision and not to see outside the virtual environment.

The HTC Vive Pro is a well-known HMD providing a resolution of 1440×1600 pixels (2880×1600 for both eyes) at a 90 Hz framer-

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ate and a 110-degree FOV. The inter-pupillary distance (IPD) can be adjusted for each user thanks to a control knob on the HMD. We relied on each participant to correctly adjust their vision. The controllers offered by HTC were used to interact within the virtual environments created under Unity3D.

4 Experiment 1: Free navigation in building

In this experiment, we study the influence of a difference in the FOV and the FOR on virtual navigation and user experience. The *C1* CAVE and the HTC Vive devices were used for the experiment. Participants were immersed in a complex two-floor indoor environment comprising 25 rooms per floor and corridors, with each room identified by a different sign (see Figure 3). They were required to complete a navigation path passing through different rooms and using a virtual elevator to travel between floors. To aid orientation, a map with different signs corresponding to the rooms was provided (see Figure 2).

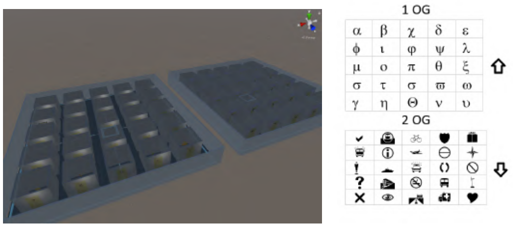

Figure 2: *Left: Virtual environment for the experiment. Right: Map to help participants orient during the experiment.*

The following research questions and hypotheses were made:

RQ. If the same theoretical virtual environment is offered with both systems, will the differences in the FOR and the FOV significantly impact user experience and the way users navigate in a virtual environment?

Addressing this question may guide the development of VR applications toward achieving a similar user experience on both devices. This could involve, for example, asking users not to rotate their bodies when using HMDs.Our hypotheses for this first experiment are as follows:

H1. Due to the restricted FOR in the CAVE, the completion time will be longer in the CAVE than with the HMD.

H2. Participants will favor the HMD due to its unrestricted FOR, resulting in easier navigation.

H3. Cybersickness will be lower in the CAVE, thanks to the ability to still see his/her body.

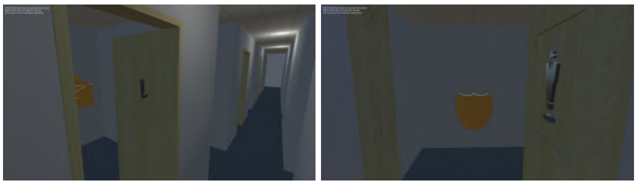

Figure 3: *User's views within the VE.*

4.1 Participants

21 participants (mean age$= 25 \pm 15$, 5 females) were recruited from different backgrounds inside and outside the university. They were all requested to be free for at least one hour to participate in this experiment. Upon arrival, they were asked to sign a consent form. Before and until the end of the whole experiment, the purpose of the experiment was hidden from them. At the end of the experimentation, they were free to ask any question they could have. During the experiments, they were also free to quit if requested. Four participants did not participate in both conditions: one due to time constraints, and three due to experiencing discomfort and requesting to discontinue. Thus they were excluded from the data analysis.

4.2 Experimental protocol

The application was introduced to the participants along with an explanation of the tasks they needed to complete and how to interact within the virtual environment. The application required users to navigate the virtual environment, interact with doors, and use an elevator. For navigation, participants used the joystick on their controller (Moving at 4.5km/h and rotating at 40°/s maximum depending on the position of the joystick), while to interact with doors or the elevator, they had to physically touch the 3D model of doors to open them or interact with the elevator to change floors. In each modality, corresponding to immersion either in the *C1* CAVE (C) or with the HMD (V), participants were given a few minutes to become familiar with the environment and the interaction method. During this phase, the experimenter instructed them to reach a specific point in the virtual environment, assisted participants in reaching the first room, and ensured they understood how to use the provided map and controls. Participants were encouraged to ask questions about the application during this training session. Following the familiarization phase, the formal experiment commenced. Participants were tasked with visiting ten virtual rooms to complete the experimentation. Two navigation paths were created, one for the first trial and one for the second, within each setup. These paths were designed symmetrically to have theoretically identical lengths, a detail further validated through data analysis. Upon reaching a room, participants were instructed to open the corresponding door. Each door displayed a sign indicating the next room to visit, guiding them to a new location. The order of modalities was counterbalanced between subjects. For each modality, the recorded parameters included completion time, head rotation, and position within the virtual world. Furthermore, physiological data were collected using an Empatica E4 wristband. This wristband enabled the collection of skin conductance (measured as electrodermal activity–EDA), heart rate, and skin temperature at a frequency of 4 Hz, with precision around the μS for EDA. These parameters are recognized as being related to the severity of cybersickness [DSS18, MZBG15, PCM18]. This wristband was set up the prior the experiment to collect HR baseline. Additionally, after experiencing each modality (C and V), participants were required to complete the Virtual Reality Sickness Questionnaire (VRSQ) and the Misery Scale questionnaire (MISC) [Bos15, BdVvEG10]. These questionnaires were chosen over the well-known Simulator Sickness Questionnaire (SSQ), despite its frequent use in VR studies, due to concerns raised by several researchers regarding its suitability for VR [KPCC18, KCC20].

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Upon concluding the experiment, participants were encouraged to provide feedback regarding the entire experimental process. They were invited to pose any questions about the study or the application. Furthermore, participants were asked to specify which device they would choose if they were to repeat the experiment and to provide reasons for their choice.

4.3 Results

Physiological data, including HR and SC, as well as psychological data from the MISC and VRSQ, were collected to assess cybersickness. Additionally, behavioral data were gathered to compare user behaviors when using different VR systems throughout the experiment. However, SC data was excluded from the data analysis. This decision was made due to significant changes observed in SC data during the experiment. We suspected that two external factors had influenced the SC data, the temperature variations, the experiment took place in two different rooms, one for each VR setup, with uncontrolled temperatures. Additionally, the CAVE system emitted a considerable amount of heat, which warmed the room during the day. As a result, some participants noted a noticeable temperature difference between the two rooms. Some even complained about the heat in the CAVE, particularly after the device had been running for several hours. Due to these factors, the SC data was considered unreliable for analysis. Data analyses were performed using the SPSS software. Normality checks were performed for each data, and statistical tests were used accordingly. The significance threshold was set to .05.

4.3.1 Physiological data

Regarding HR data, we initially normalized the participants' HR values to enable a comparison of their HR means during the experiment while mitigating individual differences. In other words, we re-scaled all the HR data for each participant to a common scale ranging from 0 to 1. Here, 0 represents their minimum HR value, and 1 represents their maximum HR value. This normalization process allowed us to compare the mean HR across participants during the experiment. A Mann-Whitney test revealed that participants reported a significantly higher HR when using the HMD ($M = .594, SD = .041$) compared to using the CAVE system ($M = .529, SD = .037$), $U = 144, p = .05$). Among participants, seven had a higher HR with the HMD and six with the CAVE, and based on Kendall's correlation test, these differences were not induced by the first trial modality, $r = -.225, p = .435$.

4.3.2 Psychological data

Besides physiological data, participants had to fill a VRSQ and a MISC after each trial. The VRSQ contains nine items, while the MISC consists of a single ten-point Likert-scale question. A Mann-Whitney test between modalities on VRSQ and MISC results showed no significant differences between both hardware, $U_{VRSQ} = 106.5, p = .211, U_{MISC} = 112.5, p = .137$ (see Table 1). A finer analysis of each VRSQ item also failed to show differences Though, it may be noticed that, except for the "blurred vision" item, the scores for all items were higher for the CAVE modality, a similar observation could be done with the MISC's scores ($M_{CAVE} = 1.47, M_{HMD} = 1.06$).

4.3.3 Application data

Three different data were collected from the application during the experiment: the time needed to complete the task, the users' position in the virtual environment every 0.2 seconds, and the head rotation angle every 0.2 seconds. Figure 4 summarizes the results. A Mann-Whitney test on time completion highlighted differences between the CAVE ($M = 795s, SD = 960s$) and the HMD ($M = 616s, SD = 401s$), $U = 91.5, p = .034$. As expected, participants needed more time to complete the trials with the CAVE. From the users' position in the virtual environment, the total amound of movement in the virtual environment was computed in each modality. A Mann-Whitney test did not show any significant differences between the CAVE and the HMD ($M_{CAVE} = 453.2$m, $SD_{CAVE} = 100,1$m, $M_{HMD} = 414$m, $SD_{HMD} = 93,71$m), $U = 117, p = .178$. User's virtual movements were drawn on a 2D representation, however no conclusion could be drawn from these data.It was noticeable that some users could easily find their path and orient themselves in the environment, while other participants had more difficulties.

Similarly, from the users' head rotation angles, the total absolute rotations made during the experiment were computed in angle. A Mann-Whitney test did not result in significant differences between both VR systems ($M_{CAVE} = 7540,61\angle$, $SD_{CAVE} = 2576,305\angle$, $M_{HMD} = 7250,04\angle$, $SD_{HMD} = 2364,431\angle$), $U = 143, p = .486$.

Furthermore, the participants' looking side was checked (i.e., whether their gaze was rather oriented to the right or the left). Fourteen out of the seventeen participants looked mainly to the right side in the CAVE modality, whereas nine participants did so with the HMD. Participants' head rotations tended to vary less with the CAVE, with 82% of the participants always looking to the right side against 53% with the HMD.

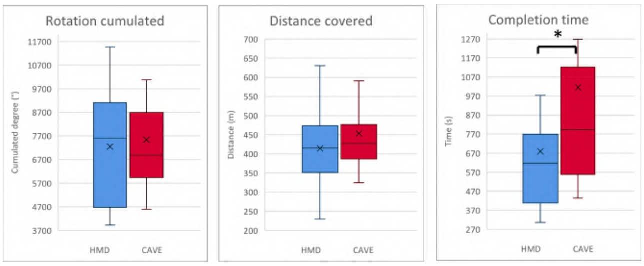

Figure 4: *Total head rotations made during the experiment, total distance traveled in the virtual environment, and task completion time.*

4.3.4 User feedback

At the end of the experiment, participants were presented with the following question: "If you had to redo the application with the same interaction, would you prefer to use a CAVE system or an HMD, and why?" In response to the first part of the question, twelve participants expressed a preference for the HMD, while two participants favored the CAVE. Three participants did not provide an answer, citing insufficient time spent within the VE to make a decision. Several recurring reasons against the CAVE system were mentioned by participants. These included perceptions that "controls are harder with the CAVE," despite the fact that the controls for both the CAVE and the HMD were identical. Other comments included observations that "we can see the screen's boundaries" in the CAVE, and that "it is easier with the HMD to look around,"

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Table 1: *Mann-Whitney test results for each item of the VRSQ*

Item	General discomfort	Fatigue	Eyestrain	Difficulty focusing	Headache	Fullness of head	Blurred vision	Dizzy	Vertigo
U	105.5	95.5	113.5	118.5	127	120.5	104.5	102	105.5
P-value	.402	.224	.590	.724	.985	.780	.381	.341	.402

often accompanied by the statement that "I tried to limit rotations because it is unpleasant." One participant also commented on the CAVE, noting a fundamental difference between the two devices: "the mix between the VE and reality is complicated to grasp." On the other hand, comments in favor of the CAVE highlighted that participants did not feel shielded from reality in this setup, and they perceived less constraint compared to the HMD. Criticisms of the HMD primarily revolved around issues such as screen resolution limitations and lens fogging (partially due to participants wearing face masks as a COVID precaution).

4.4 Discussion

Significant differences in completion time were observed, supporting H1. The task took longer to complete in the CAVE compared to the HMD. This finding contrasts the results reported by Tcha-Tokey et al. (2017) [TTLECR17] who found no differences. Given that there were no significant differences in rotation angles or movements between the two devices, this discrepancy in completion time may stem from participants taking additional time to orient themselves or establish their position within the VE. Consequently, it appears that users find it more challenging to understand their position in VR when using a CAVE compared to an HMD. Regarding head rotations, the lack of significant differences between the two devices could have several explanations, including the ease of turning to the right side with a controller, particularly for right-handed individuals. Unfortunately, the participants' dominant hand was not recorded in this study. Another factor to consider is the visibility of the user's hand in the CAVE, while in the HMD, only the controller was visible. The ability to see one's hand may serve as an incentive to look in the corresponding direction, suggesting the potential benefit of implementing users' hand avatars in the HMD.

Supporting H3, HR was higher in the HMD condition, which can be an indicator of cybersickness. However, when examining the VRSQ and MISC responses, no significant differences in symptoms or uneasiness were evident. From the participants' perspective, no cybersickness was reported. It is noteworthy that the CAVE modality yielded slightly worse results in terms of VRSQ and MISC outcomes, although the lack of significant differences prevented the distinction between the two hardware setups. Participant feedback overwhelmingly favored the HMD, confirming H2. This preference could stem from the broader popularity of HMDs compared to CAVEs, potentially resulting in a more favorable perception of HMDs.

Participants' arguments in favor of the CAVE included feeling less constrained compared to the HMD, aligning with findings by Kwok et al. (2018) [KNL18]. In summary, only HR and completion time exhibited significant differences between the CAVE and HMD, supporting H1 and partially supporting H3. These results were unexpected, given that differences between the two VR systems were expected to induce variations in perception, navigation, rotation, or cybersickness, as observed in previous research [RVH13, GFC*18, MCM14].

These findings suggest that for the same application displayed on both systems, there may be no significant impact on user experience, even though user behavior, such as longer completion time in the CAVE, was affected. However, this conclusion is specific to a VE developed with similar characteristics and interactions as ours. Indeed, the environment used in this experiment is specific.

5 Experiment 2: Virtual navigation and cybersickness

Following the first experiment, we decided to conduct a second study, employing a different navigation method and environment. Due to technical issues with the CAVE used in the initial study, we opted to utilize another CAVE, referred to as *C2*, as previously introduced. This CAVE exhibits distinct characteristics, with the most notable difference being the absence of a top screen. However, the size of the side screens is substantial enough that the absence of a top screen is practically imperceptible. Furthermore, we acquired new equipment in the meantime, enabling us to adapt our data collection methods, as elaborated upon later.

This experiment addresses cybersickness effects but within different navigation methods. The associated research questions are:

RQ1. Does optical flow have a higher impact on cybersickness?
RQ2. Is the sliding navigation preferred for CAVE applications?

Addressing this question may give insights into the development of optimized VR applications with respect to the device used, the scenario and the users. The hypothesis for this experiment is:

H1. Higher optic flow in the HMD will lead participants to experience more cybersickness symptoms than in the CAVE system.

We conducted a between-subject user experiment to assess variations in cybersickness effects between a CAVE system and an HMD, both utilizing the same application and tasks. Specifically, we employed the *C2* CAVE and HTC Vive devices for this experiment. We created an immersive application set within a virtual forest environment (see Figure 6). To ensure a meaningful comparison between the two devices, we took great care to make the experiences as similar as possible. Participants were required to enter the virtual environment, where they were subsequently guided within it. Importantly, interaction within the application was not permitted; participants were instructed to follow a fairy character using their gaze (see Figure 5). The primary role of the fairy character was to direct the user's gaze, ensuring that they knew their next direction within the virtual environment. Additionally, it served the purpose of constraining the user's visual focus in specific directions to maintain a consistent and comparable experience for all participants. The duration of the virtual walk was set at 12 minutes and 30 seconds. The design of the application was intentionally crafted to maintain the immersive quality of the simulator while still representing a plausible use case for a VR application. During the experience, users appeared to slide on the ground (similar to using a joystick) as they traversed various environments, including forests and buildings. Navigation also accelerated as they progressed through the virtual world, from 3m/s to 8m/s. (Increasing by 1m/s at 326sec, 420sec and 600sec and by 2m/s at and 690sec).

Figure 5: *The fairy environment developed for experiment 2*

Figure 6: *Top down view of the Virtual environment*

5.1 Participants

37 participants (mean age= 27 ± 5, 16 females) participated in this experiment. To participate, they were able to register by mail, and we requested them to be available for one hour upon arrival. They were divided into two groups, one (N=20, 7 females) that performed the task in the CAVE system, and the second (N=17, 9 females) in the HMD system.

5.2 Experimental protocol

The following protocol was followed for both the CAVE and the HMD modalities. These two modalities were conducted in two separate locations, spaced two weeks apart. Upon their arrival in the experimental room, participants were presented with a consent form that outlined the details of the experiment. After participants accepted and signed the form, we proceeded to place the E4 wristband on their wrist. Once the wristband was set up, it was activated to establish a baseline HR for each participant. Simultaneously, participants were requested to complete a demographic questionnaire. Following the completion of the questionnaire, we conducted an initial postural balance test to assess participants' postural stability before their exposure to VR. This test utilized the Win-Posturo device. We escorted participants to the designated experimental room (either CAVE or HMD). We introduced them to the setup and explained the task they were required to perform during the experiment. Specifically, following the fairy character with their eyes and maintaining their initial body orientation. We emphasized that they should refrain from moving their body and could halt the experience at any point if they felt the need to do so. They then started on the virtual forest walk, spending a total of 12 minutes and 30 seconds within the application, a duration necessary to complete a full lap in the virtual environment (see Figure 7). Each participant engaged in the experiment once, using one of the two systems. Upon concluding their experience with the application, we conducted another postural recording. Participants were asked to complete two questionnaires: the Virtual Reality Sickness Questionnaire and the Slater-Usoh-Steed questionnaire [UCAS00]. Prior to their departure, we offered beverages and ensured that participants were feeling well.

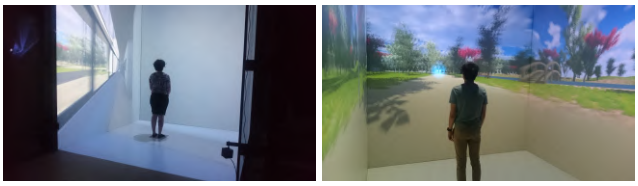

Figure 7: *The two types of virtual environment, seen through the C2 CAVE. Left: inside a building/right: in the forest*

5.3 Results

In this experiment, physiological data (heart rate–HR and postural stability–speed and distance) and psychological data (VRSQ) was collected to assess cybersickness, we did not carried MISC as it can be seen as redundant. The data of one participant was removed from the analysis of the results, since he was feeling overheated due to the room temperature. Data analyses were performed using the SPSS software. Normality checks were performed for each data, and statistical tests were used accordingly. The significance threshold was set to .05.

5.3.1 Physiological data

We proceeded to analyze HR in the same way than the first experiment (i.e., normalization and individual differences). A Mann-Whitney test revealed that the heart rate was not significantly different between the HMD ($M = .606, SD = .132$) and the CAVE ($M = .491, SD = .191$), $U = 102, p = .065$. Paired samples t-tests were used on the postural stability normal data (Shapiro-Wilk test > 0.05) to compare the pre and post measures for each device separately. The stability data was measured with a postural stability balance, from which we retrieve the distance from gravity center and speed of movement. Results show that for the HMD, both distance and speed are significantly different between pre and post experiment ($t(15) = -2.58, p = .021$ and $t(15) = -2.41, p = .029$, respectively). However, results show no difference for the CAVE system ($t(19) = -1.28, p = .215$ and $t(19) = -1.20, p = .245$, respectively for distance and speed).

5.3.2 Psychological data

A Mann-Whitney test on VRSQ reveled no significant differences between both hardware, $U_{VRSQ} = 166, p = .457$. A finer analysis of each VRSQ item also failed to show differences (see Table 2).

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Table 2: *Mann-Whitney test results for each item of the VRSQ*

Item	General discomfort	Fatigue	Eyestrain	Difficulty focusing	Headache	Fullness of head	Blurred vision	Dizzy	Vertigo
U	155	138	165.5	134	146.5	157	166.5	136	158
P-value	.321	.156	.450	.119	.175	.328	.458	.145	.353

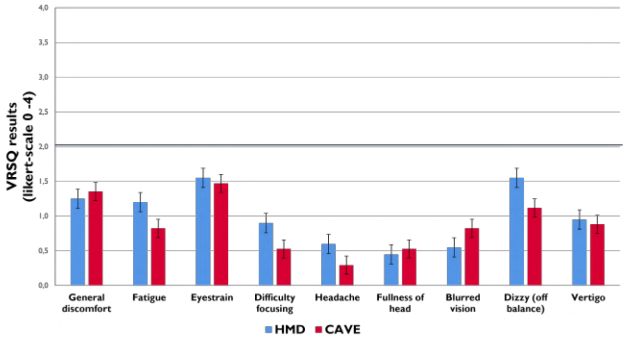

Figure 8: *VRSQ items for the second experiment*

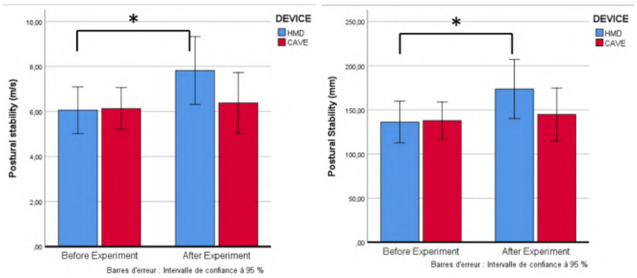

Figure 9: *Postural Stability*

5.3.3 User feedback

Participants' feedback notes their preference for wider environments and the difficulties encountered inside the building. They all perceived an increased speed inside the building. Moreover, most of them remarked that "inside the building, it was unpleasant, or less pleasant than outside." This aligns with past research that narrow environments increase cybersickness and are perceived as more uncomfortable for users.

5.4 Discussion

Only the postural stability showed some changes within the HMD modality, but not with the CAVE despite an application developed to induce simulator sickness. As the protocol follows a between-subject design, we cannot say whether participants preferred one device over the other. Nevertheless, with both devices, we noticed discomfort during the passage into the buildings. At this moment, the optic flow is higher, as there are more 3D models close to the view and moving along the user's passage, validating part of previous research that higher optic flow might induce more cybersickness [LC19, LSB22]. Although these results are surprising, they may be due to the relatively low sample size. The recent technical improvements of the devices may contribute to less severity of cybersickness effects. Another possibility is that the technology is more accessible, and people are less and less naive to these technologies, and therefore less sensitive to the effects of the simulator.

6 Conclusion

Our study aimed to compare two devices, CAVEs and HMDs, through two different experiences with distinct navigation methods. While we expected to observe differences in behavior, navigation, and cybersickness, we were surprised to find relatively few clear distinctions between the two devices. In both experiments, HMDs showed potential cybersickness symptoms, such as increased HR (in both experiences) and postural stability (in the second experience). Although we observed HR variation, this physiological data might be dependent on various factors other than just cybersickness. Therefore, we cannot draw conclusions solely based on it [CGAGZG21]. In addition, in this study, we only analyzed HR mean differences between participants, which might limit the generalization of these results. However, when participants self-assessed their cybersickness through questionnaires, no significant cybersickness was reported. We observed rotation differences in the first experiment, but these findings were inconclusive, as various factors could have influenced the results. Nevertheless, based on participant feedback, HMDs were preferred for controlled navigation, and they completed tasks faster with them. Thus, HMDs appear to be better suited for applications involving exploration in large environments. However, this preference for immersive headsets should be balanced against the risk of potential cybersickness.

One limitation of our study is that in the second experiment, participants were not free to navigate in the large environment, which could have impacted the results on cybersickness effects since they were unable to anticipate movement. Moreover, the experimental design did not allow us to directly ask participants which display they preferred, a key outcome of the first experiment. Therefore, our next step would be to combine the two experiments and investigate whether the results differ when participants have control over their movement in the virtual environment.

In conclusion, for a large environment navigation that involves frequent rotation, immersive headsets may be preferred over CAVEs, considering the shorter completion time and user preference. However, the risk of cybersickness symptoms should also be taken into account. Further research is needed to explore the effects of controlled navigation on cybersickness symptoms in both devices.

7 Acknowledgments

This work was supported in part by a grant from the French-German University (UFA-DFH) No. CDFA 03-19 and by French government funding managed by the National Research Agency under the Investments for the Future program (PIA) grant ANR-21-ESRE-0030 (CONTINUUM).

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