IMAT5120 – Assignment 1 - Evaluation of a Research Paper

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1. Introduction

For this assignment I selected "*Immersive Collaborative Analysis of Network Connectivity: CAVE-style or Head-Mounted Display?*" [1], published in the well-recognised journal "IEEE Transactions on Visualization and Computer Graphics" (TVCG), with papers bi-monthly "*on subjects related to computer graphics and visualization techniques, systems, software, hardware, and user interface issues*" [2]. IEEE has a strong peer review process with submitted articles critically reviewed before publication. This high-quality standard is reflected in the chosen article with it's clear, logical overall structure and well considered, relevant and valid research instrument.

As an enterprise technical architect within a global business analytics team, and proponent of virtual reality (VR) head-mounted displays (HMD) as game-changing visualisation platforms, I look to further understand if visualisation of big data in virtual spaces via cost-effective hardware can deliver improved, more efficient analytical sensing and insightfulness over traditional 2D methods. Sharing and discussing Excel documents, emails full of screenshots from reports and dashboards, and juggling several information sources on limited resolution displays is common practice in team collaborative investigating of complex problems. It is cumbersome and inefficient, especially when analysis requires input from different domain experts often geographically separated. This was my motivation for reading further to understand the research itself but also learn from the authors study design given their successful IEEE publication.

Two quite distinct VR solutions are incorporated in the study – CAVE (Cave Automatic Virtual Environment) and the Oculus Rift DK2 (Development Kit 2). CAVE is a more traditional, expensive and room-scale system comprising eighty 46-inch displays arranged in a horseshoe shape and providing a field of view (FOV) of 330 degrees. Users are physically present in the same space and can walk around. Scenes are rendered in 3D passive stereo, with users wearing polarised glasses, with head tracking of one user and hand gesture tracking for all users holding physical wands. The Oculus Rift DK2 is a consumer-level HMD solution, with each user equipped with a 100-degree FOV headset with scenes rendered in a 3D stereoscopic image, incorporates head tracking, and is tethered via cables to a computer. Due to tethering, the Oculus Rift DK2 is primarily a "sit-down" solution. An additional Leap Motion controller provides hand gesture tracking capability. Collaborating users of the HMD platform do not need to be in the same physical space.

The paper enquires "*Does collaborative immersive visualisation no longer require the use of expensive equipment at universities or corporate data centres?*" [1] and "*Will these differences be significant impediments to adoption of low cost HMD devices for collaborative visualisation of abstract data?*" [1]. It proceeds to evaluate both hardware platforms based on two tasks assigned to the study participants – 1. Count the number of triangles, and 2. Find the shortest path between two nodes.

2. Which research method has been applied?

The authors employ a mixed methods mode of enquiry using an after-only experimental study design. An initial view of the paper, with sections including characteristics, user study, hypotheses, experimental design, procedure, participants, measures and results tells me it is primarily a well-structured quantitative study. I classify the study as after-only experimental, being the first of its kind, with the authors observing the effect on three concepts (functionality, collaboration and user experience) transformed into measurable variables when each VR platform (independent variable) is applied to the data analysis tasks. Research questions RQ1 "*[Functionality] the ease with which groups of users can complete analysis tasks?*" [1] and RQ2 "*[Collaboration] the degree and kind of collaboration used in connectivity analysis?*" [1] are measured with scales quantitative in nature. The qualitative data collection element is introduced with RQ3 "*[User Experience] the qualitative usability aspects?*" [1] as measuring was via questionnaire containing both closed and open questions. Other indicators of a study heavily weighted towards the quantitative approach was a sample size of 34 participants and the output presented in an analytical, statistical manner.

The research questions are direct, focused and unambiguous. The research framework specifically collects data from variables within pre-experiment questionnaires, task completion times (interval scale), collaboration shared focus via head position tracking (ratio scale) and audio monitoring (ratio scale), and finally post experiment questionnaires. This clearly demonstrates the application of a quantitative research method. Additionally, 6 hypotheses are being tested, another indication the study is quantitative in nature.

3. What is the motivation for this work?

I believe the motivation behind this study goes directly back to the first question asked in the introduction of the paper: "*Does collaborative immersive visualisation no longer require the use of expensive equipment at universities or corporate data centres?*". Given the example CAVE solution has eighty screens, the purchase price is significantly more than a single Oculus Rift HMD headset at $400 today. Factoring in the running costs and associated energy footprint of a CAVE system, the physical space required, the economic challenges constraining the budgets of both educational and corporate bodies, plus a remote working and nomadic workforce makes this first question very relevant. Accounting for the differences between platforms, such as presence and movement, they look to research, understand and evaluate through quantitative, empirical research enriched with qualitative in-depth user feedback if the lower-cost HMD platform is ready to replace the start-of-the-art CAVE system for the task of collaborative abstract data analysis.

The authors claim "*no formal user studies investigating collaborative visualisation of abstract data in immersive environments*" [1] and "*we focus on a type of data and task that is rarely considered in VR type environments: analysis of connectivity in network data*" [1]. An extensive literature review was carried out, covering CAVE platforms, virtual environments, 3D visualisation of datasets and how collaboration can successfully aid understanding of big data, and sourced from IEEE, ACM and other journals/conferences, yet they still identified a gap in the body of knowledge, thereby satisfying a research criterion and validating this research as a novel contribution.

4. What is the proposed solution?

The study investigates whether the HMD platform is viable for collaborative visualisation of abstract data and through empirical data collection a comparison is made to assess whether the lower-cost HMD solution can be a viable replacement for the expensive state-of-the art CAVE system in this use-case scenario.

With the research problem clear, the study framework is further defined in scope with a research instrument comprising 3 research questions, each supported by well-formed hypotheses, which are concise, unambiguous and can be operationalised with measurement. In my opinion the hypotheses have been well thought-out. If we consider the difference in specification and hands-on use of the two hardware platforms, from display resolution, head and hand tracking to physical movement and collaborator presence, the hypotheses are allowing each solution to express its effect to the fullest degree. Examples of hypothesis from the study include "*H1 The VR platform will affect task completion time*" [1] and "*H4 The VR platform will affect the measured degree of collaboration between participants*" [1].

To answer the questions and test the hypothesis, an experimental setup facilitated the comparison of the VR platforms in the execution of two collaborative tasks repeated 12 times: the "*counting the number of triangles (3-vertex cliques)*" [1] and "*finding the shortest path between two nodes*" [1] on a 3D network. The sample 34 participants were split randomly into two groups, with the first group assigned to using the HMD, and the second group the CAVE. Within each group users were paired (to minimise time for decision-making), opening opportunities for collaboration techniques such as divide and conquer. Visual triangle and node stimuli for each task varied slightly in size to introduce an element of randomisation.

5. How did the authors evaluate the solution?

The study investigated the collaborative analysis of 3D network diagrams visualized in the VR space of two different hardware platforms. Prior to the collaboration analysis task, each participant completed a questionnaire including questions on their background, familiarity in working with graphs and any previous experience of VR platform use. The analysis task itself involved "*identifying the number of triangles (3 connected nodes)*" [1] and "*shortest path between two nodes*" [1] in 12 randomly generated 3D network graphs of varying size. The precisely defined and measurable hypothesis enabled the study to be executed in a systematic and controlled manner, with all data from primary sources. The independent variables were each of the VR platforms. Dependent variables for task completion time and accuracy (answers orally reported from participants) were quantitively measured to evaluate RQ1 Functionality and test H1/H2. Dependent variables for shared focus (head tracking) and verbal communication (audio recording) were quantitively measured with data output from the hardware platforms to evaluate RQ2 Collaboration and test H3/H4. A post-experiment survey was used to qualitatively measure RQ3 User Experience and test H5/H6.

The collected data from the pre and post-experiment questionnaires allowed quantitative classification of users (gender, familiarity with network diagrams within group: CAVE 50%, HMD 73%, experience of VR platform: CAVE 66%, HMD 62%) and quantitative measuring of perceived collaboration, more specifically communication, activity, capability and presence, using a "*Likert scale (Strongly Disagree=1, Strongly Agree=5)*" [1]. More qualitive, subjective open-ended questions such as "*Can you describe the strategy that you used to count the triangles?*" [1] were also measured.

For RQ1 Functionality, completion of tasks were measured using time (interval), with mean rate calculated for correct answers to number of triangles and shortest distance. In order to validate the measured task accuracy, the authors employed "*the non-parametric Mann-Whitney U test to compare the two platform accuracy means*" [1], with "*The result of the test showed that there were no significant differences be-tween the CAVE2 and the HMD average scores*" [1]. Task completion times for both platforms was not distributed normally, so they employed the Shapiro-Wilk test to validate. Concluding, HMD users were 40% quicker for accurate shortest path and 30% quicker for accurate triangle count.

To answer RQ2 Collaboration, measurements from positional data against time, directly captured from head-tracking (shared visualisation focus time on same approximate 3D network area), and audio from microphones (verbal communication) were captured to facilitate evaluation. For shared focus mean of shorted path, no significant difference between platforms (CAVE 53%, HMD 55%). Interestingly, participants were asked to report their strategic approach to the counting tasks, with the strategy coded by the researchers – TS1=Shared Focus, TS2=Divide and Conquer, TS3=Duplication. This allowed correlation analysis between the measured focus and reported focus strategy, in addition to comparison between strategy used and time taken to complete tasks. The post-experiment questionnaire included the question "*Discussions using this virtual reality set-up tend to be more impersonal than face to face discussions*" [1] measured by a dichotomous yes/no variable.

In response to RQ3 User Experience, a post-experiment questionnaire with closed Likert scale measures were used to evaluate the user experience, covering the "*self-perception of capability*" [1] in performing the tasks, and comfort, satisfaction, and any nausea experienced while using the VR platform. Open questions allowed more informal, deep dive, discussion orientated feedback from the participants.

The study includes several charts and tables for a visualized comparison between the two VR platforms on measures including "*overall time performance, completion time by strategy, vertical head movements*" [1] and shared focus.

6. In your opinion how satisfactory was the solution?

Overall, I believe this experimental research study was clearly defined and logically structured, with a well-designed instrument that facilitated controlled research that was measurable, empirical and verifiable. The authors clearly demonstrated their technical expertise for building a complex research instrument. They strived hard to give fair representation to each of the platforms to maximise the outcome of the VR platform independent variables, for example ensuring the centre and distance of visualized 3D networks graphs was equal across both platforms. I was convinced by the final conclusion – "*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*" [1].

At the core of the study was a solid foundation of research questions: RQ1 "*How does the VR platform affect functionality?*", RQ2 "*How Does the VR platform affect collaboration?*" and RQ3 "*How does the VR platform affect user experience?*". These are simply worded and specific. They further enhanced the study by attaching a framework of hypotheses to each of the questions, for example: H1 "*The VR platform will affect task completion time*" [1], H4.2 "*The VR platform will affect the amount of verbal communication during collaboration*" [1] and H5 "*The VR platform will affect the self-reported usability*" [1]. These hypotheses are clear with no ambiguity. The authors went into detail on how each hypothesis was measured, for example H1 with time interval and H4.2 with analysis of audio recordings. Details of distribution tests (e.g. Shapiro-Wilk) and formulae used in variable measurement analysis were included. This gave me confidence the hypotheses were verifiable and repeatable. The inclusion of charts with measurements plotted helped me to understand the study results. Attention was paid to each hypothesis in equal balance.

By choosing a mixed methods approach, integrating pre-experiment and post-experiment questionnaires with open-ended qualitative questions, I believe greater insight and value was extracted from the study. Example feedback from the CAVE group highlighted one participant commenting on how the size of the display aided analysis of large data quantities, while another reported frustration when their view was blocked by someone else stood in front. One of the HMD group participants reported comfortable discussion of tasks given they had the same shared view of the data. This mixed methods approach with inclusion of qualitative feedback enriched the study with a more detailed, richer perspective and a greater understanding.

I did note however a slightly contradictory detail on the study sample: "*Participants came from diverse backgrounds but had mainly computer science and engineering backgrounds*" [1], without any quantification on exact breakdown of profession. I question how the outcome may have been affected by a truly diverse study sample including more participants without prior experience of VR platforms and 3D graph networks. I don't believe the authors intended any bias, I believe it was more convenience sampling.

7. What are the main contributions of the paper?

The authors submitted the "*first formal study into collaborative analysis of abstract data*" [1] in a VR platform, comparing two VR hardware platforms: the CAVE system, state-of-the-art and very expensive, against the Oculus Rift DK2 HMD, a consumer level and low cost to entry solution. The study concluded no significant differences between the two platforms in terms of participant collaboration, but significantly faster task completion times using the HMD. This indicates the HMD solution is a viable alternative solution to the traditional CAVE system, at reduced cost in terms of equipment price, physical space requirements and energy footprint, whilst still offering comparable collaborative qualities.

For me personally, it has been a rewarding and educational experience in digesting and understanding how a high-quality research study is designed and executed.

8. What is not clear in the paper?

I believe a reworking of the title of the journal, "*Immersive Collaborative Analysis of Network Connectivity: CAVE-style or Head-Mounted Display*?" [1] could remove some ambiguity, as it leads me to naturally add a "for what?". Perhaps "*A comparison of CAVE-style and Head-Mounted Display?*", or "*Can Head-Mounted Displays replace CAVE-style VR platforms?*" as a stronger indication of the problem being tested.

The hardware specification of the CAVE system was not detailed until page 3, leading me to Google for further information to comprehend and put into context the first pages.

When detailing the hardware specification of the Oculus Rift DK2, the authors claim "*With the noticeable differences summarised in Table 1, one can expect a strong impact of the VR environment on collaborative visualisation of abstract data*" [1], which is a little ambiguous, as it's not clear whether they make that claim on behalf of the HMD solution specifically or VR platforms as a whole. Regardless, I didn't feel it was appropriate to make this claim so early in the study paper and outside the structure of the hypotheses definition and testing.

References

[1] M. Cordeil, T. Dwyer, K. Klein, B. Laha, K. Marriott and B. H. Thomas, "Immersive Collaborative Analysis of Network Connectivity: CAVE-style or Head-Mounted Display?," *IEEE TRANSACTIONS ON VISUALIZATION AND COMPUTER GRAPHICS,* vol. 23, no. 1, January 2017.

[2] L. D. Floriani, "IEEE Transactions on Visualization and Computer Graphics," [Online]. Available: http://ieeexplore.ieee.org/xpl/aboutJournal.jsp?punumber=2945#AimsScope.