Evaluating Navigation Techniques for 3D Graph Visualizations in Virtual Reality

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***Abstract*—Research into how virtual reality (VR) can be a beneficial technology for new and emerging large, complex data visualizations for data scientists is ongoing. In this paper, we evaluate three-dimensional VR navigation technique for data visualizations and test their effectiveness with a large graph visualization. We evaluate two prominent navigation techniques employed in VR (Teleportation and One-Handed Flying) against two less common methods (Two-Handed Flying and Worlds In Miniature) and evaluate their performance and effectiveness through a series of tasks. We found Steering Patterns (One-Handed Flying and Two-Handed Flying) to be faster and preferred by participants for completing searching tasks in comparision to Teleportation. Worlds-In-Miniature was the least physically demanding of the navigations, and was preferred by participants for tasks that required an overview of the graph such as triangle counting.**

***Index Terms*—virtual reality, visualization, navigation**

I. Introduction

In the age of Big Data, datasets are becoming unwieldy to visualize on traditional displays due to the limits of a computer monitor's size and the constraints a keyboard and mouse present when interacting with data. Recent work has explored using technologies such as CAVEs and Head-Mounted Displays [7], [8], [32] to immerse analysts into their data. With the increased immersion and potential sense of presence virtual reality (VR) provides, we developed *VRige*, a virtual reality immersive graph explorer [9]. Our motivation for developing VRige is to explore the effectiveness of Immersive Analytics for a room-scaled graph visualization (see Fig. 1). Immersive Analytics is an emerging research field which focuses on how new display technologies can assist in the decision making and analytical reasoning process required by data scientists by immersing users into the process [3].

During the design process of VRige, we worked closely with the Department of Foreign Affairs and Trade (DFAT), who commonly work with large graph visualizations. One of the primary interests of DFAT was how to approach exploring a large graph visualization using immersive technologies. Data scientists and analysts in that domain commonly work with a traditional 2D computer display using a mouse and keyboard. We believe that VR has reached a point where users can be placed into a virtual world of data, with the ability to intuitively interact with virtual objects. This virtual exploration seemed distant to researchers only a few years ago, but has come to reach its potential with todays technology [25].

The problem we were faced with is how users could navigate large three dimensional data that has no specific orientation, while supporting their sense of presence when faced with a particular task. To navigate large graphs in room-sized VR, merely walking to a point in the graph is insufficient due to the limitations of the room size; therefore interactive VR navigation techniques are required to allow the user to change their position and orientation in the graph space. To gain

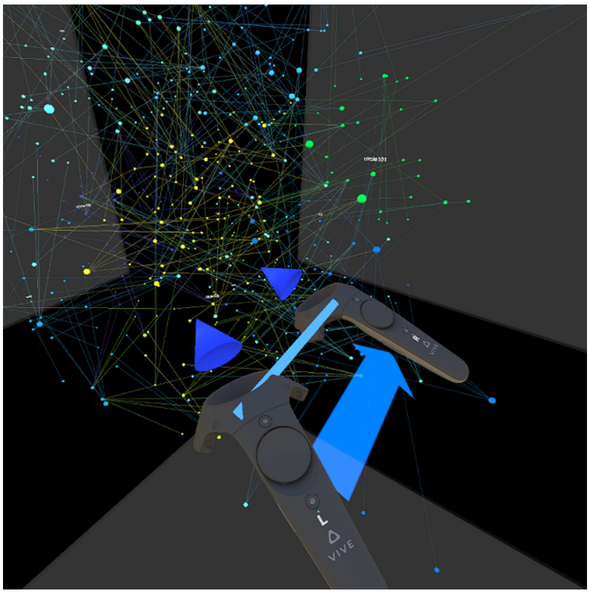

Fig. 1: Example of Two-Handed Flying in the experiment. Drawing an arrow between the two controllers, a participant can specify the direction and speed of virtual movement around the 3D graph.

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insight into a solution to this VR navigation problem, we first looked towards existing VR navigation techniques. This poses the research question: *Which VR navigation techniques are effective in an abstract 3D graph visualization space?* To address this 3D navigation research question, we analyzed four navigation techniques applicable to VR, in order to test their effectiveness and their potential as a means to explore abstract data.

This paper presents and discusses the results of a user study evaluating a set of navigation techniques — Teleportation, One-Handed Flying, Two-Handed Flying, and Worlds-In-Miniature — (see Fig. 2) using VRige as a base application. Our contributions include providing the first study of evaluating VR navigation techniques for use with an abstract graph. Our study is also the first formal study that we know of comparing Teleportation, against One-Handed Flying, Two-Handed Flying and Worlds-in-Miniature for abstract VR tasks. The purpose of evaluating these navigation techniques is that we are interested in discovering the differences between one-handed and bimodal interactions [20] for these abstract VR tasks. There also have been a lack of studies evaluating these navigation techniques in literature.

In the remainder of the paper, we discuss related work concerning the VR navigation techniques, describe the study we conducted, along with the results, related discussion, and conclude with final thoughts.

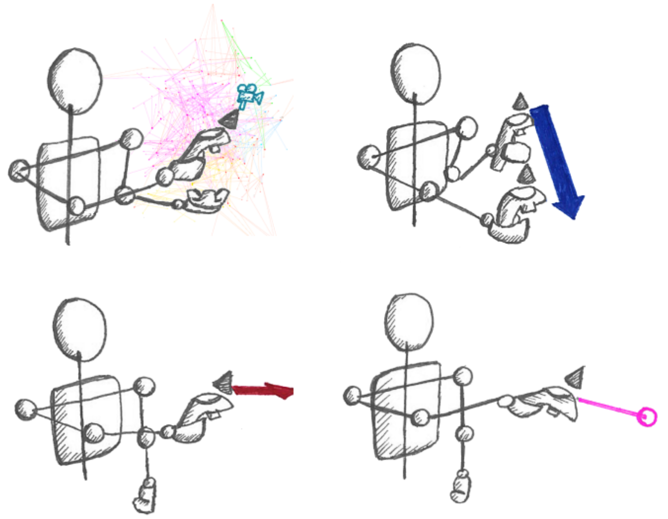

Fig. 2: An illustrative summary of the four navigations in the experiment. Top left, Worlds in Miniature (WIM). Top right, Two Handed Flying (THF). bottom left, One Handed Flying (OHF). Bottom right, Teleportation (TP).

II. Background

Despite the resurgence in VR given recent hardware advancements, how to navigate within virtual spaces remains an active research problem. This is not just a technical problem, but factors such as motion sickness mean that despite navigation techniques being promising from a technical perspective, they must be grounded within the real world. As such, there are a variety of different navigation techniques presented over the years [4], [24], [29]. In this section, we will examine four specific techniques based on their current adoption, and potential for impact. They are One-Handed Flying and Teleportation against lesser known navigations in literature, Two-Handed Flying and Worlds-in-Miniature. The final section will contain a brief discussion about 3D Graph Visualization and methods employed to interact with those visualizations.

A. *Teleportation (TP)*

Teleporting is a one-handed navigation technique common in most commercial VR applications [12], [14], [26], [28]. The most common variation of Teleportation is the "Point and Teleport" navigation technique, where a user points at a specific location they desire to move to, confirms that it is the desired location, and is instantly moved to those coordinates. A recent study into the Point and Teleport navigation found that the navigation reduced the amount of collisions through a proposed set of obstacles in a comparison to other navigation techniques such as Walk-in-Place and using a joystick [5]. Point and Teleport was also generally preferred over a walking in place navigation in the amount of effort required. In an earlier study, pointing navigations were also found to be a faster navigation in comparison to gaze-directed navigations, as well as more comfortable, as the user's head can stay stationary while navigating [4].

B. *One-Handed Flying (OHF)*

One-Handed Flying is a steering pattern commonly employed in modern VR applications, such as Google Earth VR [12]. It involves the user pointing to the direction they want to travel, and the longer they stretch out their arm, the faster they travel. An important precedent for HMD field of view (FOV) manipulation is Feiner and Fernandes's research into modifying the FOV of a HMD display [10]. Their research involved dynamically changing the FOV in response to the user's navigation around the VR environment. They argued that fixating the FOV to a specific point overall reduces presence in the VR environment, thus the FOV slowly shrinks as the user navigates from one point to the other. When the user stops moving, the FOV returns back to its original point. The results of a pilot study indicated participants' also preferred soft-edged cutout vignettes, to hard-edged cutouts vignettes. They found that participants in the study who used FOV restrictors experienced significantly less discomfort in comparison to participants without the FOV restrictors. Google Earth VR recently used FOV restrictors for navigating long distances in order to reduce VR motion sickness for traveling across locations with a One-Handed Flying navigation technique [12].

C. *Two-Handed Flying (THF)*

Mine, Brooks and Sequin [21] originally described two-handed flying (THF) in 1997 as a technique where the user draws a vector between both hands, which specifies the direction and the speed of the user through a virtual environment based on the length of the vector. The authors recount two-handed flying as ergonomically easier than one-handed flying, due to the user not needing to turn their hand around awkwardly to oneself. The other argument they provide for two-handed flying is that users do not need to stretch their arms out to navigate. Two-Handed Flying is a bi-manual navigation categorized as a steering pattern, since it allows continuous motion without any movement of the feet and requires both arms to use. Steering patterns are described as being effective for traveling long distances, however they can cause visually-induced motion sickness due to visual-vestibular conflict [15]. Visual-vestibular conflict involves the abnormality of spatial orientation, which can cause motion sickness due to the disconnect of one's own physical movement from the simulated movement occurring in the VR world [1].

D. Worlds-in-Miniature (WIM)

Worlds-In-Miniature (WIM) originated for use in a VR Flight Helmet [27]. Worlds-in-Miniature involves showing a miniature version of the virtual world, usually tied to a tracked physical object. Users can interact with virtual objects and change their location by interacting with their miniature counterparts in the Worlds-in-Miniature, rather than physically interacting with the real objects in the virtual environment. In Stoakley, Conway, and Pausch's [27] original research, the miniature world appeared on a tracked clipboard, where the user would see a 3D room through the HMD. Users could grab and re-orient objects such as shelves in the miniature room, which in return would re-assign objects in the surrounding room in VR. Users could also rotate the clipboard to view the room at different angles. Worlds-in-Miniature is classified as a compound pattern, due to the navigation technique combining steering and pointing patterns [15]. More recently with VR becoming a more accessible technology, the navigation technique has made a re-appearance in research. A recent example includes a DIY World Builder research project [30], which used a HMD in combination with a tablet to create an immersive level-editor, where users could use an electronic tablet to see the miniature environment to place objects in a virtual environment. However, there is a lack of recent research into how effective Worlds-in-Miniature are for abstract data visualizations in VR.

E. 3D Data Visualizations

The topic of 3D Data Visualization has been a controversial subject in information visualisation (commonly referred to as *Infovis*) fields, however it is experiencing a resurgence with the advances in VR and AR technologies, whilst also becoming more accessible and less expensive. Positive aspects of 3D Infovis are increased engagement with the visualization and immersion, object constancy, and more dimensions to display data [6]. Issues include occlusion of information, selection and manipulation, and navigation [6].

3D graph visualization has been explored in recent years with a variety of immersive input devices and displays. Ware and Mitchell's influential graph paper was novel for using stereoscopic displays for large graphs [31]. They found that participants completed graph searching tasks significantly quicker with a 3D stereoscopic display than when viewing a large graph in 2D. Following this, visualization research began exploring viewing graphs in 3D with stereoscopic displays through VR and CAVE systems. An early example used projectors to project force-directed graphs onto a wall, with users using gestures to interact with the graph [22]. A recent research project, GION, investigated exploring and untangling large graphs using wall-sized displays [19]. Haplin et al. [13] explored comparing task times for 2D and 3D graph visualizations of large social networks in a CAVE. Their study found that mean task time was significantly less for 3D visualizations in comparison to 2D visualizations. Cordeil et al. [8] evaluated how network analysis differed in performance between CAVE systems and VR systems and found that VR had comparable task performance. Kwon et al. [16] used HMDs to place users inside a spherical graph, with users using a mouse to select different nodes. Alper et al. [2] studied graph visualisation tasks using 3D stereo highlighting (using 3D stereo projection) of 2D graphs. They found that 3D stereo highlighting outperformed 2D monoscopic rendering display for node adjacency search tasks. Research into room-scaled VR data visualization interactions however has not currently been investigated thoroughly in literature, and navigation around a large data visualization remains an open problem.

III. User Study

The study was a within-subjects study. Participants performed the four navigation techniques for 10 trials each, for four different tasks: Simple Find, Complex Find, and Path Find. Participants also completed one trial for each navigation for a Feature Find task. Therefore, each user completed 124 trials $(4 \times 3 \times 10 + (4 \times 1))$. Sixteen graphs were used for the study, with ordering of graphs and task order counter balanced across participants. The following measures were captured over the course of the experiment:

- Completion time between trials (TBT): Time taken to complete a trial during a task, for example finding (by tapping with a controller) one red node to the next red node or finding a path between two green nodes. The first task for Simple Find, Complex Find and Path Find was disregarded to avoid outliers. Time was captured at 1/90th of a second precision.
- Physical head movement and rotation: Distance between head position and rotation was recorded every 1 second over the course of the experiment to observe physical demand of the head between navigation techniques.
- Paas [23] mental effort for each navigation: Participants were also asked to fill out a PAAS scale (on a scale of 1-9 their mental effort to complete all tasks using the navigation) after each navigation technique to measure cognitive load.

- Qualitative measures: Participants filled out a questionnaire for each navigation technique involving ease to learn, difficulty to perform, accuracy of the navigation technique, and disorientation experienced while using the navigation technique. At the end of the experiment participants were asked which navigation techniques they preferred for searching tasks (Simple Find and Complex Find), Path Find, and Feature Find.

A. *Experimental Apparatus*

The study was conducted using our application VRige [9], which was built using the Unity Engine and uses the HTC Vive Pro Head Mounted Display and HTC Vive Controllers for interacting with a large graph visualization. The experiment was run on a computer with an Intel Core i7-7700K processor, GeForce GTX 1080 Ti graphics card and 64 GBs of RAM. We developed the study using the Unity games engine (version 5.5). The graph was generated using a Google Plus Social Circle Dataset retrieved from Stanford Snap [18] with a subset graph of 2000 nodes from an undirected graph. The graph layout was created using a spring force layout [11]. The study took place in a VR experiment space with approximately 2.5 $\times$ 2.5 metres ($6.25m^2$) of tracking space for the controllers and HMD. Edges of the graph were drawn at a low opacity with an alpha value of 0.2 to reduce occlusion issues. Graphs were subdivided into coloured clusters using K-Means Clustering based on the locality of the nodes world-position in the graph. The purpose of clustering the graph into different colours is to avoid overwheming the users visually, enabling users to distinguish different areas in the graph and improving understanding of an individual's own orientation in the graph.

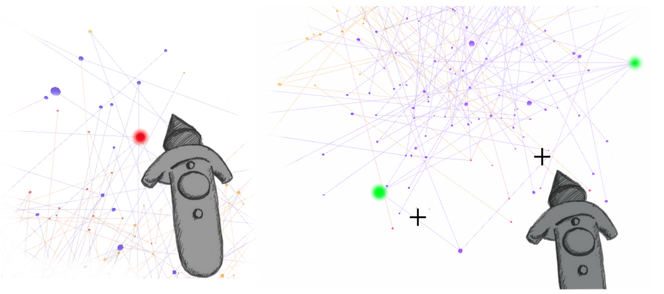

Fig. 3: An illustration of two of the tasks from the experiment. In Simple Find (left), participants had to find and tap the red node. In Path Find (right), participants had to finding and mark a path between two green nodes.

B. *Tasks*

The following subsection discusses each of the four tasks the participants performed in detail. Simple Find, Complex Find and Path Find tasks consist of 10 trials which involve the participant traveling to various locations of the graph to complete tasks. Nodes of interest in the 10 trials are picked at random. Simple Find and Complex Find requires the participant to find red coloured nodes in the graph. This mirrors low level analytical tasks defined by Lee et al. [17] such as finding extremums or retrieval tasks where the red node might represent an extremum or retrieval point. Path Find and Feature Find are common graph taxonomy tasks based on connectivity tasks. Participants completed tasks in a different order for each navigation technique.

1) Simple Find: During the Simple Find (SF) task, users were asked to travel to the red node in the Graph Visualization and tap the red node (See Figure 3). After tapping the red node, another red node would appear in close proximity that the user was also required to tap. The user completed this task 10 times. We allowed participants to walk to the node using positional tracking in the room or navigate to the node using the navigation technique, based on whichever felt natural to the participant. Each graph in Simple Find had a size of 900 nodes divided into 10 clusters.

2) Complex Find: Complex Find also involved the participant tapping a red node 10 times, however, red nodes appear further apart than in Simple Find rather than in close proximity. Each graph in Complex Find had a size of 500 nodes divided into 10 clusters.

3) Path Find: Path Find involves two nodes in the graph being highlighted as green. The participant is then asked to identify a path between the two green nodes by placing markers for each edge leading from node A to node B (See Figure 3). Markers can be erased if the participant makes a mistake or changes their mind about a path. Participants place a marker on the graph by pressing the Grip button on the HTC Vive Controller, and erase markers by pressing the trigger on the Controller. Every graph during the Path Find task had a size of 50 nodes divided into 5 clusters.

4) Feature Find: Feature Find involves participants identifying and counting the amount of triangles in a graph. Counting triangles is a common graph-based task, important for understanding inter-connected entities in a graph. For each navigation, the participant is given 1 of 4 graphs in a random order. Each graph for feature find had a graph size of 25 nodes divided into 5 clusters.

C. *Conditions*

The following subsections describe how each of the four navigation techniques function in the experiment.

1) Teleportation: Our implementation of teleportation involves the user projecting a laser with the touchpad held down on the Vive Controller. The laser target is then extended by putting your thumb on the top of the touchpad on the controller, and then reduced by putting your thumb on the bottom of the touchpad on the controller. The user then points the laser at the location they desire to travel to next (See Figure 4). While pointing, a user presses the trigger to teleport to the location. The screen fades to black and fades out for one second to reduce disorientation while teleporting.

2) One-Handed Flying: Our implementation of One-Handed Flying has participants point a blue arrow that appears while holding the Vive trigger (See Figure 5). The facing direction of the blue arrow is the direction in which the

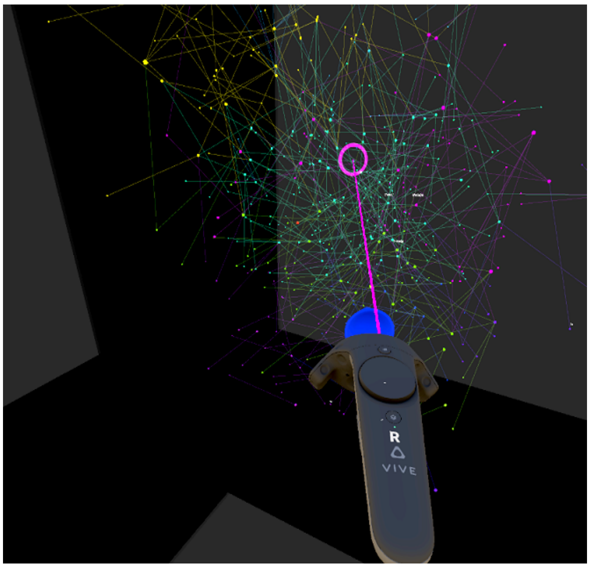

Fig. 4: Example of Teleportation with the Vive Controller. The end point of the laser pointer specifies the location the participant teleports to. The laser's length is adjusted using the touchpad on the VR controller.

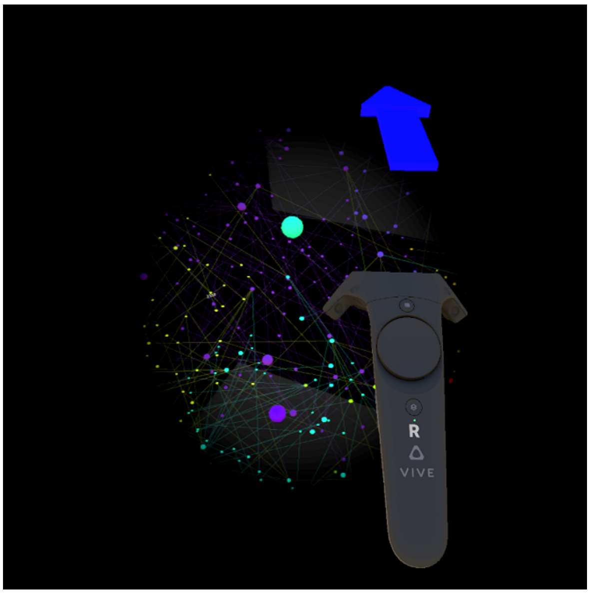

Fig. 5: Example of One-Handed Flying in the experiment, where the arrow specifies the direction of virtual movement. To reduce the participant's FOV, a vignette is enclosed around the participants view to minimize disorientation while navigating.

user moves. The distance of the Vive Controller from the user's origin also determines the speed of movement. We implemented FOV restriction using vignettes similar to recent work [10], [12]. As the user navigates, the FOV is restricted via a softened edged vignette to reduce discomfort while navigating through the graph.

3) Two-Handed Flying: Two-handed flying involves a two-handed navigation technique where users hold back both

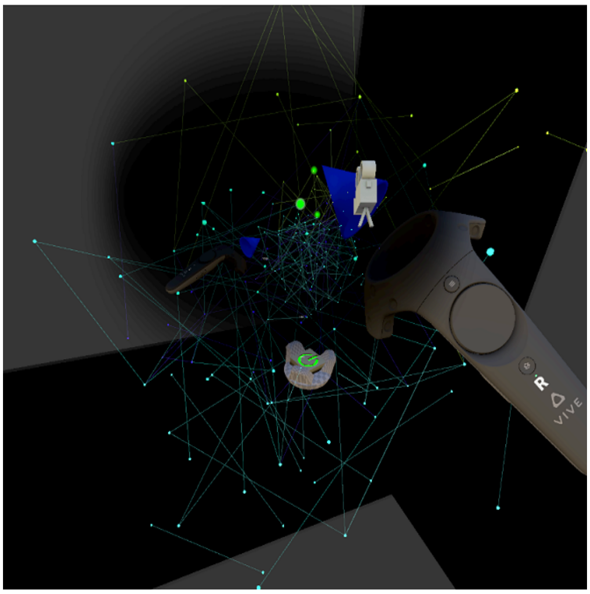

Fig. 6: Example of Worlds-In-Miniature in the experiment using a miniature camera to move around the graph. A black vignette is displayed behind the miniature graph to make it more readable against the real graph.

triggers on two Vive Controllers to produce an arrow (See Figure 1). The arrow creates a vector, where based on the direction and length of the vector is where the participant navigates. The original implementation of Two-Handed Flying used a dead zone to determine when to stop by tracking the distance + direction of the users own hands in contrast to our implementation which uses controllers and buttons to stop virtual movement [27].

4) Worlds-In-Miniature: Worlds-In-Miniature (WIM) is another two-handed navigation technique where the participant has a Vive Tracker in one hand and a Vive Controller in their dominant hand (See Figure 6). The user can look at the WIM to determine their current location in the graph by looking at a Miniature Camera within the WIM. Participants pick up the Miniature Camera with the Vive Controller by holding the trigger, and then the real position in the graph is affected by the miniature position in the WIM. The WIM is at a scale of 1:15 in comparison to the real graph.

D. Procedure

Every participant went through the same protocol as follows: (1) Introduction, (2) Screening, (3) Pre-Survey and Calibration, (4) Training, (5) Main Tasks, and (6) Survey. For Step 1, the experiment was explained to the participants and afterwards they completed the consent form. During Step 2, participants completed a brief survey to survey their experience with VR, as well as gender, age, and whether they were colour-blind. During Step 3, participants were run through inter-pupillary distances (IPD) tests to determine the focal distance of the HMD lenses to ensure the display of the HMD for each participant was clear and calibrated correctly. Participants were also asked whether they were left-handed or right-handed in order to adjust bi manual navigation techniques (WIM and THF). In Step 4 of the experiment, participants were trained each of the navigation techniques. Participants were trained using each navigation in accordance to an assigned permutation (i.e. one participant might go through WIM, OHF, THF and TP). For each training navigation, participants completed three trials. During Step 5, participants were guided through the main tasks with the navigations in the assigned permutation. After each navigation the participant went through a questionnaire including a Paas [23] mental effort questionnaire, easy to learn, difficult to perform, and how disorienting the navigation was to use. Participants were also left the option to leave a comment in the questionnaire after each navigation. For Step 6, participants went through a final qualitative survey, where they were asked which navigations they preferred for finding red nodes, path finding and triangle counting. The experiment took approximately 1 hour to complete, and each participant received a $25 gift card for their time.

E. Hypotheses

We developed a set of hypotheses relating to task completion times, kinetics involving the HMD, and qualitative measures.

Time: We believe Teleportation will take longer to complete trials (TBT), due to the need to adjust the laser to move to a desired location. Additionally, we hypothesize participants who use Two-Handed Flying will complete tasks significantly quicker (TBT) than other navigations due to the increased amount of control associated with bi-manual steering.

- **H1**: Teleportation will be the slowest navigation to complete trials (TBT).
- **H2**: Two-Handed Flying will be fastest navigation to complete trials (TBT).

Physical Movements: We hypothesize that Worlds-in-Miniature will have significantly less physical head movement than other navigations, due to the ability to remain stationary and orbit around the graph using the WIM. We also believe that there will be more physical head movement with Teleportation due to participants wanting to physically walk to targets, to avoid using the navigation. Reasons participants would want to avoid using the navigation is the fade in to fade out effect, and the cost in time to adjust the laser to navigate to a point. We also hypothesize that there will be no significance for physical head movement between Two-Handed Flying and One-Handed Flying due to the navigation techniques being similar steering patterns.

- **H3**: There will be less physical head (distance) movement with Worlds-In-Miniature than other navigation techniques.
- **H4**: There will be more physical head (distance) movement with Teleportation than other navigation techniques.
- **H5**: There is no significance in head (distance) movement between One-Handed Flying and Two-Handed Flying.

Qualitative: We believe that participants will feel the most disoriented using Worlds-in-Miniature, due to hand shakiness while grabbing the miniature camera causing shakiness with the real camera. We also hypothesize Two-Handed Flying will be the most accurate navigation for participants due having more control over speed and orientation in comparison to other navigation techniques. Lastly, we also hypothesize that participants will have the least amount of disorientation using steering patterns such as One-Handed Flying and Two-Handed Flying, due to the increased amount of control associated with steering patterns.

- **H6**: Participants will feel the most disoriented in WIM.
- **H7**: Two-Handed Flying will be the most accurate navigation for participants.
- **H8**: People feel less disoriented with Steering Patterns (One-Handed Flying and Two-Handed Flying) than with Teleportation.

F. Statistical Analysis

1) Time: For contrasting the trial times of the four navigations, Mixed Effects Analysis of Variance was used. Separate models were specified for each task, as we were interested in comparing the navigation techniques within each task rather than between them. All models were defined with a gamma probability distribution and a log link function. For Simple Find, Complex Find and Path Find, the models were specified with fixed effects of navigation technique and task, with a random effect of participant on the intercept. Feature Find consisted of one trial instead of 10, due to the potential of having a large number of triangles to count. As such, the model for Feature Find was specified with one fixed effect of navigation technique. To further investigate differences within the navigation technique fixed effect, pairwise comparisons were conducted. Due to the number of trials, planned contrasts were conducted on the trial fixed effect such that all trials were contrasted against the final trial reference category (Trial 10). Trial 1 was omitted to avoid outliers due it being an establishment task. Multiple comparisons were corrected with Bonferroni adjustments.

2) Physical Movement: To obtain physical movement of participants over the experiment, the position and Euler angle of the HMD was recorded each second. Distance was then recorded by subtracting the current vector A from the previous vector B recorded for the HMD position and Euler angle. After subtracting both vectors, the square magnitude was calculated for the vector to obtain the distance. At the end of each trial, the sum of all square magnitudes of the HMD distance traveled and HMD Euler angles was calculated. The square magnitudes for a given participant, trial, and navigation were then used in our calculations.

For contrasting the head movement and rotation differences between the navigation techniques Mixed Effects Analysis of Variance models were specified as per Time above. Both the distance and rotation results fit a normal distribution so therefore linear distributions and identity link functions were used.

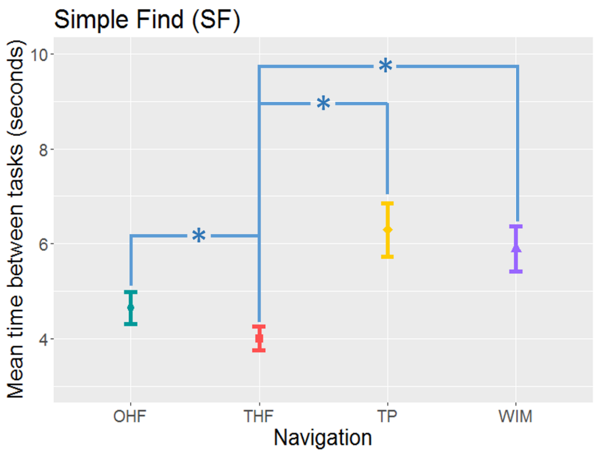

Fig. 7: Simple Find Results for Time Between Trials (Seconds). Two-Handed Flying (THF) was found to be significantly faster than all other navigation techniques.

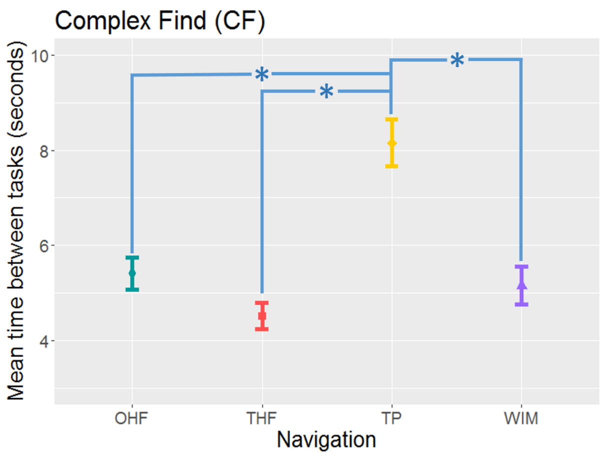

Fig. 8: Complex Find Results for Time Between Trials. Teleportation (TP) was found to be significantly slower than all other navigation techniques.

3) Qualitative: A Friedman's Two-Way Analysis of Variance by Ranks was used for the Paas [23] mental effort scores and other qualitative results (ease to learn, difficulty to perform, disorientation and accuracy).

IV. Results

There were 25 participants recruited (16 male, 9 female) for the experiment. Participants were aged from 19 to 57 ($M = 29.68$, $SD = 9.48$). For distributions of experience with VR, five participants used VR once a week (20%), four participants once a month (16%), four participants once a year (16%) and twelve participants never use VR (48%). For colour blindness, one participant was colour blind, although they were still able to complete the experiment. The experiment mostly consisted of right-handed participants (96%), with one left-handed participant (4%). The following sections describe the results we obtained from the experiment in regards to mean trial time for the navigations, physical movement measured between the navigations and qualitative results.

A. Trial Completion Time

For the Simple Find task, significant differences were observed for the navigation technique $F(3, 864) = 18.696, p < 0.001$, and trial $F(8, 864) = 3.946, p < 0.001$ fixed effects. For each navigation technique, pairwise comparisons revealed that Two-Handed Flying was the fastest ($p < 0.05$), followed by One-Handed Flying ($p < 0.05$). No significance difference was found between Worlds-In-Miniature and Teleportation (see Figure 7). For trial, planned contrasts revealed a significant difference between trial 9 and 10 ($p < 0.05$). No other significant differences were observed.

For the Complex Find task, significant differences were observed for the navigation technique $F(3, 864) = 36.990, p < 0.001$, and trial $F(8, 864) = 7.474, p < 0.001$ fixed effects. For each navigation technique, pairwise comparisons revealed that Teleportation was the slowest ($p < 0.01$). No significant difference was found between Worlds-In-Miniature, One-Handed Flying and Two-Handed Flying (see Figure 8).

For the Path Find task, significant differences were observed for the navigation technique $F(3, 861) = 3.293, p < 0.05$, and trial $F(8, 861) = 11.498, p < 0.001$ fixed effects. For each navigation technique, pairwise comparisons revealed no significance between the navigation techniques. In regards to some of the results lacking significance, obtaining more participants for the experiment might show finer degrees of differences. However, the differences between the navigation techniques was not large enough to show significance after all the pairwise adjustments were made.

For the Feature Find task, no significant differences were observed for the navigation technique and trial fixed effects. For each navigation technique, pairwise comparisons revealed no significance between the navigation techniques despite finding a a significant fixed effect of navigation technique.

B. Physical Movement

For Simple Find, significant differences were found for the navigation technique for head movement $F(3, 96) = 30.513, p < 0.001$. Pairwise comparisons revealed that Two-Handed Flying had significantly more head movement than all other navigation techniques ($p < 0.01$). Worlds-in-Miniature also had significantly less head movement ($p < 0.001$) than all other navigation techniques. Significant differences were also found for head rotations $F(3, 96) = 4.103, p < 0.01$. Pairwise comparisons revealed Teleportation had significantly more head rotations than Two-Handed Flying ($p < 0.01$).

For Complex Find, significance was found for the navigation technique also in regards to head movement $F(3, 96) = 65.776, p < 0.001$. In pairwise comparisons, Two-Handed Flying had significantly more head movement ($p < 0.001$) than all other navigations. Worlds-in-Miniature had significantly less head movement ($p < 0.001$) than all navigation techniques. For head rotation, significance was found between the navigation techniques $F(3, 96) = 18.069, p < 0.001$. Teleportation was found to have significantly more head rotation than other navigation techniques ($p < 0.001$).

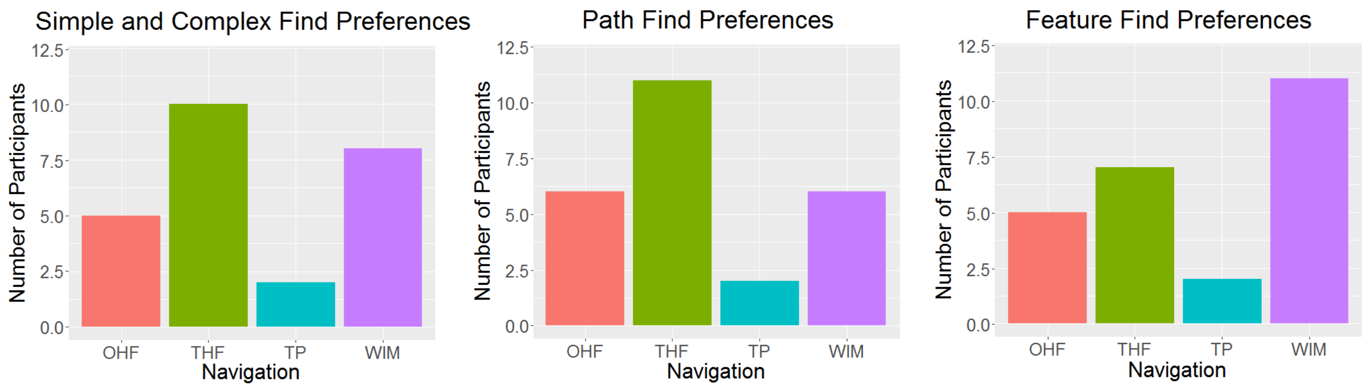

Fig. 9: Participants' first preferences of navigation technique for different tasks. Simple Find and Complex Find were combined for a participant's preference for finding red nodes.

For Path Find, significance was also found for head movement for navigation technique $F(3, 96) = 34.186, p < 0.001$. In pairwise comparisons, Two-Handed Flying again had more head movement than other navigation techniques ($p < 0.001$). Worlds-in-Miniature also had the least amount of the head movement ($p < 0.001$) than other navigation techniques. For head rotations, no significance was found in Path Find tasks.

For Feature Find, significance was also found for head movement for navigation technique $F(3, 96) = 19.389, p < 0.001$. In pairwise comparisons, Two-Handed Flying had the most amount of head movement ($p < 0.01$). Worlds-in-Miniature also had the least amount of head movement against other navigation techniques ($p < 0.05$). No significance was found for head rotations in Feature Find tasks.

C. Qualitative

For Paas mental effort results we did not find any significance between the navigation techniques, $\chi^2(3) = 3.817, p = 0.282$. For ease to learn results, we did find significance between the navigation techniques $\chi^2(3) = 10.070, p < 0.05$. However in our pairwise comparison we found no significance. For difficulty to use, we did find significance between the navigation techniques $\chi^2(3) = 8.186, p < 0.05$. Pairwise comparisons however revealed no significance. For disorientation, we also found significance $\chi^2(3) = 13.418, p < 0.01$. For our pairwise comparison, we did find significance between One-Handed Flying and Worlds-In-Miniature ($p < 0.05$). For accuracy, we also found significance $\chi^2(3) = 8.227, p < 0.05$. However, a pairwise comparison revealed no significance between the navigation techniques.

At the end of the experiment participants were asked to fill out which were their preferences of navigation for specific tasks in the experiment. We found that participants preferred Two-Handed Flying for finding red nodes, which entails Simple Find and Complex Find tasks (See Figure 9). Worlds-In-Miniature was their second favourite for Simple Find and Complex Find tasks. Two-Handed flying was also preferred over the other navigations for path finding tasks (See Figure 9). For counting triangles participants preferred to use Worlds-In-Miniature, followed by Two-Handed Flying (See Figure 9). Teleportation was the least preferred navigation technique for all trials by participants.

V. Discussion

Two-Handed Flying was the fastest navigation to complete Simple Find and Complex Find tasks. Therefore, we can partially support H2 for Simple Find and Complex Find tasks. Two-Handed Flying fast completion times are likely a result of being able to quickly move backward and in different directions by adjusting the arrow with the controllers. A participant who had experience playing archery games in VR commented the navigation technique as an "intuitive metaphor" and "easy to use". Other participants reported that it was "harder to pick up, but once I got it felt very easy" and felt "very natural due to the ability to use both hands as if turning the space like a ball". Additionally, participants could use Two-Handed Flying to quickly obtain and overview of the graph to move to the next point.

One-Handed Flying required participants to put their arm over their shoulder to go backwards, which is likely why it was slower since backtracking was more difficult. Participants commented that One-Handed Flying could have benefited from a "speed boost", thus results may improve if the speed is increased for the navigation technique. Participants also commented that "the reduced vision while moving was disorientating" and "didn't like the narrow focus when travelling"' suggesting that the FOV restriction may have made the technique more disorienting for some participants rather than less. However, One-Handed Flying generally received positive feedback such as "very natural and easy to learn and use" and "easiest one so far because the arrow guided me".

Teleportation was significantly slower than other navigations in Complex Find, therefore we can partially support H1 for Complex Find tasks. Teleportation's long completion time was likely due to the time required to adjust the laser target and the one second delay imposed to reduce disorientation. Removing the one second delay and the fade in to fade out transition effect may improve results. It was observed that the transition effect caused disorientation for participants, due to losing orientation for one second as it faded back in. Faster transition effects may improve results, but we do not recommend using it due to the cause of disorientation and visual removal from the VR environment. H4 has some evidence, such as the significant amount of head rotations associated with Teleportation with Complex Find tasks. There was not enough evidence to reject the null hypothesis for H4.

We did find significantly more head movement with Two-Handed Flying than other navigations, rejecting H5 that One-Handed Flying would have the same amount of head movement. Participants who were less familiar with VR were also observed to use navigation techniques less, and preferred walking to targets. This was risky, due to incidents during the experiment where participants would nearly walk into a wall or desk. Worlds-In-Miniature appeared to be a safer option due to participants staying more stationary and, as a result, reducing the likelihood of walking into obstacles. This supported our hypothesis H3, that less physical movement would occur with the HMD with participants using Worlds-in-Miniature. Thus we recommend using Worlds-in-Miniature for smaller VR spaces, where there is less physical space to move around. Participants commented that our Worlds-in-Miniature implementation made them “feel a little motion sick”, could benefit from “some smoothing on tracking”, and was “pretty shaky”, suggesting smoothing on the movement of the Worlds-in-Miniature may reduce some disorientation that occurs due to hand shakiness. However, some participants preferred Worlds-in-Miniature the most, commenting “World in miniature felt the most natural to use, as I could see the whole graph at once” and was “the easiest and most intuitive technique”. Comments on Teleportation included that it was “slower and less accurate because have to keep teleporting” and that it “took time to extend the ray when moving further away. The black out while teleporting was holding me back a bit”.

Discussing cognitive effort, Paas mental effort scores were inconclusive likely due to the variance of experience in VR across participants. Nearly half of the participants had little to no experience with VR (48%), with the other (52%) using VR at least once a week, month or year. Therefore removing Qualitative and Paas scores for participants with little to no experience with VR may provide more significant results. For studies that involve more intermediate navigations such as Worlds-in-Miniature, we may recommend finding participants who have more experience in VR in contrast to little in the case of measuring mental effort specifically.

We observed that participants new to VR were more overwhelmed by the experience and the navigations, thus reporting higher mental effort for some of the navigations. We suggest that participants with more experience with VR are more likely to have more evenly distributed Paas mental effort scores if their results are isolated from participants who have little to no experience with VR. This may have also affected other qualitative results such as accuracy and disorientation, due to the results being less evenly distributed where we found significance between the distributions but were not able to report significance for navigation techniques individually. A participant with little to no experience with VR may be more disoriented for a navigation technique than a participant who has more experience with VR. Thus, qualitative hypotheses H6, H7 and H8 are not supported to lack of significance in pairwise comparisons.

VI. Limitations

As discussed above, obtaining participants who have a variety of experience with VR may affect qualitative results for intermediate VR experiments. For our experiment we targeted the general population for participant recruitment, however future VR experiments that require more mental and physical effort may have more informative qualitative results if recruited participants have more experience with VR. A larger VR space may have worked better for the experiment additionally to counter events where participants nearly walked into walls and desks. Our graph system currently can handle up to 3000 nodes, but cannot maintain 90 fps, which would not be ideal for VR. Therefore we pertained to using graphs lesser than or equal to 900 nodes. The graph layout was also generated by using a force-directed algorithm which can cause edge crossings and occlusion, thus possibly increasing cognitive load. Worlds-In-Miniature’s accuracy could have been improved additionally due to a between the miniature camera position and the real camera position. This study also only looked into using these navigation techniques for social networks. Thus, results may differ with other graph-like structures and datasets such as lattice fields, time-varying data, and geographical data.

VII. Conclusion

From our observations Two-Handed Flying appeared to be the fastest and most preferred against other navigations for exploring and performing tasks in a large data visualization, such as a large graph. Future work could pertain to optimizing 3D graph visualizations, to analyze how such navigations could perform with a graph up to tens of thousands of nodes. Using edge-bundling for the graph may also provide more informative results, reducing cognitive load on the participant. Improvements to Worlds-In-Miniature’s accuracy may also reduce disorientation of the navigation technique for participants. We also measured how participants entered and left the graph to look for targets by obtaining an overview of the visualization, and would like to formally analyse if there was a correlation between moving in and out of the graph and the navigations being used. We believe participants are more likely to obtain an overview to find the next target, such as the next red node, than remain inside of the graph. We are interested in performing a follow up analysis on how often this pattern occurs and with which navigation techniques it is most frequent in future work.

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