Evaluation of Perspective Separation for Collaborative Task Performance in Shared Virtual Environments

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ABSTRACT

Virtual reality has the power to enable users to collaborate on tasks remotely in real-time. As it stands, however, the industry lacks a mainstream application involving collaboration with other individuals within a shared virtual environment (SVE). Therefore, we implement an application that explores the potential for improving individual task performance by introducing a collaborator with a unique perspective on the shared environment. In our study, individuals navigate a predefined set of three-dimensional mazes in a SVE, collecting as many coins as possible during the allotted period of time. We seek to determine whether users' performance on the task will benefit from the introduction of a collaborator with a high-level, "bird's-eye" perspective of the same SVE with whom they are encouraged to communicate. Additionally, we analyze whether the addition of path-tracing information improves user performance when completed under individual and collaborative conditions. Finally, we study the relationship between presence, co-presence, and performance when dealing with collaborative tasks to create better informed SVEs for real-world applications. We discovered that collaboration did not improve task performance. However, the introduction of path-tracing information improved task performance for users completing the task individually and reduced task performance for users completing the task collaboratively. Although there was no observed relationship between presence/co-presence and performance, we discovered that the low-level participants felt more present than their high-level counterparts during collaborative trials. Finally, we urge future studies to explore the effects of collaboration on a variety of tasks, as well as the impact that interaction fidelity may have on user performance within shared virtual environments.

1 INTRODUCTION

An individual's performance on a task involving navigation of an unfamiliar environment is often limited without additional information about his/her surroundings. With only a first-person view of the local setting and little context regarding its position within the larger world, the individual can face difficulty in developing a strategy to approach the task at hand. A real-life example of this situation is a search-and-rescue operation, in which personnel on the ground are tasked with locating and assisting people in distress whose specific whereabouts are unknown. From the immersed perspective of the searchers, the overall layout of the target environment can be obscured by the immediate surroundings (e.g. doors, walls, buildings, trees, etc.). Virtual reality (VR) has the potential to improve performance on such tasks, given its ability to accurately model real-world environments and virtually augment them with information relevant to the task at hand. This serves as the motivation for the VR application presented in this study, which provides a real-time path tracing display for the user(s) immersed in the virtual environment (VE) to assist them with navigation. If applied to the aforementioned search-and-rescue scenario, this tool could help searchers iteratively and more efficiently devise an optimal route by which to traverse the environment and rescue those in need. This improvement in performance could be the difference between life and death for the individuals in distress, underlining the importance of such an application if implemented correctly.

Another aspect of VR worth exploring for improving performance on navigational tasks is its ability to enable real-time collaboration in a unique manner. By giving users located remotely in the physical world the means to exist in the same shared virtual environment (SVE), VR can essentially eliminate distance as a hindrance to communication. The application in this study utilizes this benefit by allowing two users to collaboratively navigate an SVE with the goal of improving overall performance an object-collection task. This is accomplished by offering each user a different perspective of the environment: one with a first-person ("egocentric") view and the other with a bird's-eye ("exocentric") view, henceforth referred to as the "mortal" and "deity" respectively. Although only the mortal is capable of directly navigating the environment in pursuit of completing the required task, he/she is empowered with aid informed by high-level knowledge about the SVE as a whole. For search-and-rescue missions and training applications, this form of collaboration could help identify the most promising areas to visit early during development of a

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navigation strategy. Furthermore, users of networked VR applications experience to a certain degree a feeling of “co-presence,” which is the sense of being with other people in a SVE. Increasing co-presence has been shown to improve performance on collaborative tasks, which is an additional relationship that will be investigated in this experiment. Assessing the effects of co-presence on performing navigational tasks will hopefully better inform the design of future SVEs for real-world applications related to those previously mentioned.

2 RELATED WORK

2.1 DOLLHOUSE VR: A MULTI-VIEW, MULTI-USER COLLABORATIVE DESIGN WORKSPACE WITH VR TECHNOLOGY

In this paper, Hikaru Ibayashi et al. present a system that facilitates collaboration among users within a Virtual Environment from two separate vantage points. Their system involves two groups: one group observes and manipulates the VE from a ‘top-down’ perspective using a multi-touch tabletop interface, while the other group occupies the environment via a head-mounted display. While Ibayashi et al. intended for their system to be used for cooperative architectural design purposes, their methodology can be applied to any collaborative task that might benefit from the two separate perspectives involved. We drew heavily on the system described in this paper in designing our experimental setup.

2.2 A TAXONOMY FOR NETWORKED VIRTUAL ENVIRONMENTS

Michael Macedonia and Michael Zyda discuss the development process for building distributed virtual environments in this study, largely within the context of scaling these VEs. Written in 1997, the paper describes and addresses contemporary obstacles to the creation of large distributed VEs: namely bandwidth requirements, optimal distribution schemes, latency issues, and communications reliability. The authors argue that due to technological constraints, a purely client-server architecture is a ‘future dead-end’ in distributed VE development. Rather, they claim that developers should make use of hybrid architectures which incorporate communication between clients as well as with a server. Due to the fact that our application involved only two users, a traditional client-server architecture proved sufficient; however, networking issues faced during development made it evident that a hybrid architecture would likely be necessary for future scaling of the application. This is in agreement with Macedonia’s and Zyda’s argument and must be kept in mind for developers seeking to build SVEs for a relatively large number of concurrent users.

2.3 EMBODIED SOCIAL PRESENCE THEORY

Brian Mennecke et al.’s definition of Embodied Social Presence (ESP) Theory provides a theoretical framework for understanding interaction and communication in multi-user virtual environments (MUVEs). Their paper seeks to establish the role of users’ physical bodies and accompanying sense of embodiment in experiencing presence and co-presence within MUVEs. The authors conclude that users are empowered by their embodiment in a digital avatar which increases presence, and perceiving the presence of other avatars within a MUVE similarly facilitates high levels of co-presence. Our study adheres to Mennecke et al.’s theory by providing avatars for both users to experience embodiment. In this manner, we expect that sensations of presence and co-presence will be heightened within our custom MUVE.

2.4 QUANTIFYING THE BENEFITS OF IMMERSION FOR COLLABORATION IN VIRTUAL ENVIRONMENTS

Conducted by Michael Narayan et al. at Virginia Tech in 2005, this study analyzes the impact of different aspects of immersion on collaborative task performance within a VE. Participants were instructed to pass a ‘curve shaped object’ through a ‘hoop,’ and data was collected regarding the number of collisions as well as the amount of time elapsed. The independent variables in the study were stereoscopy and head-tracking, both of which had ‘on’ and ‘off’ conditions. The experimenters concluded that the introduction of stereoscopy had a positive effect on task performance, while introducing head-tracking had no significant effect. Additionally, the study determined that when the two users experienced differing levels of immersion, performance was best when the total level of immersion was maximized: it was not deemed important that the users experienced similar levels of immersion. These conclusions support our expectation that offering users differing perspectives (and likely differing levels of immersion) will not negatively impact overall task performance. Moreover, we predict that offering both users the relatively high level of immersion afforded by stereoscopic HMDs will increase the total level of immersion and thus improve performance.

In discussing future work, the authors note that it would be beneficial to further study the relationship between immersion effects and gender. We attempt to address this by collecting data about participants’ genders and analyzing the statistical relationship with performance.

2.5 SOCIAL INTERACTION IN VIRTUAL ENVIRONMENTS: KEY ISSUES, COMMON THEMES, AND A FRAMEWORK FOR RESEARCH

In this text, Ralph Schroeder provides an overview of topics relevant to research on shared virtual environments (SVEs), including but not limited to presence, co-presence, and communication. He defines SVEs as “VR systems in which users can also experience other participants as being present in the environment and interacting with them,” the evaluation of which is the central focus of our study. The two approaches mentioned for studying interaction in VEs are experimental, utilizing “purpose-built” environments, and qualitative, making use of more “naturalistic” settings. Although our research involves a primarily experimental method, we also seek to observe participants’ natural interactions and take qualitative data (questionnaires and audio/video recordings, as suggested by this paper) to assess co-presence. Because of the richness of VR as a medium, given that it allows people to interact via a variety of senses, it is possible to increase co-presence relative to traditional 2D displays. One potential limitation of the medium noted by the paper, however, is the difficulty in displaying social/bodily cues. While we map avatar movements and rotations in the SVE to tracked positions of the users, we keep in mind that some expected cues are missing.

2.6 PRESENCE IN SHARED VIRTUAL ENVIRONMENTS AND VIRTUAL TOGETHERNESS

This paper discusses relationships among people, their avatars, and their workstations within an SVE, emphasizing the fundamental role of tactual communication in creating “togetherness” (synonymous with co-presence). Similarly to the previous paper, this one asserts that “the extent to which the participants feel present in this common environment will depend on the same factors that determine presence in individual virtual environments that are not shared by the participants” (high graphics-update rate, low latency, wide FOV, etc.). Furthermore, the author states that co-presence can be increased by fostering interactions with the environment in which environmental changes caused by another participant (or even collaborative work between participants) is perceived by many/all participants within the SVE. The author places special importance on the role of perceived touch, rather than speech or visual communication, and suggests that it has the greatest potential for enhancing co-presence in SVEs. Though not a primary focus in our study, it is certainly an important consideration for future iterations of our interface and perhaps other related SVE applications.

2.7 REVEALING THE REALITIES OF COLLABORATIVE VIRTUAL REALITY

Fraser et. al., in this study, explore the differences between collaboration in virtual environments and physical reality by concentrating on three areas: field-of-view, haptic feedback, and network delays. By making these discrepancies “visible,” the authors look to develop a deeper understanding of system and co-user behavior. One suggestion they provide for dealing with field-of-view limitations is explicitly displaying a user’s actual view frustum as a graphical object, helping other users within the SVE discern what they can see. Implementing a variation of this within our application prevents misunderstandings that arise between the higher-level and lower-level users, due to inferences made about each other’s perspective. To compensate for a lack of haptic feedback, the authors propose using other media (such as audio or visual cues) to portray the effects of forces applied by users. In our application, we provided users with auditory feedback upon the collection of each coin to compensate for the lack of haptic feedback in the SVE. Finally, this study visually displays network delays associated with an object or user with the goal of urging other users to view behavior as a result of “delay induced phenomena.” We believe that employing the method they presented proved effective in mitigating the network delay issues experienced while running our application during experimentation.

2.8 LESSONS LEARNED FROM EMPLOYING MULTIPLE PERSPECTIVES IN A COLLABORATIVE VIRTUAL ENVIRONMENT FOR VISUALIZING SCIENTIFIC DATA

This study investigates the concept of allowing remote participants to customize their views, user-interfaces, and roles to their particular needs with the goal of enhancing collaboration. Conducted within a CAVE-based SVE for visualizing oceanographic data, the study provided a variety of interesting observations during both its training and guided search sessions. The two that were of greatest relevance to our study were the following: participants tended to “work mostly independently except to converge on their discoveries,” and they “preferred to use localized views to test out small individual hypotheses without disturbing the overall view while they were searching, then used global views to present their findings to their partner.” This information was useful when designing the roles/perspectives of both users in our study and the tools they used. Additionally, the paper states that over-the-shoulder views, radar views, action indicators, and process feedthrough mechanisms are worth considering for increasing collaborative awareness between users.

2.9 CALVIN: AN IMMERSIMEDIA DESIGN ENVIRONMENT UTILIZING HETEROGENEOUS PERSPECTIVES

In this paper, Jason Leigh and Andrew E. Johnson of the Electronic Visualization Laboratory at the University of Illinois at Chicago describe CALVIN, a multimedia VR application for architectural design and collaborative visualization with a multi-perspective user interface. Its emphasis on multiple perspectives and viewpoints allows for application of VR during the earlier stages of the design process, employing visual, gestural, and vocal input in its interface. Interestingly, the paper's separation of perspective into the "mortal" (egocentric) and "deity" (exocentric) viewpoints is the exact area of research explored in our study. Additionally, this experiment was conducted in networked CAVEs, creating co-presence for the users within the SVE. This experimental setup is similar to the one we have implemented, with the exception that users of our SVE utilize networked HMDs. The authors conclude that they believe their approach would generalize to other fields such as collaborative engineering, but acknowledge that at times offering multiple perspectives causes more confusion than insight. This is especially important to take into account when attempting to evaluate the results of our experiment, following analysis of experimental data.

2.10 USER EMBODIMENT IN COLLABORATIVE VIRTUAL ENVIRONMENTS

This study explores user embodiment in shared virtual environments, representing users with avatars to assist in various collaborative tasks. Of the design issues they tackle, the most relevant to our research are presence, location, activity/viewpoints/actionpoints, and manipulating one's view of other people. Their proposed techniques for dealing with them, respectively, are associating users with representative graphics objects, conveying position/orientation within the given spatial reference frame, displaying where in space a user is attending and manipulating, and giving users control over their view of other users. These are all essential design recommendations we strongly considered when making decisions about how best to represent each user within the collaborative VE we implemented. The paper concludes that user embodiment is a key issue for collaborative virtual environments/collaborative systems, so it is crucial not to overlook this important aspect of SVEs.

3 EXPERIMENTAL DESIGN

3.1 RESEARCH QUESTIONS AND HYPOTHESES

The purpose of this study is twofold: one facet is to understand how aid from a user with an exocentric perspective impacts an egocentric user's performance on a navigational task in an immersive SVE. The second is to determine how augmenting the environment with path-tracing information affects performance on said task.

We hypothesized, first of all, that task performance would improve with the addition of a collaborator serving in the deity role. This is justified by the fact that the deity has access to knowledge of the overall layout of the environment that, when combined with the low-level perspective of the mortal, will lead to development of a more optimal strategy with which to approach the task. Next, we predicted that providing the mortal with a real-time display of his/her path taken through the environment would improve task performance, irrespective of the presence of a collaborator. Theoretically, making this information available to the mortal should ensure that he/she refrains from traversing previously visited areas and thus navigates the environment using a more efficient route. Finally, we expected that providing only the deity with this path-tracing display during collaboration on the task would produce the best performance overall. Based on the findings in *Lessons Learned from Employing Multiple Perspectives in a Collaborative Virtual Environment for Visualizing Scientific Data*, we believed that the deity would be primarily responsible for strategizing on a higher-level while the mortal would serve to validate the deity's hypotheses. Therefore, the performance improvement resulting from this communication would be enhanced if the deity was able to instantly eliminate previously visited areas during his/her formulation of an approach to future navigation.

3.2 SETUP

The application used during experimentation was developed using the Unity3D platform and engine, and its high-level scripting API for the networking component. This design constrained the networking architecture to a traditional client-server model, in which the machine used by the mortal functioned as both a host (communicating with a Unity3D cloud server) and a client while the deity's machine served solely as a client. Each machine (utilizing an Nvidia GeForce GTX 10 series graphics card) ran an independent build of the application, connected to the other through Unity3D's built-in game lobby manager. Given the nature of the mortal's role, he/she used an HTC Vive HMD (90 Hz refresh rate, 110-degree field of view, 1080x1200 display resolution per eye) along with its Lighthouse base stations; this provided the mortal with room-scale tracking capability that made their navigation of the environment more realistic. The deity's movement, on the other hand, was constrained to a horizontal plane above the target environment which roughly mimicked the piloting of an aircraft. Thus, room-scale tracking was not absolutely necessary and he/she used an Oculus Rift CV1 HMD (90 Hz refresh rate, 110-degree field of view, 1080x1200 display resolution per eye) with a single Constellation desktop tracking sensor. For both roles, locomotion itself was performed using the joystick on an Xbox One controller for which strafing was disabled to minimize simulator sickness (forward and backward movement corresponded to the direction that the participant was facing). Spatialized audio output resulting from interactions with the SVE was perceived by the participants through headphones, which were integrated into the deity's HMD and separately connected to the mortal's HMD. Finally, trial timing and data collection were conducted within our application and verbal communication between participants was recorded using an iPhone 7 microphone.

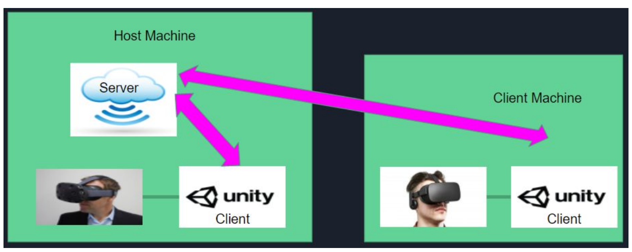

Figure 1: Symbolic diagram depicting application networking architecture, flow of data, and experimental setup.

3.3 PROCEDURE

This study's experiments were conducted on a total of 15 participants (ages 18-22, one female, all Duke University undergraduate students) in CIEMAS 1411 at Duke University. They were all recruited through social media postings and had varying academic backgrounds and prior experiences with VR/video games. 10 participants ran their trials collaboratively (for a total of 5 experimental sessions), and 5 participants ran their trials individually (5 experimental sessions).

Before each experiment, participants were required to complete an informed consent form and demographic questionnaire, intended to assess their backgrounds and prior exposure to VR and/or video games. The experimental procedure conducted thereafter, was dependent on which one of our two conditions was being tested - individual or collaborative. These two conditions were tested in a between-subjects manner, with participants being assigned to one of the two conditions prior to the start of their experimental session. In the individual condition, following the pre-experiment paperwork, the sole participant (the mortal) was informed that he/she would be navigating a virtual one-floor maze containing evenly distributed coins with the goal of collecting as many coins as possible within the allotted time. He/she was then given an approximately one-minute-long practice run to become familiar with navigating the maze and collecting coins, after which the actual experimental trials began. The experiment was subdivided into two additional conditions (path-tracing display vs. no path-tracing display) tested in a within-subjects manner, each sub-condition consisting of three one-minute-long trials. During each of the three trials, the placement of doors, walls, and coins in the maze were randomized according to a seed in the application to control for learning effects (the same three seeds were used across all experiments to maintain consistency). In addition to randomizing the order of the mazes, the order of the two path-tracing sub-conditions presented to the participant was randomized as well. Following the trials and recording of data, each participant completed the Slater-Usoh-Steed (SUS) Questionnaire (See Appendix A) to assess his/her sense of presence during the experiment.

While similar in structure to the individual condition, the collaborative experiment varied in a few important ways. The first of these is the obvious fact that the collaborative trials involved both the mortal and deity roles, who both completed the aforementioned informed consent form and demographic questionnaire. Next, both participants were briefed about their respective roles and allowed to engage in the practice run until they were both comfortable with performing the collaborative version of the task. The mortal completed the task standing up (as in the individual condition) while the deity was seated in a chair across the room (to simulate flying a vehicle), but both navigated the environment using the joystick on an Xbox One controller as previously stated. Since both users were represented as human-like avatars within the SVE, they were visually aware of each other's movement and orientation throughout the experiment. Using the same three randomized mazes as in the individual condition, the participants performed the same task while communicating verbally. This time, however, the experiment was divided into three sub-conditions consisting of nine total trials: no path-tracing display, path-tracing display visible to the mortal only, and path-tracing display visible to the deity only (the order of which was once again randomized between experiments). It is also worth noting that the deity was unable to see the coins from his/her perspective, which was a design decision intended to more accurately simulate a search-and-rescue scenario and make the task less trivial. The verbal exchange between mortal and deity during each trial was recorded as well, to be used for subsequent qualitative analysis. Finally, in addition to completing the SUS presence questionnaires, both participants filled out post-experiment Networked Minds Questionnaires (See Appendix B) intended to assess their sense of co-presence.

Figure 2: In-application screenshots of the perspectives of both the mortal (left) and deity (right) for the collaborative, deity path-tracing display conditions.

4 RESULTS

4.1 OBJECTIVE METRICS

After each trial, the experimenters recorded the number of coins collected during the minute allotted and divided it by the total number of coins in the given maze configuration to generate a "coin percentage" metric. This coin percentage was used for the remainder of our calculations as the primary metric of task performance.

Taking the average coin percentage of all trials within the collaborative condition yielded a result of 41.03% (rounded to 2 significant figures). Interestingly, taking the average coin percentage of all individual trials yielded an unexpectedly similar result of 40.05%. In addition to these averages, however, we analyzed performance data across differences in path-tracing sub-conditions, specific maze configurations, and another "session completion" metric discussed below.

The three path-tracing sub-conditions analyzed within our study were no path-tracing (NPT), mortal path-tracing (MPT), and deity path-tracing (DPT). The NPT condition yielded an average coin percentage of 43.88% (SE=0.02264) for collaborative trials and 38.66% (SE=0.02597) for individual trials. The MPT condition yielded an average coin percentage of 41.45% (SE=0.01981) for collaborative trials and 41.44% (SE=0.02018) for individual trials. The DPT condition was only relevant to collaborative trials and yielded an average coin percentage of 37.76% (SE=0.02548).

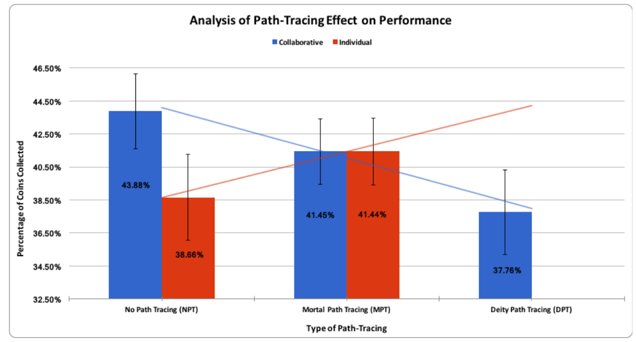

Figure 3: Comparing performance across path-tracing sub-conditions for individual and collaborative trials. Trendlines are shown for the two main conditions, and error bars depict the standard error for each group.

Users conducted the study in one of three maze distinct maze configurations (labeled Mazes 1, 2 and 3) generated by passing one of three specific seeds to our application. Maze 1 saw an average coin percentage of 43.72% (SE=0.01746) for collaborative trials and 42.09% (SE=0.02311) for individual trials. Maze 2 yielded an average coin percentage of 39.19% (SE=0.0277) for collaborative trials and 42.93% (SE=0.03025) for individual trials. Finally, maze 3 saw an average coin percentage of 40.17% (SE=0.02316) for collaborative trials and 35.13% (SE=0.02704) for individual trials.

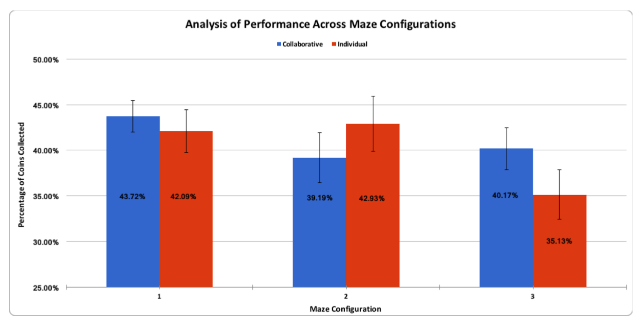

Figure 4: Comparing performance for individual and collaborative trials across the three distinct maze configurations used in the study. Error bars reflect the standard error for each group.

Our final objective analysis sought to measure the impact of learning effects on task performance by graphing coin percentage against a new "session completion" metric taken for each trial. This measurement, representing the progress that participants had made within a given experimental session at the start of each trial, was calculated by dividing the order number of a trial by the total number of trials in that experimental session.

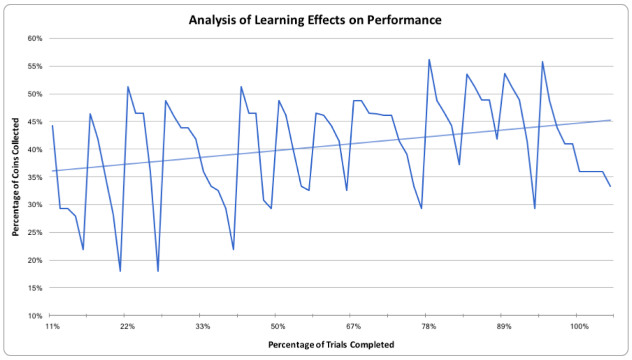

Figure 5: Analyzing the impact of learning effects on coin collection. As session completion increased, participants benefited from prior exposure to each maze configuration before their trials began. Additionally, participants had an increased familiarity with navigation controls and with the task itself.

4.2 SUBJECTIVE METRICS

At the beginning of each trial, we collected data about each individual's prior experience with VR systems (CAVE and HMD) as well as with several categories of video games (Logic/Puzzle, Dexterity, Strategy, First-Person Shooter, Sports/Action, and Other). Of the 15 participants tested, 5 had prior experience with CAVE systems, and 13 had some prior exposure to VR with an HMD. Additionally, 12 participants reported significant experience with video games, 2 participants reported some expertise, and 1 participant reported insignificant skill. There appeared to be no significant correlation between coin percentage and either of these subjective metrics.

After the completion of each trial, we also assessed each user's sense of presence, and for collaborative trials, co-presence, via two separate questionnaires. Presence was assessed using a 7-point Likert scale, with the experimenters calculating the "mean presence score" (MPS) for each participant by averaging their responses to all questions on the SUS survey. MPS seems to have little correlation with task performance (see Figure 6). The average MPS for all participants in the individual condition was 3.56 (out of a maximum of 7). For the collaborative condition, participants assigned the deity role reported an average MPS of 3.08, while participants assigned the mortal role reported an average MPS of 4.2.

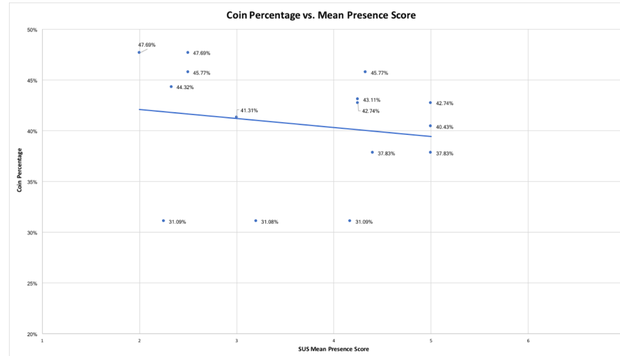

Figure 6: Analyzing the relationship between coin percentage and mean presence score for each participant (represented as points on the scatter-plot). The trendline shows a slight inverse correlation, although the relationship is trivial. Note that points with the same coin percentage represent collaborators from the same trial.

The data we gathered from the Network-Mind Questionnaires was qualitative, with participants writing brief responses to each question. They indicated that participants assigned to the deity condition experienced a lesser sense of presence than their mortal partners. For instance, one individual in the deity role reported that he thought of the environment "more as somewhere that [his] partner visited" than as a place that he visited himself. Another deity's response indicated that he felt as though he was visiting a "fake place" rather than a real one.

The final set of qualitative data recorded was the transcribed audio of participants' conversations during each collaborative trial. From analyzing the recordings, the main takeaway seemed to be that a common strategy developed during the collaborative trials: the deity tended to direct the mortal towards the largest open areas in the maze. Conversations tended to be largely one-directional, however, with the deity communicating information about the environment to the mortal and the mortal offering little dialogue in return.

5 DISCUSSION

From our results and observations, we have concluded that by and large, the introduction of a deity had little overall impact on the mortal's coin collection performance. One possible explanation for the nearly equivalent average coin percentage between the two conditions was the deity's inability to view the position of each coin. While this design decision was made in an attempt to make the task less trivial, the result was that the deity had little relevant information to offer the mortal, and was consequently ignored in most cases. Furthermore, the deity had no way to interact with or manipulate the environment, which may have contributed to a decrease of presence and/or co-presence for them (in support of the findings in *Presence in Shared Virtual Environments and Virtual Togetherness*). Regardless, we have drawn four primary conclusions regarding which variables did in fact have an impact on coin collection performance.

It is worth noting that in a small subset of trials, participants experienced connection issues with the Xbox One controllers that prevented them from starting and stopping the movement of their avatar. We believe, however, that the existence of these infrequent issues do not invalidate our conclusions.

5.1 PATH-TRACING AIDED INDIVIDUALS AND HINDERED COLLABORATORS

The introduction of path-tracing information improved the average coin percentage of participants in the individual condition, as expected. Interestingly, however, introducing path-tracing information to individuals in the collaborative condition had a negative impact on coin percentage. Collaborators performed best in the absence of any path-tracing information. Granting path-tracing to the mortal lowered average coin percentage to roughly that of participants in the individual condition (suggesting the irrelevance of the deity), and granting path-tracing information to the deity lowered average coin percentage even further.

These last two observations directly contradict our hypotheses that path-tracing would improve performance slightly when granted to the mortal and even more so when granted to the deity. One possible explanation for this phenomenon is that while path-tracing introduced helpful information to participants without a collaborator, the presence of both a collaborator and path-tracing information induced sensory overload in the mortal completing the task. As a result, the extraneous information caused the mortal more confusion than aid.

5.2 MAZE CONFIGURATION WAS IRRELEVANT

After analyzing the average coin percentage for the individual and collaborative conditions within each maze configuration, there appears to be no consistent relationship between the two variables. While the average coin percentage for collaborative trials was highest with maze 1 and lowest with maze 2, the average coin percentage for individual trials was highest with maze 2 and lowest with maze 3. These results suggest that the task was no more difficult within any single maze configuration than any of the others.

5.3 LEARNING EFFECTS WERE LARGELY INSIGNIFICANT

While on average, the trendline of the graph in Figure 5 suggests that average task performance improved as session completion increased, the data clearly shows that coin percentage varied vastly even between trials with the same session completion value. It is undeniable that as session completion increased, participants benefited from greater exposure to each maze configuration. Additionally, participants learned to more easily navigate their environment using the Xbox One controller, and they were able to form strategies for better performance based on earlier successes and failures.

However, the data reflects a very slight improvement in average task performance, with many peaks and valleys along the trendline. Hence, while learning effects may have caused a slight improvement in performance on average, these effects had much less of an impact on coin percentage than, for instance, the presence or lack of path-tracing.

5.4 PRESENCE AND CO-PRESENCE HAD A NEGLIGIBLE EFFECT ON TASK PERFORMANCE

The trendline of the graph in Figure 6 shows a trivial inverse relationship between coin percentage and Mean Presence Score. While one might conclude that presence negatively impacted performance on the task, we argue that this relationship is negligible. The data points on the scatter-plot are arranged randomly, with individuals covering a large range of coin percentage points for each MPS value.

One notable finding regarding presence in our study, however, was that individuals assigned the deity role reported a lower level of presence on average than either the individual participants or the collaborative participants assigned the mortal role. One explanation for this observation is that the deity's incapability of interacting with or manipulating the environment in a meaningful way caused them to feel less present than their peers navigating the SVE from within the maze. The mortal participants reported the highest MPS of all conditions, indicating that the introduction of a deity improved presence for the participants completing the task itself. Perhaps hearing another individual vocalize cues about the same SVE validated the mortals' sense of being in the virtual rather than physical world. Regarding co-presence, after analyzing the responses given by participants on the Networked Minds questionnaire, we were unable to draw any qualitative conclusions; we thus note that co-presence did not appear to play a significant role in task performance.

6 CONCLUSIONS AND FUTURE WORK

Although the introduction of an exocentric perspective did not appear to significantly improve performance on a coin collection task in an SVE, the data collected in this study reflect an interesting trend regarding the maximum amount of information that can be introduced to an egocentric user before performance becomes hindered. It is possible that our task of choice was not conducive to collaboration: especially with the deity lacking both knowledge about coin positions and the ability to interface with the environment. For future work, we might consider increasing the deity's involvement by granting him or her more ways to interact with the SVE. Such interactions might allow the manipulation of aspects of the environment itself, and the impact of these changes on task performance could thereafter be explored.

Additionally, it might be interesting to explore the impact of varying interaction fidelity on task performance, presence, and co-presence. Participants could complete the experiment across a variety of displays, including but not limited to a CAVE system and a 2D desktop display, and the resulting data would be compared.

Finally, further research should investigate the effects of collaboration on a variety of different collaborative tasks. Perhaps these experiments' research would validate our conclusion that introducing an exocentric perspective to an egocentric task does not improve performance, but we suspect that this is not the case for all tasks. Collaboration remains an exciting application of virtual reality, and there remains much to be considered before the scientific community can unlock its full potential.

7 ACKNOWLEDGEMENTS

We would like to thank Dr. Regis Kopper, our professor and director of the Duke immersive Virtual Environment (DiVE) laboratory, and Zekun Cao, our teaching assistant, for their invaluable guidance throughout this study. They were instrumental in assisting our study design process, application development, and post-experiment analysis and we greatly appreciate their efforts.

APPENDIX A: SLATER-USOH-STEED (SUS) QUESTIONNAIRE[1]

1. Please rate your sense of being in the virtual environment, on a scale of 1 to 7, where 7 represents your normal experience of being in a place.
2. To what extent were there times during the experience when the virtual environment was the reality for you?
3. When you think back to the experience, do you think of the virtual environment more as images that you saw or more as somewhere that you visited?
4. During the time of the experience, which was the strongest on the whole, your sense of being in the virtual environment or of being elsewhere?
5. Consider your memory of being in the virtual environment. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today? By 'structure of the memory' consider things like the extent to which you have a visual memory of the virtual environment, whether that memory is in colour, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such structural elements.

APPENDIX B: NETWORKED MINDS QUESTIONNAIRE[2]

Items assessing co-presence:

Isolation/ Aloneness
1. I often felt as if I was all alone.
2. I think the other individual often felt alone.

Mutual Awareness
3. I hardly noticed another individual.
4. The other individual didn't notice me in the room.
5. I was often aware of others in the environment.
6. Others were often aware of me in the room.
7. I think the other individual often felt alone.
8. I often felt as if I was all alone.

Attentional Allocation
9. I sometimes pretended to pay attention to the other individual.
10. The other individual sometimes pretended to pay attention to me.
11. The other individual paid close attention to me
12. I paid close attention to the other individual.
13. My partner was easily distracted when other things were going on around us.

[1] Slater, M., Usoh, M., & Steed, A. (1994). Depth of presence in virtual environments. Presence: Teleoperators and Virtual Environments, 3, 130-144.

[2] Adapted from: Biocca, F., Harms, C., & Gregg, J. (2001). The Networked Minds measure of social presence: Pilot test of the factor structure and concurrent validity. In Proceedings of 4th International Workshop on Presence. Philadelphia, USA, 21-23 May, 2001.

14. I was easily distracted when other things were going on around me.
15. The other individual tended to ignore me.
16. I tended to ignore the other individual.

Items assessing Psychological Involvement:

Empathy
1. When I was happy, the other was happy.
2. When the other was happy, I was happy.
3. The other individual was influenced by my moods.
4. I was influenced by my partner's moods.
5. The other's mood did NOT affect my mood/emotional-state.
6. My mood did NOT affect the other's mood/emotional-state.

Mutual Understanding
7. My opinions were clear to the other.
8. The opinions of the other were clear.
9. My thoughts were clear to my partner.
10. The other individual's thoughts were clear to me.
11. The other understood what I meant.
12. I understood what the other meant.

Items assessing Behavioral Engagement:

Behavioral Interdependence
1. My actions were dependent on the other's actions.
2. The other's actions were dependent on my actions.
3. My behavior was in direct response to the other's behavior.
4. The behavior of the other was I direct response to my behavior.
5. What the other did affected what I did.
6. What I did affected what the other did.

Mutual Assistance
7. My partner did not help me very much.
8. I did not help the other very much.
9. My partner worked with me to complete the task.
10. I worked with the other individual to complete the task.

Dependent Action
11. The other could not act without me.
12. I could not act without the other.

REFERENCES

[1] Hikaru Ibayashi et al., "Dollhouse VR: A Multi-View, Multi-User Collaborative Design Workspace with VR Technology", SIGGRAPH Asia 2015 Posters, Association for Computing Machinery Inc., Kobe Japan, 2 November 2015.

[2] Michael R. Macedonia and Michael J. Zyda, "A Taxonomy for Networked Virtual Environments", IEEE Multimedia Volume 4 Issue 1, IEEE, pp. 48-56, 1997.

[3] Brian E. Mennecke et al., "Embodied Social Presence Theory", 2010 43rd Hawaii International Conference on System Sciences, IEEE, Honolulu HI, 2010.

[4] Michael Narayan et al., "Quantifying the Benefits of Immersion for Collaboration in Virtual Environments", VRST '05 Proceedings of the ACM symposium on Virtual reality software and technology, ACM, New York NY, pp. 78-81, November 2005.

[5] Ralph Schroeder, "Social Interaction in Virtual Environments: Key Issues, Common Themes, and a Framework for Research," The Social Life of Avatars, Springer, London, pp. 1-18, 2002.

[6] Nat Durach and Mel Slater, "Presence in Shared Virtual Environments and Virtual Togetherness", Presence: Teleoperators and Virtual Environments Volume 9 Issue 2, MIT Press, Cambridge MA, pp.214-217, April 2000.

[7] Mike Fraser et al., "Revealing the Realities of Collaborative Virtual Reality", CVE '00 Proceedings of the third international conference on Collaborative virtual environments, ACM, New York NY, pp. 29-37, 2000.

[8] Park, Kyoung S., Kapoor, Abhinav, and Leigh, Jason, "Lessons Learned from Employing Multiple Perspectives in a Collaborative Virtual Environment for Visualizing Scientific Data", CVE '00 Proceedings of the Third International Conference on Collaborative Virtual Environments", ACM, New York, NY, pp. 73-82, 2000.

[9] J. Leigh and A.E. Johnson, "CALVIN: An Immersimedia Design Environment Utilizing Heterogeneous Perspectives", Proceedings of the Third IEEE International Conference on Multimedia Computing and Systems, 1996, IEEE, Hiroshima, Japan, 1996.

[10] Benford, Steve et al., "User Embodiment in Collaborative Virtual Environments", CHI '95 Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM, New York NY, pp. 242-249, May 1995.