Immersive Collaborative Analysis of Network Connectivity: CAVE-style or Head-Mounted Display?

Maxime Cordeil, Tim Dwyer, Karsten Klein, Bireswar Laha, Kim Marriott, Bruce H. Thomas

Abstract— High-quality immersive display technologies are becoming mainstream with the release of head-mounted displays (HMDs) such as the Oculus Rift. These devices potentially represent an affordable alternative to the more traditional, centralised CAVE-style immersive environments. One driver for the development of CAVE-style immersive environments has been collaborative sense-making. Despite this, there has been little research on the effectiveness of collaborative visualisation in CAVE-style facilities, especially with respect to abstract data visualisation tasks. Indeed, very few studies have focused on the use of these displays to explore and analyse abstract data such as networks and there have been no formal user studies investigating collaborative visualisation of abstract data in immersive environments. In this paper we present the results of the first such study. It explores the relative merits of HMD and CAVE-style immersive environments for collaborative analysis of network connectivity, a common and important task involving abstract data. We find significant differences between the two conditions in task completion time and the physical movements of the participants within the space: participants using the HMD were faster while the CAVE2 condition introduced an asymmetry in movement between collaborators. Otherwise, affordances for collaborative data analysis offered by the low-cost HMD condition were not found to be different for accuracy and communication with the CAVE2. These results are notable, given that the latest HMDs will soon be accessible (in terms of cost and potentially ubiquity) to a massive audience.

Index Terms—Oculus Rift, CAVE, Immersive Analytics, Collaboration, 3D Network

1 Introduction

In 2016 personal head-mounted displays (HMDs) for immersive virtual reality (VR) are reaching a mass market with the release of consumer products such as the Rift by Oculus and the Vive by HTC. While there are still technical hurdles around miniaturisation, focus depth and resolution, the current massive investment [7, 26, 40] into these technologies can be reasonably expected to resolve these issues in the near future. It is therefore timely to ask:
Does collaborative immersive visualisation no longer require the use of expensive equipment at universities or corporate data centres?

Over the last two decades expensive room-filling immersive visualisation facilities have been built at many universities and data centres (pioneered by the CAVE Automatic Virtual Environment [5]) to enable visualisation (particularly in scientific and engineering applications). Collaborative sense-making has long been regarded as one of their most important potential benefits. In particular, spatially immersive platforms such as the Allosphere (UCSB), the YURT (Brown University), CAVE2 (UIC), all consider support for multiple simultaneous users as a key requirement.

Collaborative visual data analysis is undoubtedly important. It allows multiple people to work together directly in a shared environment, improves shared understanding of the data, and is crucial for teams of users with different domain expertise [14]. While there have been some studies into collaborative scientific visualisation in immersive environments, to the best of our knowledge (§2) the study described here is the first to investigate collaborative visualisation of abstract data in any immersive environment.

There are obvious differences between these CAVE-style environments and the new breed of consumer HMD devices, for example: resolution, presence and freedom of movement (§1). Thus, to answer the question above, we need first to consider:
Will these differences be significant impediments to adoption of low-cost HMD devices for collaborative visualisation of abstract data?

This paper sets out to experimentally evaluate the relative merits of the HMD and CAVE-style environments in order to answer these questions for one representative collaborative visualisation task. Specifically, we focus on a type of data and task that is rarely considered in VR type environments: analysis of connectivity in network data.

We asked pairs of users to collaboratively complete two tasks: counting the number of triangles (3-cliques) and finding the shortest path between two nodes. Our research questions consider the effect of the VR platform on user task performance, collaboration and experience as detailed in §3, with more detailed hypotheses in §4.1. We found (§5) that:

- There were significant differences in task completion time and physical interaction between the two VR platforms;
- On the other hand, no significant differences were found in the degree and type of collaboration used by participants between the two VR platforms.

This is the first formal user study into collaborative analysis of abstract data using immersive virtual reality. Such a study is inherently complex with many linked aspects. It required:

- Developing an experimental platform for collaborative network visualisation tasks that tries to make the best use of immersion without unfairly disadvantaging either of the particular display technologies tested. This was a difficult and carefully considered part of our experimental design (§4.2).
- Constructing a multifaceted evaluation model to evaluate and analyse collaborative abstract visualisations in the VR platforms. This combines techniques and measures from HCI, VR, and InfoVis communities, and includes a mixture of objective and subjective measures. We consider self-perception of collaboration as well as shared focus (i.e. the proportion of time spent viewing the same parts of the 3D network) and communication (i.e. the verbal and non-verbal oral exchanges) between collaborators (§4.7).

In our study we chose to use a 3D network visualisation. While the use of 3D representations for abstract data like networks is not common in the Information Visualisation community there is some

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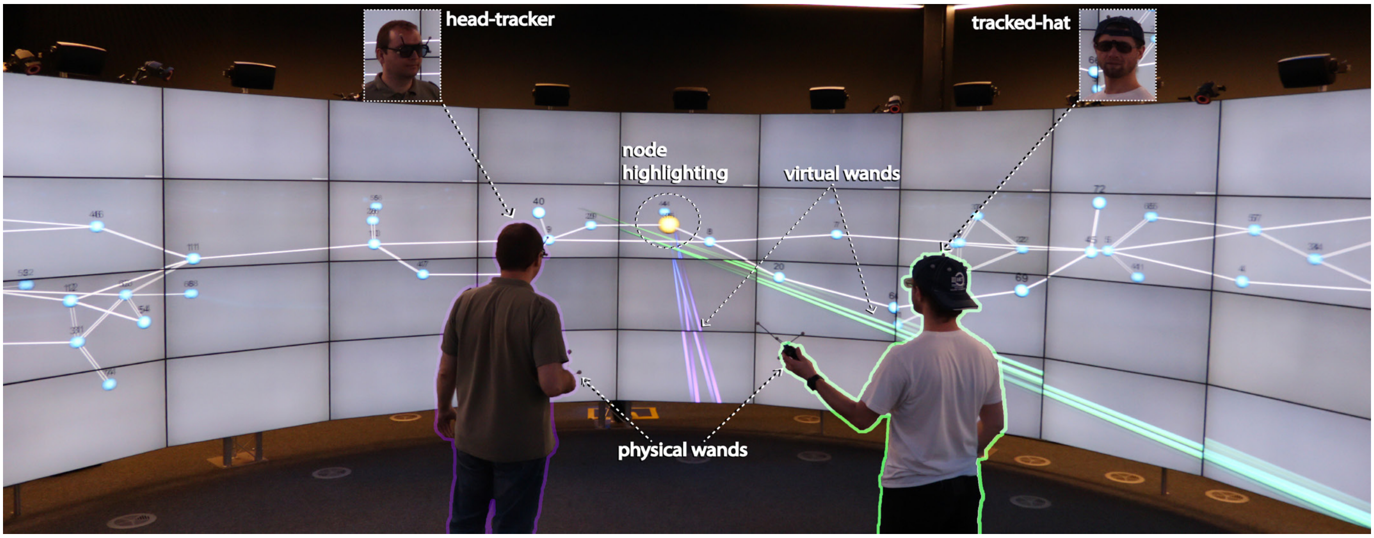


Fig. 1: The HT (purple, highlighting a node, left) and non-HT (green, right) participants viewing the 3D network in the CAVE2. The scene is rendered from the HT position. The virtual green wand is aligned from the HT participant view position.

evidence that stereoscopic 3D representations have advantages over 2D [11] and VR platforms naturally support such representations. However, our focus was not on comparing 2D and 3D network representations, rather it was on exploring the impact of VR platform on task performance, collaboration and user experience for some representative abstract visualisation.

2 Related work

Immersive environments for visualisation: During the last three decades, visualisation research employing Immersive Environments has largely focused on large spatial immersion displays and Virtual Environments (VEs), such as CAVEs and Head Mounted Displays (HMDs). These technologies are employed to immerse users into data graphics. High-resolution tiled displays have been shown to improve perception and navigation for visual tasks by Ball and North [3]. Their study showed that larger display area and resolution positively affects peoples' ability to find and compare visual targets. Shupp *et al.* [34] studied viewport size and curvature of large high resolution displays. They found that curved tiled displays increase user performance for route and target search tasks in the context of map visualisation.

VEs have proven effective in many scientific applications such as brain tumour analysis [41], archaeology [22, 35], geographic information systems [4], geosciences [17, 15] or physics [20]. Features such as head tracking and stereoscopy clearly improve user performance. These studies were mainly focused on the general field of scientific visualisation in a single-user virtual environment. Collaborative visual sense-making remains largely untested in immersive environments.

Abstract data visualisation in virtual reality: Raja *et al.* [33] evaluated 3D scatterplot visualisations in a CAVE environment for individual users. The results of the study suggested that higher degrees of physical immersion (e.g. number of projected walls and head tracking) allow less errors and completion time to solve the tasks. The authors also found that when enabled, head tracking reduces disorientation.

Ware and Mitchell [38] studied the perception of 3D node-link diagrams in different immersive conditions, such as stereoscopy and motion. They showed that stereoscopy reduces errors and response time in the perception of paths in 3D node-link diagrams. Alper *et al.* studied 3D stereo highlighting of 2D graphs [2]. They found that stereo enhances visual task performance such as finding elements in a graph and counting connections between nodes. Kwon *et al.* [23] investigated the effectiveness of graph visualisation and the impact of different layout techniques on readability in an HMD. The authors report that their 3D stereoscopic graph visualisation with an Oculus Rift outperformed traditional 2D graph visualisations.

Collaborative visualisation: Collaboration can play an important role in information visualisation by allowing groups of people to make sense of data [13, 19], and is a significant method for successfully understanding big and complex data [6, 9]. Paul *et al.* [32] have highlighted how important sense-making is when seeking information together, in addition to combining different roles and expertise of group members to resolve ambiguity in data interpretation. To date, little research has focused on collaborative and immersive environments for abstract visualisation.

VR platforms have shown benefits to support collaborative tasks such as puzzle solving [16], navigation with individualized views [39], and complex manipulations such as moving a ring on a U-shaped hoop [30]. Distributed virtual reality systems such as MASSIVE have been developed for supporting communications between people [10]. Szalavri *et al.* developed a collaborative augmented reality system with see-through HMDs in order to support collaborative scientific visualisation [36]. They observed that their system seems to be superior to a classic desktop environment, but did not provide formal results.

Mahyar and Tory explored how communication and coordination can be supported to facilitate synchronous collaborative sensemaking activities in Visual Analytics [28]. Recently, Donalek *et al.* published a progress report of the exploration of VR as a collaborative platform for information visualisation [6]. They describe iVIZ, a web-distributed collaborative VR visualisation system that supports the Oculus Rift. Their studies are still at an exploratory level and thus the authors did not provide evidence of how effective this system is for collaborative visualisation of big and complex data. Telearch [22], a virtual reality system for collaborative archaeology, and Shvil [27], an augmented reality system for collaborative land navigation, both support distributed collaboration. However, both systems are designed for specific use cases. A further prominent use of augmented reality is in industrial applications, e.g. to support asynchronous collaboration [18].

VR platforms featuring 3D stereoscopic vision, high resolution and head tracking, provide considerable benefits for collaborative visual analytics. But as we have seen there have been no formal user-studies evaluating their use for collaborative analysis of abstract data. While the current technologies each have some limitations (§3), they are now adequate to allow us to explore a design space for collaborative abstract data exploration in immersive environments.

3 Characteristics of the Virtual Platforms

The focus of this paper is the study of collaborative abstract visualisation of 3D network diagrams in CAVE-style and HMD platforms. We chose these because CAVE-style platforms are currently considered the state-of-the-art for immersive collaborative visualisation, while HMD displays like the Oculus Rift will soon be commodity devices that may represent a low-cost CAVE alternative. These systems are located at the same place on the Mixed Reality continuum [29] as Virtual Reality devices. However, CAVE-style devices are designed to be collaborative and present physical affordances, while HMDs are designed for a personal and more immersive experience with limited physical movements (Table 1 shows platform differences).

	CAVE2	Network of Oculus Rift + Leap Motion
Display	Higher angular resolution 330 degrees horizontal field of regard, 360 degrees field of view	Lower angular resolution 360 field of regard, 100 degrees horizontal field of view
Physical movements for changing viewpoints	Unrestricted full body movements for navigation (**single head-tracking**)	Head movements for navigation (user tethered to a computer)
Tracking input	6DOF physical objects (wands)	Hand and finger-based tracking
Collaboration space	Physically collocated Can see other users	Collocated and remote Cannot see other users

Table 1: Differences between our two platforms

CAVE2 The CAVE2 is a room with a 3.7m radius, which contains eighty 46-inch HD screens with a resolution of 1366×768 pixels per screen. The screens in the room are arranged in a horseshoe shape, which provides a display field of 330 degrees (Fig. 1). Users are physically immersed in the room in which they can walk within the virtual models and naturally see one another. The size and the shape of the display allow users to visualise graphics at the maximum field of view of the human eye (180 degrees).

The CAVE2 is equipped with a 6 degrees-of-freedom (6DOF) tracking system with a latency of 5ms. The screens render 3D scenes in passive stereo (users wear polarised glasses). The tracking system obtains one user's 6DOF head pose for 3D scene rendering. A set of 6DOF controllers (Fig.1) can also be tracked in the room allowing direct interaction with the 3D scene. The other *non-head-tracked* (non-HT) users do not benefit from the same physical immersion as the scene is not rendered from their perspective, but they are able to use the 6DOF controllers. As a consequence, when the HT user moves, non-HT users see the scene moving beyond their control. A second consequence is that when non-HT users point at 3D objects with a 6DOF wand, the origin of the virtual wand in the scene is offset to its physical position in the room, according to the HT user (Fig. 1). This is a physical limitation of CAVE-style displays common to all but a few experimental installations used exotic view multiplexing techniques, e.g. [1].

Oculus Rift Unlike a CAVE-style set-up, an HMD is designed for a single user. The Oculus Rift DK2 (OR DK2) is equipped with a positional head tracker with a latency of 20ms. This allows a 360-degree field of regard. However, the OR DK2 limits the human field of view to 100 degrees horizontally, and also limits body movements as users are tethered to the computer with a cable. In addition, the OR DK2 is not see-through, which makes it a pure VR device according to the Milgram classification. HMDs, like CAVE-style VR displays, employ trackers for sensing user interaction such as hand gestures. A common practice is to mount a Leap Motion controller [1] on the face of the Oculus Rift to enable finger tracking and gesture recognition in front of the user's viewpoint, Fig 2 (a).

With the noticeable differences summarised in Table 1, one can expect a strong impact of the VR environment on collaborative visualisation of abstract data. Factors that differ across environment are: the users' physical movements for viewpoint changes; the input tracker; the field of view; and the ability to physically see the collaborator. These disparities need to be examined for collaborative abstract visualisation in order to understand how groups of users can use these devices to efficiently work together. Hence, we introduce the following research questions which ask how the different immersive VR platforms will affect:

RQ1 [Functionality] the ease with which groups of users can complete analysis tasks?

RQ2 [Collaboration] the degree and kind of collaboration used in connectivity analysis?

RQ3 [User Experience] the qualitative usability aspects?

In the next section, we present a user study which aims to answer these questions.

4 User Study

We designed an experimental set-up that allowed us to compare collaborative task performance between two VR platforms, 1) a set of two HMDs (OR DK2s, Fig. 2) and 2) a CAVE-style environment (CAVE2, Fig. 1) with respect to our research questions. In this section we formulate hypotheses to test the research questions, introduce a methodology to evaluate and compare the two platforms, and explain our experimental design. In summary, the independent variable is the VR platform, the dependent variables will be highlighted in the following. For our study we chose analysis of connectivity in 3D networks as representative abstract data visualisation task.

4.1 Hypotheses

RQ1 [Functionality] We expected that the resolution and the size of the display will affect the accuracy but we had no initial assumption on the results. We expected that the ability to physically walk to change viewpoints would influence the completion time. Because of the head-tracking, we expected to observe the collaboration strategies to be less tightly-coupled in the HMD than in the CAVE2, i.e. the non-HT participants were expected to follow the HT participants more in the CAVE2. Our first hypotheses relate to the affect of platform on basic independent variables:

H1 The VR platform will affect *task completion time*.

H2 The VR platform will affect *accuracy*.

RQ2 [Collaboration] In the CAVE2, users can directly see each others' body position, facial expressions and gaze direction. In contrast, in the HMD condition participants see only their partner's finger position and an indication of their field of view (§4.3).We expected this disparity in non-verbal cues would make it easier to communicate and share points of interest in the CAVE2, while workload would be more evenly distributed in the HMD because of their independent points of view. We also expect that HT participants in the CAVE2 will have more head movements and be more physically engaged than their non-HT collaborators.

H3 The VR platform will affect *strategies* reported by our participants in the post-hoc survey.

H4 The VR platform will affect the measured degree of collaboration between participants regarding:

H4.1 the amount of *shared focus*,

H4.2 the amount of *verbal communication* during collaboration,

H4.3 the perceived determination of *sub-tasks and their assignment*,

H4.4 the perceived emergence of *leadership*,

H4.5 the balance of *physical interaction*.

RQ3 [User Experience] We suspected that people would be more satisfied in the CAVE2 because of its seamless merging of the virtual and real-world, where participants can see their own and their collaborator's physical body while performing the task in VR. Further, both HMDs and CAVEs suffer from the *vergence-accommodation conflict*

[1]www.leapmotion.com

which is widely known to affect performance and cause visual fatigue [21], which could potentially vary between the platforms. The only downside in the CAVE2 that we expected was that the non-HT participants would have lowered satisfaction as are forced to play a subordinate role in the collaboration. That is, they lack the independent head-tracked viewpoint and due to visuo-proprioceptive mismatch [31] may experience confusion and motion sickness.

H5 The VR platform will affect the self-reported usability.

H6 The CAVE2 will differently affect the HT and the non-HT participants' self-reported usability.

4.2 Experimental design

We used a between-participants 1×2 (one factor VR platform with two levels: HMD and CAVE) experimental design, in which we tested two collaborative visualisation tasks. Participants were allocated randomly to the HMD groups and the CAVE2 groups. The order of appearance of the stimuli was initially randomized so that the participants did not view them in a predictable order. The task order was counterbalanced (§4.4). Participants were asked to evaluate their leadership level initially by responding on a Likert 1-5 scale to "In team work, I often take the leadership role". This response was used to counterbalance participants wearing HT by leadership (i.e. equal numbers of leader and non-leader participants had the correct viewpoint). The HT participant was then fixed for the experiment.

Design rationale We decided to make the experimental set-up as fair as possible and make the best use of each display platform. We addressed the shortcomings in each platform and tried to provide equivalent features to the two groups of participants (§4.3). This choice influenced a series of design considerations which are highlighted in the following and summarised in Table 2.

Display The CAVE2 has an inherent horseshoe layout of display screens, as previously mentioned. We made use of the maximum display surface of the 80 screens and used the horseshoe geometry to make the 3D network wrap around the participants, Fig. 1. To avoid issues related to incorrect parallax and to minimise the participants' obstruction, the visualisation was placed beyond the screens with a positive stereo (i.e. no graphics were rendered at the centre of the room). The inner and outer nodes were located at a range of 0.4m to 2m beyond the CAVE2 screens. The horizontal layouts of network covered most of the CAVE2 display surface ($\sim$300°). They varied vertically but were up to 80% of the vertical field.

In the HMD condition, because of the limited physical interactions, the visualisation was scaled down to 10 percent (approximately 47cm radius) of the CAVE2 size, so that the participants were immersed at the centre of the horseshoe and the visualisation was within arms reach, Fig. 2 (a). The visualisation proportions were preserved, i.e. the network was closer to their point of view but not distorted.

Physical movements and highlighting interaction In the CAVE2, participants were allowed to walk around the room. They could highlight parts of the visualisation with a wand: a Playstation Move controller with a 6DOF tracker mapped to a virtual wand rendered in the 3D scene, Fig. 1. When the virtual wand intersected a node, the node doubled in size and turned yellow.

For safety reasons, participants wearing the HMD were sitting on a chair next to each other, as the HMD was tethered to a desktop PC. Participants were allowed to lean and rotate fully on their chair. A mini virtual selection wand was attached to the index finger (Fig. 2) of each participant in the HMD condition, using the Leap Motion sensor. The same node highlighting function as with the CAVE2 was enabled. We decided against using sophisticated navigation mechanisms involving "magical" interactions (e.g. flying around the model) due to the degree of training they may require.

	Display	Interactions
CAVE	1. 3D network enlarged, viewable through the CAVE2 screens in negative parallax 2. horseshoe network layout	1. free walking 2. wand-based interaction
HMD	1. 3D network displayed within arm's reach of co-located participants 2. horseshoe network layout	1. users seated in chairs; head-rotations and leaning 2. bare-hand (finger-tracked) interactions with Leap Motion

Table 2: Design choices for the experimental set-up

We were concerned about the time participants spent in the HMD. In order to avoid eye fatigue and dizziness that stereoscopic displays can induce, we designed the experiment to not last longer than 40 minutes. We forced participants to take a 5-minute break between blocks of tasks, but also allowed them (optionally) to take up to 3 minutes after each trial.

Finally, we restricted the size of the collaborative groups to two individuals in order to reduce the agreement and decision-making time. We also specified how groups reported their answers as a team. In order to limit interaction in both environments, participants both had to say *we agree* before reporting their answer to the experimenter.

4.3 A minimal set-up for collaboration with two networked Oculus Rift DK2

We designed a minimal collaborative environment which combines two HMDs (Oculus Rifts DK2) connected to a local network (Fig. 2). We mounted a Leap Motion sensor on each HMD in order to enable hand and finger tracking. The vertical field of view of the Leap Motion sensor is 150 degrees wide. When mounted on an HMD, the physical position and the rotation of the Leap Motion sensor are mapped to those of the participant's head. Hence the direction and position of the sensor's field of view is updated when users rotate their head. This allows continuous finger tracking in the visual frame of reference.

We developed collaborative virtual environment software clients to support collaborative visualisation with Unity. Each HMD position and rotation data, along with finger tracking data from the Leap Motion, are sent over the network using a UDP socket connection. In order to augment the sense of presence [25], the field of view of each user was rendered in the virtual space (a wire-frame pyramid drawn from each user's perspective), along with their index finger position (rendered as a virtual mini wand, Fig. 2).

This minimal set-up allowed the participants to highlight the nodes of the visualisation using natural gestures as in the CAVE2, with independent perspective for each user, but with restricted movements (users could not walk freely because they were tethered to the computer by the Oculus Rift DK2 HDMI cable). User interactions (such as pointing and highlighting nodes) from each participant were sent over the network and rendered in real-time in each client.

4.4 Stimuli and tasks

We tested two 3D network visualisation tasks, which address the topological level of graph analysis [24]:

- **Path:** Finding the shortest path between two nodes
- **Triangles:** Counting the number of triangles (number of 3-vertex cliques).

These tasks were selected because of their potential for collaboration, such as divide and conquer. The shortest path task consisted of finding the least number of edges between two green nodes of the 3D-network (all the other nodes were coloured blue). Participants were asked to report orally the list of nodes of the shortest path. Three different path lengths were used with six 3D-networks: eight, nine and

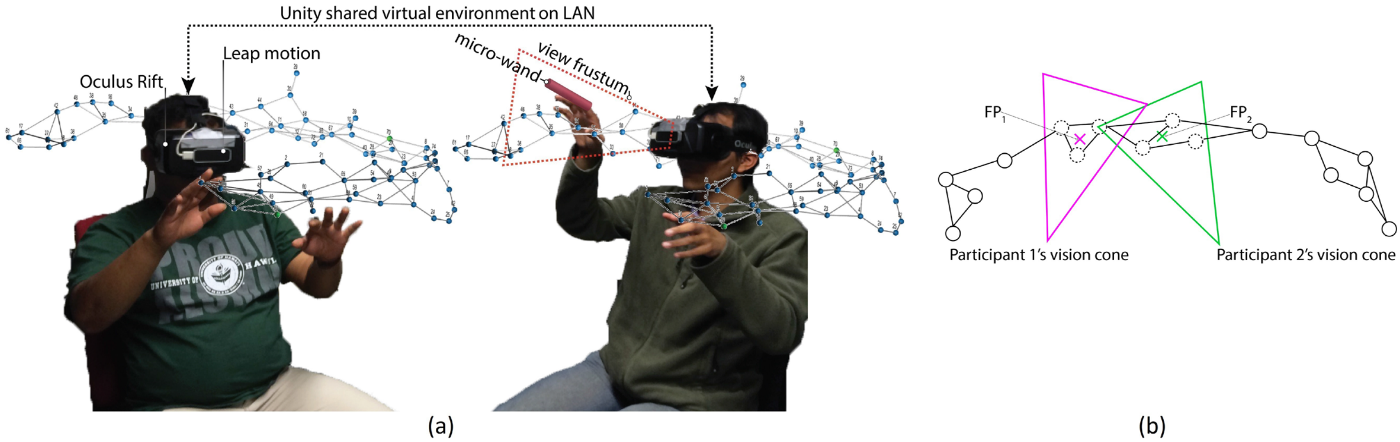


Fig. 2: (a) Minimal set-up for a collaborative environment using two OR DK2 + Leap motion, connected on LAN. Each user has an independent view of the visualisation in a Unity client, and sees each other's view frustum and wands. (b) Determination of the participants' focus points (FP_1, FP_2) using the intersection of a near peripheral vision cone with the network visualisation nodes (dashed nodes).

ten nodes. The triangles task consisted of searching and counting the "triangles" in the 3D network. A triangle (i.e. a 3-vertex clique) was presented as three mutually connected nodes. Participants were asked to orally report the number of triangles they found in the 3D network. We used three different numbers of triangles with six 3D-networks: three, four and five triangles. The size of the 3D-networks (number of nodes and edges) varied slightly between tasks (75 nodes and 110 to 140 links for the path task; 80 nodes and 100 to 110 links for the triangle task).

The networks were randomly generated and Cola [8] was used to generate the 3D layout. The nodes were rendered as blue shaded spheres and the edges as white-grey shaded cylinders. The node size/edge thickness ratio was preserved across the two VR platforms. Labels (numbers) were placed above each node and rendered to a bill-boarded quad. In the HMD condition, the labels were always facing the camera (i.e., the participants' eye). In the CAVE2 condition, the labels were pointing towards the centre of the room, in order to be legible for both participants. A multi-directional light was placed at the centre of the visualisation to ensure visual clarity of the rendered graphics.

4.5 Procedure

The participants were first given a pre-experiment survey concerning demographic data and questions about previous knowledge of the VR platforms and the visualisation tasks. Participants were then acquainted with the VR equipment in their particular experimental condition. In the CAVE2 platform, one participant was given the head-tracker (mounted on polarized eyeglasses), while the other participant was given a cap with a 6DOF tracker layout (Fig. 1, used to measure their head position and rotations only). Team members then received a 6DOF wand tracker. In the CAVE2 condition, the different head-tracking capabilities were explained to the team.

Next, a 3D network visualisation was displayed in the virtual environment in order to familiarise the participants with the visualisation. In the HMD condition, the participants were asked to use the Leap Motion sensor to select specific target nodes to practise with the sensor. In the CAVE2, participants practised with the wands and were asked to highlight specific target nodes. Once comfortable in the VR platform, the participants were instructed to report their answers: both had to say we agree to stop the trial and provide the answer. The first task was then explained to the team, which was either finding the shortest path or counting the number of triangles in the network, according to the counter-balanced order. Participants were told that the main goal was to find the correct answer and that they should try to do it as fast as possible. They were also encouraged to collaborate and find their own strategy. The participants were also encouraged to discuss those strategies between the trials. The team was then trained with the task with one network.

Once ready, the participants completed six trials for the first task in the following order:

- Both team members started at the centre of the visualisation.
- The experimenter displayed a new 3D network on the VR platform, using a control interface on a tablet PC wirelessly connected to the virtual environment (the start time of the trial was automatically recorded), and participants started the task.
- When the participants found the answer and both said *"we agree"*, the experimenter used the control interface to stop the timer (the trial end time was then recorded) and to collect their answer (the path chain or the number of triangles).[2]
- In the CAVE2, participants were then told to go back to their starting positions. In the HMDs, participants' view and chairs were re-centred.
- The display was blank for five seconds and the next 3D network was sent from the control interface.

At the end of the first six trials, the participants were given a five minute break. They then proceeded to do the other six trials for the second task, following the same steps. Last, the participants completed a post-experiment survey on a laptop, where information was collected on their experience. Participants were not allowed to communicate while filling out the survey.

4.6 Participants

There were 34 participants recruited. They were allocated to nine teams of two participants in the HMDs, and eight teams of two participants in the CAVE2. The mean age of the participants was 36 ($SD = 9.25$) for the HMD group (15 males and 3 females), and 31 ($SD = 9.23$) for the CAVE2 group (6 males and 10 females). Participants came from diverse backgrounds but had mainly computer science and engineering backgrounds. In the CAVE2, participants were 50% familiar with network diagrams and 66% familiar with the environment. In HMD, 73% of the participants were familiar with network diagrams and 62% were familiar with the HMD. Participants were asked if they knew each other (50% knew each other in each condition). This information was used to allocate the groups to the task order (§4.5).

[2]We tried different mechanisms to stop the trials–e.g. pushing virtual buttons–in the end an oral cue proved most foolproof.

4.7 Measures

We introduced objective and subjective measures used to evaluate the differences between the platforms in terms of the hypotheses listed in §4.1. The most basic of these were time to solve tasks (H1) and accuracy (percentage of correct answers divided by the total number of trials, H2).

Participants' perception of their collaboration in the virtual environment was captured through a post-hoc survey. We adapted questions from a study of presence in computer mediated collaboration [12], for collaboration in VEs. Specifically, our questions aimed to measure perceived *communication*, *activity*, *capability* and *presence* (the "feeling of being there"). Responses were given on a Likert scale (Strongly Disagree (1) - Strongly Agree (5)), except where explicitly stated otherwise:

Strategies employed to solve the task (H3, open discussion question)

- "Can you describe the strategy that you used to count the triangles?"
- "Can you describe the strategy that you used to find the shortest path?"

Communication (H4.2) through the virtual reality set-up and *information sharing*

- "I communicated frequently with my partner"
- "I openly shared all relevant information when completing the tasks"

Organisational workload (H4.3)

- "Each of us had a clear sub-task"
- "There was conflict when determining the sub-tasks"

Evaluation of the *perceived effort* in completing tasks (H4.5)

- "My partner and I put a lot of effort into the tasks"
- "I was an active contributor when doing the tasks"

Usability (H5 and H6) of the system to perform the tasks

- "I felt comfortable using the virtual reality set-up"
- "I felt sick during the study"
- "I enjoyed myself"

In addition, we recorded head-tracked positions (6 DOF) (H4.5) and audio (H4.2). We were then able to estimate degree of shared focus in two ways (H4.1):

- *Reported shared focus:* through coding (by our first author) of participant reported strategy (§5.2);
- *Measured shared focus:* a metric based on actual view frustum of each participant.

Measured shared focus (H3) is determined from the positional and rotational head movements provided by the VR tracking system (recorded every 0.25 seconds). We assumed a vision cone to determine which portion of the 3D network the participants were viewing, with an opening angle of 60° (corresponding to near peripheral vision, also called the useful field of view, Fig. 2 (b)).

For each position and rotation recorded, we calculated the intersection of the vision cone with the nodes of the 3D network. Since we do not know the depth of the participants' focus we infer an approximation from the centre of gravity of these nodes. Thus, at each instant, we have both participants' spatial focus-points $FP_1, FP_2 \in \mathbb{R}^3$, Fig. 2 (b). Then $dist(FP_1, FP_2) = |FP_1 - FP_2| \in \mathbb{R}_0^+$ gives an estimate of the distance between these.

A minimum threshold of the focus-distance $fd(\text{platform})$ was used to determine whether the participants were in focus on the same portion of the 3D network or not. We take this from the diagonal distance of a single panel of the CAVE2's tiled display wall such that $fd(\text{CAVE}) = 116\text{cm}$. This was scaled proportionally to the model size in the HMD condition, $fd(\text{HMD}) = 11.6\text{cm}$. The *measured shared focus* value $sf \in [0,1]$ gives the proportion of time the participants focused together over the total trial time (T):

$$sf = \frac{1}{T}\sum_{t=0}^{T} x \begin{cases} x = 1 & \text{if } dist(FP_1(t), FP_2(t)) \le fd(\text{platform}) \\ x = 0 & \text{otherwise} \end{cases}$$

5 Results

In this section we present a set of quantitative results of groups of participants' accuracy, speed of task performance (completion time), proportion of oral communication and amount of shared focus regarding the two collaborative tasks in the CAVE2 and in the HMD set-up.

5.1 Functionality (RQ1)

In the following, we analyse the impact of the virtual environment on functionality in terms of time and accuracy.

Accuracy (A) The mean rate of correct answers for the path task was 85% for the CAVE2 and 78% in the HMD. The distribution of correct answers in both CAVE2 and HMD conditions were negatively skewed (participants provided a high number of correct answers), thus assumption of normality could not be met. We used the non-parametric Mann-Whitney U test to compare the two path accuracy means. The result of the test showed that there were no significant differences between the CAVE2 and the HMD average scores. The average amount of correct answers for the triangle task was 69% for CAVE2 and 72% for HMD, again with a negatively skewed histogram (participants also provided a high amount of correct answers). The result of the Mann-Whitney U test showed no significant differences between these two means.

Completion Time (CT) The completion times for correct answers from both groups were not normally distributed. The distribution of completion time were slightly positively skewed, so we used a square-root transformation (the Shapiro-Wilk test indicated that the transformed distribution was normal, $W = 0.99313$, $p = 0.5096$).

The average completion time (Fig. 3(a)) for correct answers for the path task was 107 seconds for the CAVE2, and 69 seconds for the HMD. The result of the independent t-test showed that the average completion time between the CAVE2 group and the HMD group were significantly different ($t(93) = -4.56$, $DF = 94$, $p < .001$).

The average completion time (Fig. 3(a)) for correct answers for the triangle task was 102 seconds for the CAVE2, and 71 seconds for the HMD. The result of the t-test showed that the average completion time between the CAVE2 group and the HMD were significantly different ($t(89) = -5.85$, $DF = 94$, $p < .001$).

Conclusion On both platforms groups of participants achieved a high accuracy, and no significant differences were found between the CAVE2 and the HMD condition (H1 was not confirmed). Rather, we found a significant difference in completion time between the two platforms for equivalent accuracy. For both tasks, participants were faster to provide correct answers in the HMD than in the CAVE2 condition. Participants were overall 40% faster to find correct answers for the path task, and 30% faster for the triangles task (H2 was confirmed).

5.2 Collaboration (RQ2)

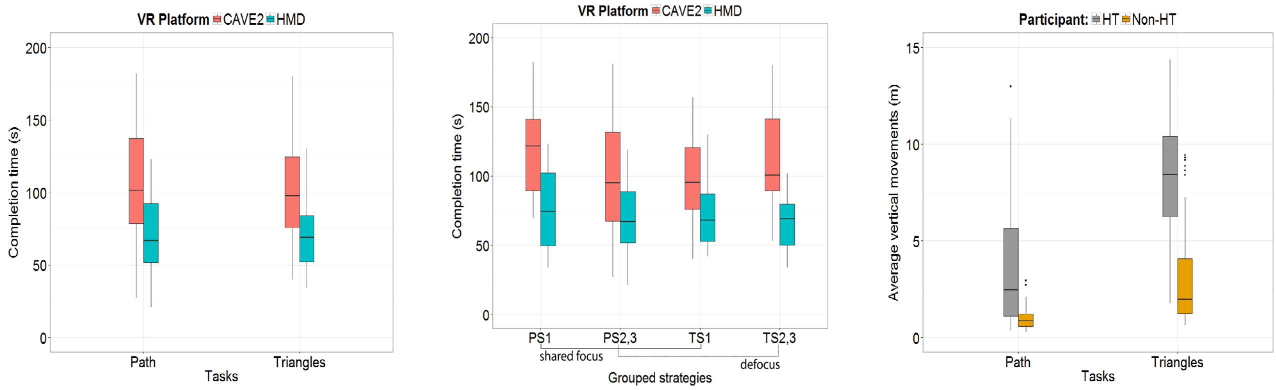
Here we discuss the results of the evaluation of collaboration in terms of collaboration strategies and shared focus, proportion of oral communication, tasks allocation and balance of physical movements between team members, in the two platforms.

Collaboration strategies (CS) Participants were asked to describe their strategies in the survey. These were coded by two of the experimenters. Where there was inter-coder variability or uncertainty categorisation was also informed by the observing experimenter. Final strategy categorisation is summarised in Table 3.

Three main "path strategies" (PS) emerged to solve the shortest path task in both virtual environments:

- PS1, **Shared Focus**: following paths, focused together on the same edges and nodes.
- PS2, **Divide and Conquer**: participants agree on a mid-point node to split the path and work independently to find the shortest sub-path before combining their answer.
- PS3, **Duplication**: the participants worked independently before comparing their answers.

We found that the emerged triangle count strategies (TS) followed the same logic:



(a) Overall Time performance (b) Completion time by strategy (c) Vertical head movements in the CAVE2

Fig. 3: (a) Average completion time in seconds for the path and triangles tasks, and (b) per strategies. Average vertical head movements in meters in the CAVE2 for the path and the triangle tasks (c) (HT in grey and non-HT in dark yellow).

- TS1, **Shared Focus**: explore the network together (with shared focus), left-to-right or right-to-left, counting triangles at the same time.
- TS2, **Divide and Conquer**: split the network into two parts, independently count left and right triangles, and sum the result.
- TS3, **Duplication**: scan the network from one side to the other, count the triangles independently, and compare and discuss the results at the end.

Strategy	CAVE2	HMD
PS1	37.5%(3 groups)	11% (1 group)
PS2	25%(2 groups)	44.5%(4 groups)
PS3	37.5%(3 groups)	44.5%(4 groups)
TS1	75%(6 groups)	67%(6 groups)
TS2	0%	22%(2 groups)
TS3	25%(2 groups)	11% (1 group)

Table 3: Percentage and number of groups who employed the different strategies

For path finding, the results suggest that the more independent strategies (PS2 and PS3) were more popular in the HMD condition while in the CAVE2 condition participants reported a balanced choice of strategy. For the triangle task, participants in both environments chose mostly a shared-focus strategy. However, these results have to be treated with caution due to the small sample size.

Strategies, shared focus and completion time (CS,SF,CT) No differences were found between the two VR platforms in terms of the *measured shared focus*. We found that the mean shared focus for the shortest-path task was 53% in the CAVE2 and 55% in the HMD condition. The results for the triangle task were also close in both VR platforms (63% in the CAVE2 condition, 61% in the HMD condition).

In the following we report the results of a deeper analysis which aims to understand how different shared-focus strategies impacted users' performance in the two VR platforms. Our expectation was that the *reported shared focus* strategies (PS1 and TS1, which we now refer to as *shared focus strategies*) correspond to a higher degree of *measured shared focus*, i.e. participants were more synchronously focused on the same nodes and edges to complete the tasks. Conversely, we expected that PS2,3 and TS2,3 (which we collectively refer to as *defocused strategies*) correspond to less *measured shared focus*.

We plotted these grouped strategies across the two platforms against the proportion of measured shared focus (Fig. 4). The analysis of the visualisation confirmed the correlation between the proportion of shared focus and strategies. We also produced visualisations of participants' positions and focus points to assess reported strategies and measured shared focus. The visualisations in Fig. 5 illustrate a TS2 strategy in (a) HMD, where green and magenta calculated focus points are separated (low shared focus); and a TS1 strategy (b) in the CAVE2

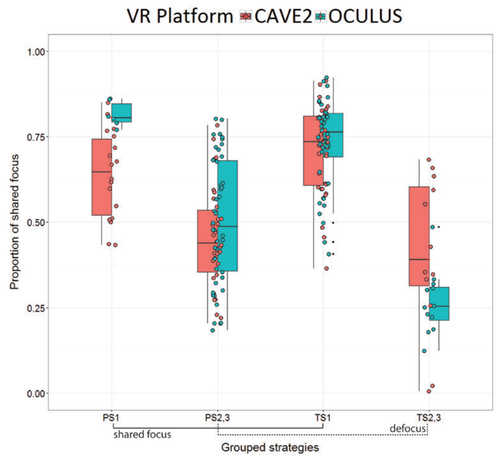


Fig. 4: Shared focus distribution per strategies.

where the calculated focus points and head movements paths of the HT and the non-HT participants are synchronous and close to each other (higher shared focus).

We then analysed the impact of these strategies on user performance. No evidence was found that strategies influenced the accuracy. We used the same square-root correction as in §5.1 for the completion time distribution. Two-way analysis of variance (ANOVA) tests on task completion time do not show any significant interaction between VR platforms and strategies. However, we did find a significant main effect of the strategies on the completion time for the path task ($F(1,92) = 11$, $p = 0.001$). Also, *shared focus* strategies (PS1) elicited faster completion times than the *defocused* strategies ($M = 111s$ for PS1, $M = 83s$ for PS2,3) (Fig. 3(b)). No significant effect of strategy was found for the triangle task, probably because of the smaller reported sample size (TS2,3). Still, Fig. 3(b) suggests a trend of faster completion time with the two strategies in the triangle task with the HMD.

Self-perception of collaboration (SPC) In order to analyse collaboration, our questionnaire contained questions on perception of leadership, workload and task division, along with ease of oral communication. Self-perception of leadership was measured with the open-ended question "Was there one person who led the team? If so, who, and how was this determined?". We were expecting to observe biased results in the CAVE2 with the HT participants. However, participants reported ambiguous answers to this question so no conclusion could be made on the influence of head-tracking on leadership. However, one non-HT participant reported that her partner was leading because of the control of the viewpoint.

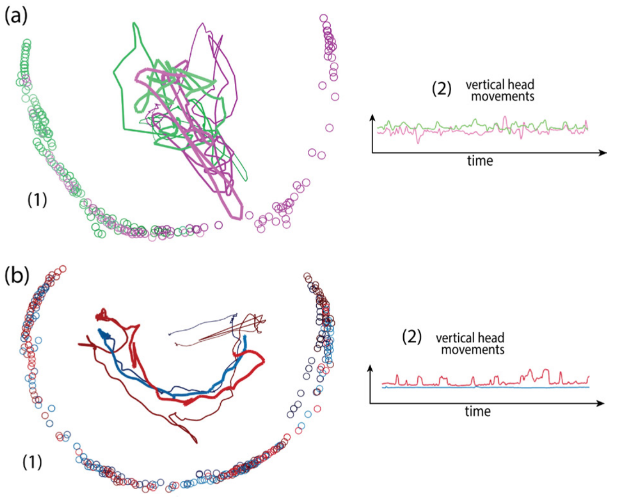


Fig. 5: Two triangle count trials in the HMDs (a) (green and magenta) and (b) in the CAVE2 (red (HT) and blue (non-HT)), showing horizontal (1) and vertical (2) head movements. The horseshoe layout of the 3D network emerges from the position of the calculated focus points, represented by circles. Colour saturation and line thickness increases with time (1). Spatial scale of (a) is 10% of (b).

The questionnaire results scoring analysis of workload, contribution to the tasks and organisational questions did not show a significant difference between the two environments. Yet, we found a trend for the mean answers to the question "There was conflict when determining the sub tasks". In the CAVE2 the average score was 1.2, and 1.9 in the HMDs. The Mann-Whitney U test results showed a trend of difference between the two average scores ($W = 99.5$, $DF = 32$, $p = .06$). Although not statistically significant, this indicates that dividing work could have been easier in the CAVE2, but the reported scores are low in both environments.

To measure ease of communication, we posed the question "Discussions using this virtual reality set-up tend to be more impersonal than face to face discussions". Participants reported that the discussion with the HMD was more impersonal than in the CAVE2 environment. In the latter, the average score was 2.2 compared to 3 for the HMD (16% difference). Answers to this question were not normally distributed. The Mann-Whitney U test indicated a significant difference between these two average scores ($W = 80.5$, $DF = 32$, $p = 0.023$).

Analysis of oral communication (AOC) The participants conversations were recorded during the experiment. In order to evaluate the influence of the VR platform on oral communication, we analysed the proportion of oral communication (POC), i.e. the proportion of speaking time between the two team members during the total completion time per task. Audacity was used to blank the audio between the trials, filter out the noise and isolate the two participants' voices. No significant differences in POC between the two environments were found (53% of POC for the path task in the CAVE2 and 54% in the HMDs; 60% in the CAVE2 for the triangles count task and 55% in the HMDs).

Balance of physical movements (BPM) The visualisation of the recorded trial positions and rotations over time suggested that HT participants in the CAVE2 were more likely to do vertical head movements than non-HT participants (see a snippet in Fig. 5, right). The histogram graph of the accumulated head vertical movements over time indicated that the distribution of the movements was not normal, hence we used the independent Mann-Whitney U test to analyse the average movements between participants. In the CAVE2, we found that HT participants moved their head vertically significantly more than the non-HT participants did, to find the shortest path (Fig. 3(c), HT in grey and non-HT in yellow). The average accumulated vertical head movements over time for the shortest path task was 3.5m for the HT participants and 1m for non-HT participants ($W = 1852$, $DF = 94$, $p < .001$). HT participants vertically moved their heads 3.5 times more than the non-HT participants to solve this task. We also found that the HT participants' accumulated vertical head movements were significantly higher than the non-HT participants' ones for the triangle task. On average, HT participants vertically moved their head 2.7 times more than non-HT participants, accumulating a total of 8.8m vs. 3.2m for non-HT ($W = 2046$, $p < .001$, $DF = 96$). In the HMD condition, no differences were found between the accumulated average vertical head movements over time of both participants for both tasks. The average head vertical movements was 0.7m for the path task, and 1.8m for the triangle task.

Conclusion HMD participants reported more defocused strategies, but the analysis of shared focus did not reveal significant differences between the two environments for either task (H3 and 4.1 were not confirmed). We found that strategies had no impact on accuracy, but the results indicated they influenced the path task in that focused strategies were significantly slower than defocused strategies. The results showed that within each strategy group, HMD participants were significantly faster than the CAVE2 participants. No differences were found in terms of the proportion of oral communication in the two platforms thus H4.2 was not confirmed. Likert responses indicated that participants' allocation to subtask was less clear in the HMD than in the CAVE-style environment (supporting H4.3). The questionnaire did not reveal any difference in terms of leadership in the CAVE-style environment (H4.4 was not confirmed). Finally, the analysis of physical movements showed an asymmetry between the participants of the CAVE2 condition; HT participants moved their head significantly more than the non-HT participants (H4.5 was confirmed).

5.3 User experience (RQ3)

We evaluated user experience between the two VR platforms and between the HT and the non-HT participants in the CAVE2, using a Likert-scale (Strongly agree(1) - Strongly disagree(5)) questionnaire and open-discussion questions.

We measured participants' self-perception of capability of doing the tasks, comfort of use, satisfaction and sickness induced by the display, for the two VR platforms. Participants in the CAVE2 reported slightly higher usability scores for the usability criteria in Table 4. No significant differences were found in terms of perceived capability of completing the two tasks in the two environments. The investigation of perception of usability of the CAVE2 between the HT and the non-HT participants showed slightly more satisfaction for the non-HT participants and slightly more comfort for the HT participants. However, no statistical differences were found between the two participants answers (Table 5).

Despite the lack of significant differences in these results, open discussions collected from the post-experiment questionnaire allowed us to get more informal feedback on the usability of the two VR platforms and between HT and non-HT participants.

One CAVE2 participant reported that the size of the display helped them view a large quantity of data at once. Two participants reported that they felt comfortable discussing the tasks; especially given they share the same view of the data (3 participants), which supported the decision taking process. However, one participant reported that stepping in front of each other while viewing the network can be disruptive and generate frustration (display obstruction), and that the lack of head-tracking for the non-head tracked collaborator made it difficult to view complex parts of the network (4 participants). In addition, one participant reported that the uncontrolled movement of the 3D visualisation is disturbing for the non-HT user. One HT participant reported that physical interactions for this visualisation task were awkward.

Six HMD participants reported that being able to track the viewpoint (the wire-frame pyramid) and finger position (the mini wand) from their partners was a crucial and really useful cue to follow each other's gaze. One participant also reported that being able to share the same position and view within the 3D network really helped communication while doing the tasks. Three participants reported that they were focused on the visualisation and less on the environment, which allowed them to concentrate more on the tasks (and one participant reported that not being able to literally look at his partner helped in focusing on the tasks).

	CAVE2		HMD	
Criterion/Question	M	σ	M	σ
Capability *I felt capable of doing the path task*	4.5	0.8	5	0.6
Capability *I felt capable of counting the triangles*	5	0.5	5	0.7
Satisfaction *I enjoyed myself*	5	0.8	4	0.7
Comfort *I felt comfortable using the system*	4	0.6	4	0.9
Sickness *I felt sick during the study*	1	1.0	2	1.0

Table 4: Self-perception of usability of VR platforms, median M and standard deviation σ.

	HT		Non-HT	
Criterion/Question	M	σ	M	σ
Capability *I felt capable of doing the path task*	4.5	0.7	4.5	0.9
Capability *I felt capable of counting the triangles*	4.5	0.5	5	0.5
Satisfaction *I enjoyed myself*	4.5	1.0	5	0.4
Comfort *I felt comfortable using the system*	4.5	0.7	4	0.5

Table 5: Self-perception of usability for HT and non-HT participants

Conclusion No statistically significant differences were found in terms of our quantitative measures of usability between the two VR platforms and between the HT and non-HT participants in the CAVE2 (H5 and H6 were not confirmed). The overall reported strength of the CAVE2 for collaboration was the sharing of the display and the ease of communication. The lack of correct head-tracking viewpoint was the most reported downside of the CAVE2. The main reported downside of the HMD set-up was the Leap Motion tracker; participants felt frustrated when the sensor lost track of their finger position. Only three HMD participants felt slightly disoriented during the experiment.

6 Discussion

The analysis of functionality (RQ1) indicated high accuracy in both environments (§5.1 – A). Participants achieved faster completion times in both path and triangle tasks in the HMD than in the CAVE2 (§5.1 – CT). The lack of head-tracking for one of the two participants in the CAVE2, occasional display obstruction and the size of the room are possible factors for longer task execution times.

Participants reported more independent strategies in HMD, but the shared-focus analysis showed no differences between the two VR platforms (§5.2 – CS). However, a deeper analysis of their strategies grouped by shared focus showed that strategies leveraging shared focus elicited faster completion times in the path task, independent of the VR platforms (§5.2 – CS,SF,CT). Testing full independence between strategies and platform would require an equivalence test with a significantly higher sample size, and is beyond the scope of this paper.

The investigation of collaboration only showed minor differences in perceived communication (§5.3). HMD participants reported that they found the platform impersonal for communication more frequently than CAVE2 participants. Our initial thoughts were that the minimal HMD set-up would prevent participants from communicating orally and alter perception of presence, but the study of the POC did not show any differences between the two VR platforms (§5.2 – AOC). In the HMD condition, participants responded positively to "I felt that my partner was really there with me inside the virtual visualisation" with an average score of 4 over 5 (MD = 4, SD = .8).

The main collaboration difference found was the asymmetry of physical movements in the CAVE2 (§5.2, (BPM)). HT participants were more physically involved in analysing the graphics as they moved vertically more than non-HT participants during the trials. The HMD did not suffer from this asymmetry and the results showed that the head movement quantities were balanced between the team members.

Overall then, the self-reported measures did not show significant differences in user experience between the two VR platforms. Some participants reported issues related to the finger-tracking sensor (Leap Motion) in the HMD environment. New products shipping in 2016 such as the HTC VIVE and Oculus Touch offer hand-controllers with very accurate tracking that may ameliorate this issue. In the CAVE2, some participants were bothered by the asymmetry of the correct perspective being rendered for only one head-tracked participant.

7 Limitations

The results of this study are limited to sparse small and medium sized networks (~80 nodes). We used a force-directed layout that wraps around the participants' field of view and with limited depth (§4.2), though enough to force the participants to move their heads to access hidden nodes or crossed edges. This was chosen as a reasonable default use of space for the particular VEs used, but clearly there are many other layout possibilities which may profoundly affect readability and also participants' task solution strategy.

Only the most commonly used set-up for multi-participant visualisation in the CAVE2 environment was tested. That is, only one participant had saw the correct view-point for their head position. There are other possibilities, such as allowing participants to interactively switch the viewpoint or multiplexed viewpoints (as described above). However, evaluation of these possibilities is left as future work.

Participants were randomly assigned to the virtual reality platforms, but due to the small sample size, imbalance in demographic (in particular graph visualisation expertise, skill and gender) may have skewed the results (§4.6). The two platforms were located on different campuses and we could not easily re-assign participants to the platforms. Finally, collaborative strategies were interpreted from coded questionnaire responses, precise head and view-frustum positions of participants over time, and analysis of amount of speech over time. Other methods are of course possible, and may reveal more or different insights, e.g. [37] used detailed talk aloud and video analysis.

8 Conclusion

In this paper we have presented the first formal user study into collaborative analysis of abstract data in an immersive VR platform. In particular we compared two collaborative network connectivity tasks using 3D network visualisations on two popular but quite different VR platforms: a CAVE-style environment and a modern HMD. Our aim was to investigate whether the modern HMDs like the Oculus Rift meant that collaborative immersive visualisation of abstract data no longer required the use of expensive facilities like CAVEs.

Investigation of collaborative data visualisation is inherently complex. Our study required developing an experimental platform that allowed a fair comparison between the two environments without compromising the experience on either. We also needed to develop a multifaceted evaluation model. This comprised objective and subjective measures such as accuracy, times, movements, oral communication, tasks allocation and strategies, in order to highlight differences between the two VR platforms. The main results found were that participants were:

- highly accurate in both environments, but
- substantially faster in the HMD, independent of the strategy employed to solve the tasks.

Somewhat to our surprise we found no major differences in terms of oral communication and shared focus between the two platforms. In addition, we found that physical engagement between the team members in the HMDs were balanced, which makes the set-up more equitable. These results suggest that modern HMDs, such as the Oculus Rift, provide a comparable experience for collaborative abstract data analysis to more expensive purpose-built CAVE-style facilities, and may even reduce the time required to complete the tasks.

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