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Theo COMBE, Jean-Rémy CHARDONNET, Frédéric MERIENNE, Jivka OVTCHAROVA - CAVE and HMD: distance perception comparative study - Virtual Reality - Vol. 27, n°3, p.2003-2013 - 2023

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CAVE and HMD: distance perception comparative study

Théo Combe¹  · Jean-Rémy Chardonnet¹ · Frédéric Merienne¹ · Jivka Ovtcharova²

Abstract

This paper proposes to analyse user experience using two different immersive device categories: a cave automatic virtual environment (CAVE) and a head-mounted display (HMD). While most past studies focused on one of these devices to characterize user experience, we propose to fill the gap in comparative studies by conducting investigations using both devices, considering the same application, method and analysis. Through this study, we want to highlight the differences in user experience induced when using either one of these technologies in terms of visualization and interaction. We performed two experiments, each focusing on a specific aspect of the devices employed. The first one is related to distance perception when walking and the possible influence of the HMD's weight, which does not occur with CAVE systems as they do not require wearing any heavy equipment. Past studies found that weight may impact distance perception. Several walking distances were considered. Results revealed that the HMD's weight does not induce significant differences over short distances (above three meters). In the second experiment, we focused on distance perception over short distances. We considered that the HMD's screen being closer to the user's eyes than in CAVE systems might induce substantial distance perception differences, especially for short-distance interaction. We designed a task in which users had to move an object from one place to another at several distances using the CAVE and an HMD. Results revealed significant underestimation compared to reality as in past work, but no significant differences between the immersive devices. These results provide a better understanding of the differences between the two emblematic virtual reality displays.

Keywords Virtual reality · Distance perception · Interaction paradigms · CAVE · HMD

Jean-Rémy Chardonnet, Frédéric, Merienne and Jivka Ovtcharova have contributed equally to this work.

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1 Introduction

Cave automatic virtual environments (CAVEs) are still barely used compared to popular virtual reality broadcasting tools, such as head-mounted displays (HMDs), used for training, education or events. Currently, CAVE systems are mainly employed for collaborative reviews or data visualization. Through the financial lens, there is no point in using CAVEs instead of HMDs, while it may not be that clear through the user experience lens. Even though the same application is displayed on both systems, they offer different user experiences (Mohler et al. 2008; Tcha-Tokey et al. 2017) due to their physical characteristics, including the devices worn to use them and the eye–screen distance. This paper focuses on two technical differences between a CAVE and an HMD that may influence user experience. We focus on these two features (weight and eyes–screen distance) because they are inherent differences between both devices and are not avoidable.

2 Background

2.1 Device characteristics

The main differences between an HMD and a CAVE relate to their hardware properties. The resolution, computer rendering capabilities, latency, the distance between the eyes and the screens, screen curvature, field of view (FOV) and field of regard are among the main differentiating factors that might influence users' perception and immersion, independently of the applications being displayed.

A fundamental influencing difference between HMDs and CAVEs is the eyes–screen distance. The focal distance is determined in HMDs by the system itself, thanks to their optical properties (i.e. screen curvature or image deformation). The focus distance is set by the manufacturer and is fixed. Therefore, for objects not placed at the focal distance of the HMD, the user will face a visual conflict (Kramida 2015; Zhan et al. 2020). This conflict can lead to a vergence–accommodation conflict, vergence and accommodation representing both usual distance estimation clues used by our brain to estimate distances in our daily life, especially short distances. Indeed, according to Cutting and Vishton [5], motion parallax and binocular disparity are cues that are used to estimate distance for distances under 30 ms, and convergence and accommodation are effective for estimating distances under 2 ms. Vergence and accommodation are not visible cues that we can affect with visual stimulus. When user look at a specific point, his eyes will respond in specific ways. Vergence refers to the process where the eyes converge or come together to focus on the object, while accommodation involves the eyes adjusting their lenses to ensure a clear and sharp image (Shibata et al. 2011). This well-known conflict has been reported to impact distance perception (Ghinea et al. 2018; Marsh et al. 2014). In CAVE systems, the focus distance might be variable, according to the movement allowed within the application (i.e. if the user is allowed to move physically inside the system, the focus distance will vary) (Zhan et al. 2020), which can create a visual conflict, but of a different nature. Inside an HMD, this distance is fixed (the average distance is between 0.75 to 2 ms). At this point, it is interesting to acknowledge the study of Hartle and Wilcox (Hartle and Wilcox 2021). They compare depth perception within a virtual and physical environment and the impact of binocular disparity and motion parallax. Similar results were found within both modalities. These results contrast with other research, which claims that the difficulties in estimating distance when using VR devices arise due to technological limitations.

The HMD's weight is another critical differentiating feature *vis-a-vis* CAVEs. While HMDs usually weigh

between 500 and 1000 gs (e.g. 1038 g for the HTC Vive Pro, 503 g for the Oculus Quest 2 and 600 g for the PlayStation VR), the device worn by users in CAVE systems (which is typically a paired of tracked stereoscopic glasses) is lighter, usually less than 100 gs. The HMD's weight is five to ten times larger on the users' heads than with CAVE systems. We could rightfully wonder whether this factor impacts the distance perceived when walking with such devices on the head. The HMD's weight might influence distance perception when the application requires physical movement. Past research has indicated that the intention to interact within a virtual environment, the expected effort, or the weight inflicted on users impact distance perception (Proffitt et al. 2003; Renner et al. 2013; Witt et al. 2004).

Another significant difference with HMDs is that CAVEs allow for seeing physical cues, starting with our own body, which can help better estimate distances (Mohler et al. 2008). For instance, Marsh et al. demonstrated that participants tend to use visual cues outside the visual information provided by the environment, such as the screen edges, and they use them to estimate distances in the virtual world (Marsh et al. 2014). In fact, virtual worlds are generally created with only usable or relevant visual cues, therefore, without any objects considered useless, whereas these may be useful to estimate distances correctly. On the contrary, in the real world, accurate estimations can be performed by looking at surrounding objects. Whatever the VR system used, CAVE or HMD and their characteristics, distances are usually underestimated in virtual reality compared to reality. On average, this misestimation is 74% of the modelled distances (Renner et al. 2013).

As VR technologies rapidly progress, distance estimation with recent HMDs seems to improve (Kelly et al. 2017), which may originate from an enhancement in image quality, FOV, miniaturization, focus depth or tracking systems. These technical issues may disappear with technological progress (Kelly et al. 2017; Renner et al. 2013; Cordeil et al. 2017), thus improving all aspects of user experience, including cybersickness, distance perception or eye strain. These improvements are, however, less observed with CAVE systems, as they tend to become prevalent in research laboratories or big companies since their price is still high, making them not easily available for personal use. At this point, it is worth noting that CAVE systems are defined by wide screens and tracking systems allowing applications to provide consistent viewpoints in the virtual environment according to the users' head rotations and movements. Such systems are of particular interest for some applications, including collaborative XR. There exists a whole spectrum of devices labelled as CAVEs, but they are noticeably different from each other. For instance, some have wide screens put side by side, forming a horseshoe shape. Others are like corridors, with wide curved screens, or box-like with three to five

sides. These differences in the structure of these devices may impact past results and make it difficult to compare results from different studies. Indeed, the variety of the technology used in CAVE systems depends mainly on the cost associated with its acquisition (i.e. projectors, tracking system, GPUs and hardware, display method and additional interactive devices). The price associated with such systems might range from 10.000 euros (for an L-shape CAVE) to more than 100.000 euros, reaching even prices above 1 million euros (BlueLemon)¹. In contrast, HMD systems have been more democratized in the past years, with prices ranging from 400 (Meta Quest 2²) to 4.000 euros (Varjo VR-3³)

2.2 Virtual environment development

In addition to differences in device characteristics, limitations may also arise from the application itself, including the graphics quality, the environment size, the behaviour accuracy and the interaction easiness. Past studies explored the effect of an abrupt change caused when entering a virtual environment. Since the displayed virtual environment is generally different from the real one where virtual immersion is proposed, a sudden change of environment may be too brutal for the brain, which may lead to considering all the visual information displayed when the change occurs as fake (Ries et al. 2006). Results revealed that immersion and distance estimation could be significantly improved. A study measuring the participants' movements inside a virtual environment, considering both an HMD and a CAVE, was conducted (Colley et al. 2015). Regarding the characteristics of size, impression, height, movement, control and realism, participants preferred the HMD over the CAVE, even though eight out of thirty participants noticed that the picture was sometimes "choppy" when using the HMD. Additionally, participants reported difficulties in orienting themselves when using the CAVE.

According to a review made in 2013 Renner et al. (Renner et al. 2013), different aspects may be important for presence, immersion and distance perception. Indeed, they pointed out that presence in a virtual world may enhance distance perception, which means that some specifications for the virtual environment may positively influence distance perception. Since, in real life, we use many different visual cues to determine the correct size of an object or distance, modelling rich virtual environments could improve distance estimation in virtual environments too. Therefore, in this study, we decided to reproduce an office with the exact size and add some furniture on the surroundings.

¹ <https://steantycip.com/vr-cave/>.

² <https://www.meta.com/quest/products/quest-2/>.

³ <https://b2b-store.varjo.com/product/varjo-vr-3>.

3 Methods

3.1 Research questions

Since a CAVE and a head-mounted display present strong differences while both allowing immersion in a virtual environment, the user experience may be consequently impacted. In this study, we first focus on fundamental differences inherent to the technology itself. Three research questions were then derived as follows:

- When using a CAVE, we wear only a pair of light glasses, while when using an HMD, we wear a helmet with a possibly significant weight. Therefore, does the device's weight significantly affect perception and to what extent?
- Screen-eye distance: while both display systems suffer from accommodation-vergence conflict, HMD's eye to screen distance (or focal distance to the screen) is fixed compared to CAVE's eye to screen distance (which can vary depending on user's position). Therefore, we asked ourselves to what extent does this eye-screen difference impact distance perception at close range?
- By applying past research results on VR development for improving distance estimation, will distance underestimation significantly decrease?

3.2 Contributions

This paper aims to characterize user experience with two different systems, a CAVE and an HMD. More specifically, we try to isolate differences to highlight whether these specific dissimilarities are meaningful for user experience. Past research has mainly focused on the effect and usability of HMDs rather than CAVEs, or the usability of CAVEs for collaborative virtual environment (CVE), while studies comparing both systems are still sparse, (Cordeil et al. 2017; Ens et al. 2019). Thus, in this paper, we present two different user studies, each with a specific goal.

The first experiment concentrates on the HMD's weight, as past research has assessed its contribution but keeps biases, such as virtual reality visualization or a restricted FOV. Here, we tried to remove every possible bias to better characterize the effect of weight on perception.

In the second experiment, we compare interaction in virtual environments using a CAVE and an HMD, considering a simple interaction in the arm's range. The metric used is distance estimation.

3.3 Characteristics of the virtual reality systems

To carry out our experiments, we used two distinct systems: a CAVE system on one side and two different HMDs.

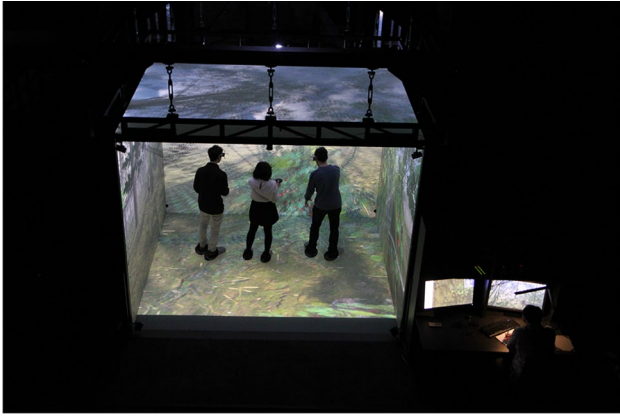


Fig. 1 The BlueLemon CAVE system

The CAVE system we used is called the BlueLemon, and it is composed of five screens (front, left side, right side, top and bottom). The dimensions of the BlueLemon are 3.40 m (W) \times 2.70 m (H) \times 3 m (D) (see Fig. 1). On each screen, active stereoscopic retro-projection is performed through Mirage 4k25 projectors, achieving a resolution of 4096 \times 2160 pixels at a 120 Hz framerate. An ART tracking system⁴ 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 a message-passing interface. Virtual environments are created with Unity3D, and the whole display and interaction process is managed by a C++ library called iiVR (internally developed), which connects all devices within the BlueLemon. For our experiment, the only device used was an ART Flystick device for users to interact (manipulate virtual objects) within the virtual environments.

Regarding the HMDs, we used an Oculus Quest 2 for the first experiment and an HTC Vive Pro for the second experiment. The choice of a Quest 2 for the first experiment was motivated by its convenience of being wireless. Since in the first experiment, our goal was only to study the influence of the HMD's weight without introducing any other bias, such as virtual environment visualization, we specified only the weight of the Oculus 2, which is 503 gs. The HTC Vive Pro is another well-known HMD providing a resolution of 1440 \times 1600 pixels (2880 \times 1600 for both eyes) at a 90 Hz framerate and a 110-degree field of view. 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 the HTC were used to interact within the virtual environments.

⁴ <https://ar-tracking.com>.

4 User studies

In this section, we detail the two experiments performed to study the differences between HMDs and CAVEs. For each of them, we present the objectives and hypotheses, then the experimental designs are presented. Our studies proceed very much in the same way as in the study of Cordeil et al., where the purpose is to only alter one factor: the VR platform used (Cordeil et al. 2017).

4.1 Objectives and hypotheses

4.1.1 Experiment 1: Impact of weight on distance travel estimation

Our first experiment evaluates the impact of the HMD's weight on walking distances. Consequently, we designed an experiment isolating this factor from other factors that could impact the user's distance perception, such as visualizing an environment. The Oculus Quest 2 HMD and a blindfold were worn by participants in one condition and only a blindfold in the other condition, ensuring that participants could not see the real environment surrounding them in any way. Unlike previous studies (Mohler et al. 2008; Marsh et al. 2014), we did not use previous perceived targets or perceptual matching. Indeed, we did not want participants to estimate distances to a target or estimate distances between two entities. The objective was for participants to estimate their own walking distance. Therefore, we analyse the walking distance perception with an HMD worn through the blind walking judgement method. We made the following hypothesis for this experiment:

H1 *The HMD's weight will negatively impact the distance participants travelled, i.e. they will overestimate their walking distance when wearing the HMD and the blindfold.*

In other words, we assume that the HMD's weight, not present with CAVE systems and impossible to avoid, is a crucial factor to be considered when developing a VR application that could be transposed from one VR system to another.

4.1.2 Experiment 2: Interaction distance estimation

In our second experiment, we wanted to assess the differences between a CAVE and an HMD in distance perception for an arm range interaction. Past research shows a positive impact of 3D modelling fidelity to the real world or the presence of different visual cues on distance perception (Renner et al. 2013; Ooi et al. 2001; Park et al. 2021). Moreover, a simple grab technique was used as the means to pick

and place objects, and it was the only interaction metaphor implemented in the environment. This allowed participants to easily understand how to interact within the virtual environment. The office furniture was modelled according to the real one in terms of size and room arrangement. The objective was for participants to estimate exocentric distances by shifting a virtual cube to achieve a target displacement. Our hypothesis for this experiment is:

H2 *Distance underestimation will be less significant than in past research due to an accurate 3D modelling environment and the presence of visual cues.*

In other words, we assume findings from past studies to be confirmed if distance underestimation is lower but still exists. Conversely, if no significant difference between the aimed distance and the one achieved by participants is observed, either the results from past literature experiments could not be replicated, or they are not as significant as announced. Whatever the results found, this experiment may help us better characterize distance estimation errors with more recent technologies than the ones considered in past work. In that sense, we believe that technological improvement, such as increased resolution, lower data transfer delays, an increase in the FOV or lower HMD's weight, should improve users' perception without modifying or applying changes to the virtual environment.

4.2 Experimental design

4.2.1 Participants

Twenty-one participants (mean age = 25 ± 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. Upon arrival, they were asked to sign a consent form and fill in a short demographic questionnaire. The purpose of each experiment was not revealed to the participants until the end of the whole experimentation (experiments 1 and 2). At the end of the experimentation, they were free to ask any question they could have.

We decided to carry out all the experiments on the same day for convenience since it was not easy to find participants and ask people to come multiple times, especially considering the constraints imposed by the COVID-19 pandemic. During the whole experimentation, hand sanitizer was available to the participants and provided between every experiment. The devices (HMD, controllers and glasses) were systematically disinfected after each use. The experimenter kept wearing a mask during the entire process. However, the participants were allowed to remove their masks only while immersed.

4.2.2 Protocols

Upon arrival, participants were led to a first room where they were briefly explained the task they would have to complete, in which order and with which device. We asked them to fill in a consent agreement before starting the experiment. The whole experimental design is explained below, summarized in Fig. 3.

First experiment: Participants were guided to the experimentation room; they could see that they had space and would not have to worry about hitting something during the experiment. That was important to mention since they would be blindfolded; thus, they should not restrain their steps due to the uncertainty of the real environment. We also ensured them that the experimenter would stay beside them during the whole walk; thus, if they lost stability, he would be there to secure them. In this room, a rope was installed as a tutor to ensure participants walked in a straight line (see Fig. 4). The rope was stretched to remove any clue of distance that could be perceived by the rope bending. Participants were asked to walk for 2, 3 and 5 ms while wearing either a blindfold only (modality "B") or both a blindfold and the HMD (modality "H"). We asked participants not to count their steps and to walk in a usual way. In the latter condition, the HMD was set to the participants when they arrived at the starting point of the rope. Throughout the experiment, the HMD was turned off to avoid any bias related to image visualization. Participants were asked not to squeeze or sustain on the rope but to hold it slightly throughout the travels. They were requested to walk along the rope 9 times under one modality (either B or H) and 9 times under the other and divided as follows: 6 trials for each distance. The order of walking distances and modalities was counterbalanced. After each trial, the travelled distance was recorded. After completing all trials, which took approximately twenty minutes, participants were taken back to the first room to rest.

Second experiment: Once they finished experiment 1, participants were conducted to the second experimental room, either the BlueLemon (modality "C") or a room with the HTC Vive (modality "V"). They were seated on a chair facing the table of the virtual environment presented above (Fig. 2). Explanations about the tasks to complete and how to interact in the virtual environment were provided. In each modality, a few minutes were given to each participant to get familiarized with the environment, the interaction device and the interaction metaphor to use. Concerning the interaction device, a flystick (weight = 280 g) was used in the CAVE system and the HTC Vive Pro standard controller (weight = 208 g) for the HMD system. Concerning the interaction metaphor, a simple grab-release interaction was implemented using the trigger of the controllers. For the HMD modality,



Fig. 2 Left and Middle: Real office used as a model for the virtual environment. Right: Virtual scene developed under Unity3D for the CAVE and the HMD

Fig. 3 Experimental protocol

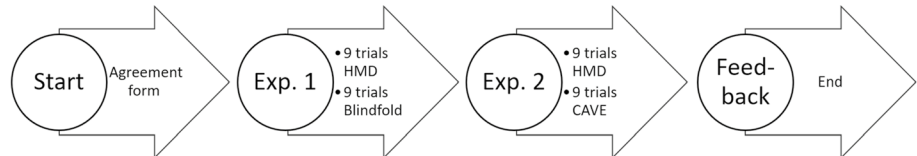


Fig. 4 Room for experiment 1. Participants were asked to hold the rope slightly as depicted by the virtual hand

we asked participants to set the IPD according to their sight. We further told them that the virtual environment corresponded precisely to a real environment in terms of size. Information concerning the interactable cube's size (side = 5 cm) and the virtual table on which it was placed (width = 1.20 m) was provided and repeated again once presented with the other modality. Participants were orally asked by the experimenter to move the cube 15, 50 and 80 cms to the right from the initial position, 9 times under one modality (either C or V) and 9 times under the other modality. The order of distances and modalities was counterbalanced. After each trial, the displacement distance was recorded.

After completing all trials for one modality, which took an average of five minutes, participants were taken back to the first room to rest before switching to the other modality.

5 Results

5.1 Data analysis

Data analyses were performed using SPSS software. The significance threshold was set to 0.05.

5.2 Experiment 1: Impact of weight on distance travel estimation

The experiment is a 2×3 within-subjects design. The first factor is the modality, with two levels: HMD (H) and Blindfold (B). The second factor is the distance, with three levels: 2, 3 and 5 ms. The dependent measure, error to target distance (in percentage), was calculated as the average of the 3 trials performed (per condition and modality). The means and standard errors are displayed in Table 1.

Concerning the statistical analysis, there were no outliers, as assessed by examination of studentized residuals for values greater than ± 2.75 . Data were normally distributed as assessed by Shapiro–Wilk's test of normality on the studentized residuals ($p > 0.05$). Therefore, a two-way repeated measures ANOVA was performed to first determine if an interaction effect exists (see Fig. 5). Mauchly's test of sphericity indicated that the assumption of sphericity had been violated for the two-way interaction ($\chi^2(2) = 8.01, p = 0.018$); therefore, results were adjusted following the Huynh–Feldt method.

The results show no significant interaction effect between the distance and the modality

Table 1 Experiment 1 mean and standard error for the distance error in percentage for the modality \times distance

	Blindfold			HMD		
	2 m	3 m	5 m	2 m	3 m	5 m
Mean	4.52	-0.47	-6.43	0.49	-3.75	-8.47
Std. error	5.27	4.13	3.69	3.36	3.23	2.85

Fig. 5 Experiment 1, distance to the target (in percentage). The mean and standard error for each modality and target distance

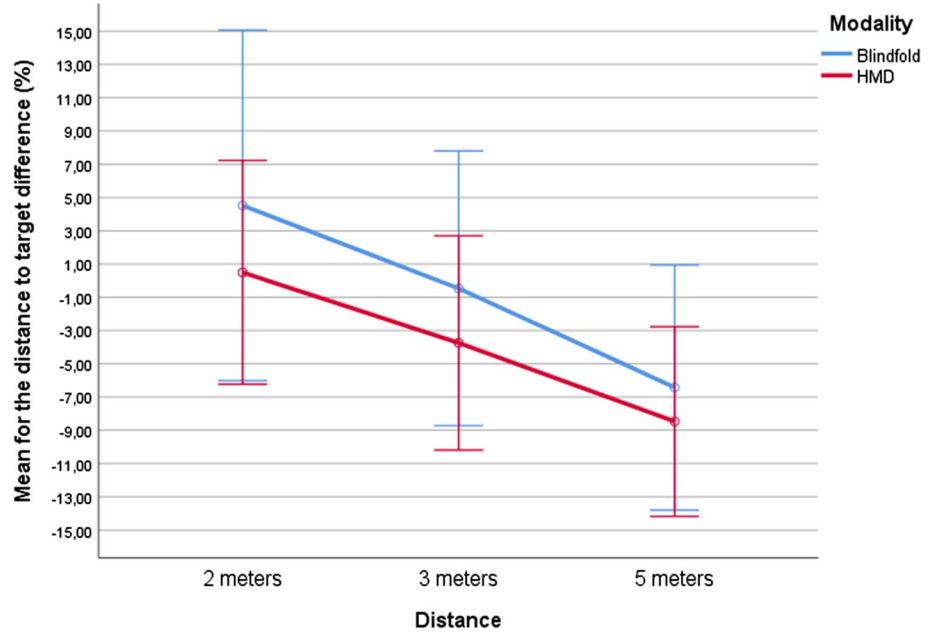


Table 2 Experiment 2 mean and standard error for the distance error in percentage for the modality \times distance

	HMD			CAVE		
	15 cm	50 cm	80 cm	15 cm	50 cm	80 cm
Mean	22.87	-8.26	-7.43	22.16	-6.22	-7.09
Std. error	4.08	1.64	1.91	3.83	3.11	1.89

($F(1.58, 31.61) = 0.23, p = 0.748, \epsilon = 0.790$). We analysed the main effects. No significant main effect of the modality was present ($F(1, 20) = 0.97, p = 0.336$). Mauchly's test of sphericity indicated an assumption of sphericity for the distance factor ($\chi^2(2) = 3.49, p = 0.175$). There was a significant main effect of the distance ($F(2, 40) = 11.21, p < 0.001$) on participants walking distance estimation. Pairwise comparison with Bonferroni correction show that there is no significant difference between two and three meters ($p = 0.109$), but a significant difference was found between two and five meters ($p = 0.002$), and between three and five meters ($p = 0.017$).

5.3 Experiment 2: Interaction distance estimation

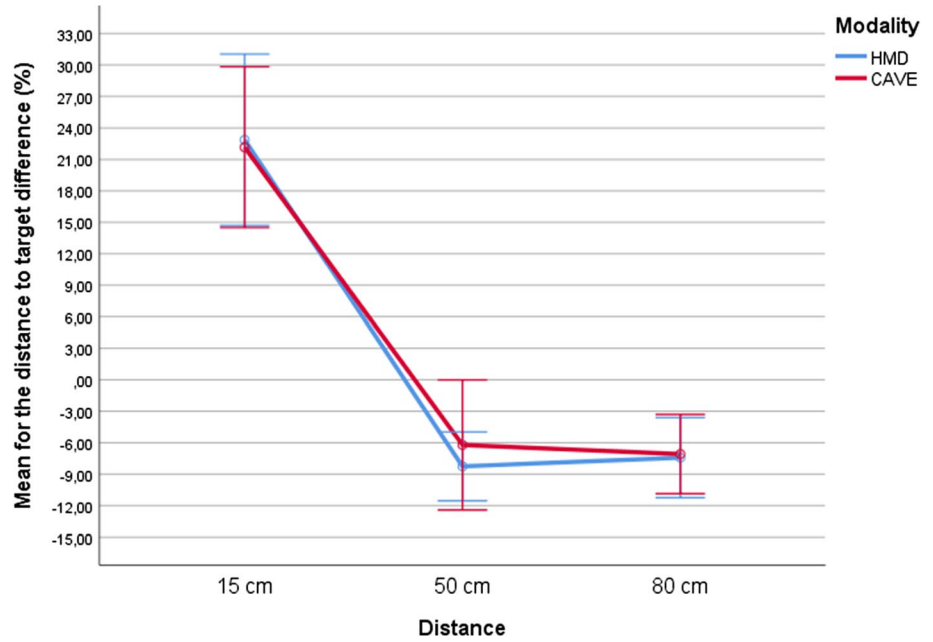
The experiment is a 2×3 within-subjects design. The first factor is the modality, with two levels: HMD (V) and CAVE (C). The second factor is the distance, with three levels: 15,

50 and 80 cms. The dependent measure, error to target distance (in percentage), was calculated as the average of the 3 trials performed (per condition and modality). The means and standard errors are displayed in Table 2.

Concerning the statistical analysis, two data points were considered outliers, as assessed by examination of studentized residuals for values greater than ± 2.75 . Outliers were removed from the positional data and replaced with the group means before analysis, following other researchers' works (Ricca et al. 2021). Data were normally distributed as assessed by Shapiro-Wilk's test of normality on the studentized residuals ($p > 0.05$). Therefore, a two-way repeated measures ANOVA was performed to first determine if an interaction effect exists (see Fig. 6). Mauchly's test of sphericity indicated an assumption of sphericity for the two-way interaction ($\chi^2(2) = 2.06, p = 0.357$).

The results show no significant interaction effect between the distance and the modality

Fig. 6 Experiment 2, distance to the target (in percentage). The mean and standard error for each modality and target distance



($F(2, 40) = 0.27, p = 0.767$). We analysed the main effects. No significant main effect of the modality was present ($F(1, 20) = 0.89, p = 0.769$). Mauchly’s test of sphericity indicated that the assumption of sphericity had been violated for the distance factor ($\chi^2(2) = 11.54, p = 0.003$). The Huynh–Feldt method was used to adjust the results. There was a significant main effect of the distance ($F(1.44, 28.44) = 50.65, p < 0.001, \epsilon = 0.721$) on participants’ exocentric distance estimation. Pairwise comparisons with Bonferroni correction show that there is no significant difference between 50 and 80 cms ($p > 0.05$), but a significant difference was found between 15 and 50 cms ($p < 0.001$), and between 15 and 80 cms ($p = 0.001$).

6 Discussion

6.1 Experiment 1

We observed that travel distances were significantly underestimated for distances greater than three meters, no matter which modality was used, HMD worn or not. However, we noticed that, with the blindfold worn, distances were slightly more overestimated than with the HMD. According to our study, we can conclude that the HMD’s weight itself can impact travel distances above three meters, partly assessing our first hypothesis (H1), but also confirming past works which show that distance underestimation can originate from the HMD’s weight and a restricted FOV (Grechkin et al. 2010; Willemsen et al. 2004; Vienne et al. 2020; Nilsson et al. 2015).

Additionally, some participants reported being destabilized by the HMD’s weight, leading them to walk less far. Several reasons can be proposed for this observation. First, the HMD’s weight may induce the body’s centre of gravity to move out of the participant’s postural stability area. Second, since the participants’ vision was occluded from reality, it may have impacted postural stability (Galeazzi et al. 2006).

As a consequence of our results, the HMD’s weight, not present with a CAVE, can be ignored if the setup does not involve a real displacement further than three meters.

6.2 Experiment 2

We compared distance estimation between two radically different VR systems after we developed our immersive application based on past work (Kelly et al. 2017; Renner et al. 2013; Willemsen et al. 2004). We found strong underestimation for short distances (15 cm), either in the CAVE or with the HMD, which supports the results from past research (Renner et al. 2013). This underestimation reduces when the distance rises up to 80 cm ($M_{15\text{cm}} = -24.22\%, M_{50\text{cm}} = -6.19\%, M_{80\text{cm}} = -7.0\%$), according to our findings. This result is in line with the research of (Vienne et al. 2020), although other authors found opposite findings (Lin et al. 2019). Interestingly, between both VR systems, no significant differences were observed. We can assume that no matter the condition, short distances are harder to reproduce accurately. Furthermore, by faithfully modelling a real-size environment with a medium-rich visual cues environment, we could reduce distance underestimation in a virtual environment, which

is in line with previous studies (Kenyon et al. 2008; Renner et al. 2013). These results support our hypotheses that distance underestimation will be less significant with recent hardware and the use of cues. These results cannot be generalized and only apply to interaction in the arms' range in a moderate visual cue-rich environment. Partially answering our research questions, the difference in eye–screen distance between the HMD and the CAVE has no impact on distance perception, for an arm's reach interaction, with the 3D model rendered in front of the screen. In addition, previous research had an underestimation of 26%, we have a smaller error for distances greater than 15 cms, so not using an empty 3D environment and newer technology can improve distance perception.

6.3 Limitations

We are aware that our research may have limitations. The first one is that we conducted the two experiments, one after the other. We decided to do this way for practical reasons, although this could have impacted our results. However, Melo et al. found that being immersed for below seven minutes does not impact the VR experience, which is applicable in our case (Melo et al. 2018). To reduce the potential impact of such an issue, we first carried out the experiment without any VR tool, then the experiment with interaction and virtual environment exposure. Nonetheless, we are aware that to be more rigorous, our whole user study should be conducted on several days, though another side effect may then appear related to different moods and states of health depending on the day.

Second, multiple trials were conducted over a short duration, and the break time between blocks of different conditions was relatively short. Moreover, we did not record the users' behaviours during the experiment or what their dominant hand was. However, we intend to add these observations in future works to get an exhaustive overview of the factors that could influence distance perception.

Third, the fact of studying distance perception and that our participants might have been able to understand this objective, even without specifying it, might have influenced the results. According to Durgin et al. (Durgin et al. 2012), participants might have modified their actions to fit our expected results by guessing the study objectives.

Finally, for practical reasons, we carried out the first experiment with the Oculus Quest 2 HMD, which is lighter than the HTC Vive Pro. Therefore, the results presented should not be interpreted for devices heavier than 500 g.

7 Conclusions

We presented two experiments to compare distance perception in CAVE and HMD systems. Unlike other research carried out in this area, we did not find significant differences between the CAVE and the HMD.

For the first experiment, our goal was to fill the gap that, to our knowledge, no study had explored yet, which is the impact of the HMD's weight alone. Past research tends to keep factors that can bias results. For example, some studies focused on the weight but kept vision (i.e. the HMD switched on) (Renner et al. 2013; Willemsen et al. 2004). In this study, we removed all kinds of possible biases. We could assess a fundamental difference between HMDs and CAVEs from our results to determine whether it could impact user experience. We found that the device's weight does not affect walking distance perception for usual VR areas (less than nine square meters). In the second experiment, we found consistent results with past research (Renner et al. 2013), stating that short distances are significantly harder to estimate than longer ones. However, no matter the distance, we could not highlight any differences between the VR systems. While there was a difference between the distance visualized in the virtual environment and the real distance, both devices showed the same limitations. Therefore, by accurately modelling the virtual environment, for example, by providing minimal visual cues in the virtual scene, we reduced distance underestimation for distances over 15 cm compared to past research.

As mentioned in the background section, CAVE systems price can be quite expensive compared to HMD. There are, however, low-cost solutions which can allow researchers to acquire a CAVE-like system, such as L-shape portable CAVEs⁵. We also would like to point out that since not significant differences can be observed regarding user experience and distance perception, as presented in this work, CAVE systems acquisition and use might be guided by specific application needs. In addition, other characteristics of these devices should be studied to determine the full potential of such devices.

In future works, we plan to explore other differentiating factors that might lead to differences regarding user experience between CAVE and HMD systems, such as field of view, field of regard and cybersickness.

Acknowledgements 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).

⁵ <https://www.imagin-vr.com/valise-vr>.

Data availability The data that support the findings of this study are available from the corresponding author, Théo Combe, upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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