A Pilot Study on Design Performance in a Collaborative Virtual Environment

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Abstract: A Collaborative Virtual Environment or CVE extends stand alone virtual environment to include real-time collaboration, interaction and sharing of the same virtual space among users across the network. We utilize the Torque Game Engine Advanced to develop a CVE application that was customized to support architectural students’ design activities in a virtual environment. This application allows multiple users across the local area network and the internet to collaborate, interact, and share information within the same virtual space. Included in the application is an automated data-mining system to record the various users’ activities during the collaborative design sessions in the virtual environment. In this paper, we present findings from our pilot study where we evaluate performance when designing and working collaboratively in a virtual environment. Subjects were divided into four groups; Group 1: experts working as individuals, Group 2: non-experts working as individuals, Group 3: experts working in pairs, and Group 4: non-experts working in pairs. Subjects were to assemble a building structure in the virtual environment using the CVE application. Several dependent measures were computed while performing the experimental tasks. The measures included: time taken when moving objects, the movement frequency, and the average pitch angle where subject’s gaze was oriented. The results show that the overall performance of experts working in pairs in a CVE is better than that of the individuals working alone.

Keywords: 3D Game Engine, Architecture, Collaborative, Design, Virtual Environment

Introduction

Collaboration among design team members in the Architecture, Engineering, and Construction (AEC) industry is limited due to the conventional design execution which is linear in nature [1], [2], [3] & [4]. In the conventional and traditional design process, a design is complete when each team member collaborates in terms of completing their specific design task in furnishing every component of the building facility. A design team is composed by multi-disciplinary members with specific expertise to contribute into the design. Each designer completes their own discipline-specific element of the design and then passes the design to the next discipline-specific team member. For example, a structural engineer can only start designing after the architect completed the architectural design, and very rarely the two disciplines meet with each other to concurrently collaborate.

There are also restrictions on the design tools being used to create and communicate the design intentions [5], [6] & [7]. Current design approaches rely on 2D documentation, which is inadequate in representing the owner’s intended vision of a facility in its entirety. Because
of this, misinterpretations of design, and errors and inconsistencies in design are unavoidable. Starting from the owner’s requirement and description of the desired facility, 2D drawings are designed and produced by the designer based on the 3D mental model visualized in his/her mind [5], [12]. Even though the 2D drawings are packed with information (in the form of geometric, numerical and textual information), the process of interpreting 2D drawings is not perfect as 2D drawings do not adequately represent the multi-spatial information of the facility in a more intuitive way, as 3D can. Only the designer can truly visualize what the 2D drawings represent and how they look like in 3D. Thus, there is a need to represent designs not just in 2D but 3D, where designers and other project team members can view the same model of a facility. Designers can also be sure the designs they produce is what the owner envisions. Utilizing VE technology can improve the 3D representation of the design that will assist and can provide a common language for project stakeholders.

It is our hypothesis that collaboration within a virtual environment (VE) has the potential to greatly improve design execution for the design team. A Collaborative Virtual Environment (CVE) extends standalone VE to include real-time collaboration, interaction and sharing of the same virtual space among users across the network. We utilized the Torque Game Engine Advanced (TGEA) to develop a CVE application that allows for real-time collaboration and interaction among multiple users across the network. We named the tool as the Collaborative World Design Tool (CWDT). The CWDT application is customized to support architectural design activities in a CVE. Using the CWDT application with multiple users present in the same CVE, users can perform design collaboratively; individually or with each other at the same time, hence diminishing the linearity of the design process.

Collaborative design borrows important features from various cognitive theories of social cognition [8] and joint attention [9]. These include but are not limited to interpersonal coordination and synchronization of behavior [10], task-sharing, reciprocity of information flow among partners, joint responsibility etc. A CVE setting is relevant to the principles of social constructivism, and social context of learning. Unlike traditional tools for education, a CVE supports the social side of learning. Within a CVE, students have the opportunity to discover the content of what is being learned and create meaningful connections with the content through creativity and interaction. By working collaboratively with other students, they become active learners and learn to work together toward a common goal. The learning content, tasks and problems presented within the CVE learning space encourage students to think, explore, discover, and manipulate the content to become better problem solvers and at the same time, learn and gain knowledge. The CWDT application includes game playing characteristics that allow students, whether working individually or in small groups, to experience a constructivist learning where rather than being passive recipients. Students explore, investigate and solve problems, and become actively engaged in the activities in the CVE.

In this paper, findings are presented from a pilot study in regards to the design performance in a CVE. The study involves non-expert and expert designers as participants. The results of the experiments suggest that there are significant benefits of performing design collaboratively in a CVE.

The Experiment

A total of 37 students participated in the experiment, randomly assigned to either work in pairs or individually. 21 novice students were recruited from the Department of Psychology
with 14 of them formed seven pairs, the remaining seven worked alone. 16 architecture majors were recruited from the School of Construction as the expert group with 10 of them formed five pairs, the remaining six worked alone.

A 2×2 between-subjects factorial design was used with Expertise (novice, expert) and Group (single, pair) as the independent variables. There were six dependent measures that were analyzed: completion time, total duration of objects in movement, number of times objects were moved, total path length in 3D space, average speed of movement, and movement frequency (defined as the number of moves divided by the total duration of objects in movement). To be able to compare the performance of pairs with singles working alone, the dependent measures of one randomly selected member of each group were pitted against the measurements taken from singles working alone.

It was hypothesized that working in pairs will be beneficial for the design task, and that experts will perform better than non-expert. Figure 1 below shows two subjects concurrently working in the VE. As previously mentioned none of the non-expert participants had any 3D architectural design experience. For this particular set of experiments, we decided to disallow participants working in pairs the ability to communicate with each other. Subjects were placed on opposite sides of the room where the experiment was held and they were instructed not to communicate with one another. This was done to further remove any conditions which may influence the results aside from physically working in the same VE. In the future we plan to perform similar experiments while allowing various levels of communication.

The 3D model of a building used in the experiment was modeled after a Japanese restaurant. Japanese architecture is often modular in design with repetitive segments. The building, aside from the roofing and stairs, was broken into 4’ and 8’ sections. These basic sections can be seen below in Figure 2. Each small section was repeated to produce the complete flooring and walls. To further simplify the experiment for the non-experts, these smaller sections were lumped into even larger sections composed of six to ten smaller segments. Completion of the final 3D model required subjects to copy nine floor segments, move eight wall segments and three stair segments into place.

In the experimental setup all participants’ avatar started the experiment from the same spatial location, on the left side of the building construction site. The avatar had six degrees of freedom of movement (three spatial dimensions, and three orientations – yaw, pitch, and roll). Participants used the keyboard and mouse to move around and rotate the viewpoint as they wished. A combination of computer mouse and hotkeys were also used to select, drag, and drop building blocks into the desired locations. When working in pairs, no physical verbal communication was allowed. In fact, some of the subjects did not know their partner well. The avatar of their partner was visible at all times. Each time a building component was moved and placed, the action was visible in real time. This allowed participants to see what the other person is doing at all times. A brief training session preceded the start of the experiment to let the participants become familiar with the interface and learn how to operate in the CVE, and how to manipulate 3D objects.
Once subjects had completed constructing the 3D building, it was inspected for accuracy and completeness. The automatic data-recording log was saved for analysis.

**Data Collection**

During the experiment, the automated data-mining system monitored what each subject was doing. It logged data such as: how long the overall experiment took; and the number of objects moved, rotated, scaled, created, deleted, and copied. It also logged the exact amount of time a subject spent moving, and rotating objects. The exact location and orientation of each user was recorded at a rate of fifty times per second (50Hz). The time calculations were precise to the thousandth of a second to reduce repetitive rounding error since most movements take less than one second.

**Results**

A 2×2 between-subjects analysis of variance (ANOVA) was used to analyze the results with Expertise and Group as the independent variables. One of the basic measures of successful collaboration is time management, that is, how much time is needed for effective construction design to be completed, and how expertise and level of collaboration influence times savings. In order to test time management, completion time was measured, defined as the total time elapsed from the moment a person or a group log in and start the project up until they complete the task. It was hypothesized that experts should finish the project in less time than novices, and that singles would take up more time, because they had to do more work than the single members of any pair. The average results are presented in Figure 3. The only significant
result was the main effect of Group, $F(1,21) = 4.62, p < .044$, suggesting that singles working alone took longer time ($M = 15.4$ minutes, $SD = 6.16$ minutes) to complete the task than pairs ($M = 10.6$ minutes, $SD = 4.29$ minutes). There was no difference between experts and novices, nor an interaction between Expertise and Group. Our hypothesis was only partially confirmed by the results.

In order to map out the spatial character of a subject’s performance the movement of the subject’s avatar was tracked in real time through the 3D virtual space of the design environment. Total path length was calculated as the sum of all displacements as the person’s avatar crisscrossed through the CVE. Three dimensional coordinates were recorded at a sampling rate of 50Hz. As noted earlier, each pair’s total path length was represented by randomly selecting the measurement of one member of that particular pair. It was hypothesized that members of pairs will naturally cover less territory, and that experts will traverse through fewer places than novices. The average results are presented in Figure 4. Contrary to our hypothesis, results revealed that experts in fact traversed a significantly longer path ($M = 1.99$ km, $SD = 0.91$ km) than novices ($M = 0.89$ km, $SD = 0.65$ km), $F(1,21) = 11.8, p < .003$. No difference was observed between pairs and singles, and no significant Group x Expertise interaction was present.
In order to assess the speed at which subjects performed the task, we calculated average speed as the ratio between total path length and completion time. It was hypothesized that novices would be slower than experts, and that singles would be faster than pairs. The average results are depicted in Figure 5. Experts were significantly faster ($M = 3.25 \text{ m/s}, SD = 1.86 \text{ m/s}$) than novices ($M = 1.08 \text{ m/s}, SD = 0.64 \text{ m/s}$), $F(1,21) = 21.8, p < .001$. There was a marginally significant main effect of Group, $F(1,21) = 3.90, p < .06$, indicating that singles were on average slower ($M = 1.68 \text{ m/s}, SD = 0.89 \text{ m/s}$) than pairs ($M = 2.42 \text{ m/s}, SD = 2.26 \text{ m/s}$). In fact, a marginally significant Expertise x Group interaction, $F(1,21) = 3.69, p < .07$, has revealed that experts are fastest when working in pairs, and that novice pairs and novice singles moved at almost identical average speeds (around 1 m/s).
How subjects handle building blocks in the CVE may reveal how efficient their actions are. We measured the total time subjects spent moving objects. Our hypothesis was similar to the previous one, in that we predicted that experts and pairs should spend less time manipulating objects. In addition, we predicted that expertise should impact singles more than pairs. The average results are presented in Figure 6. There was a main effect of Expertise, $F(1,21) = 5.91, p < .01$, suggesting that novices spent more time moving objects compared to experts. A main effect of Group, $F(1,21) = 8.05, p < .01$, revealed that singles spent more time moving objects than pairs. The significant Expertise x Group interaction, $F(1,21) = 4.70, p < .01$, qualified these results in the following manner: Novices who worked alone moved, handled and manipulated objects for the longest time by far. In addition, being a novice or an expert did not make a difference for move time when subjects worked in pairs.
Another measure related to object handling, namely the total number of times objects were set into motion, was also tallied and analyzed. Our hypothesis stated that novices who work alone would be forced to move objects many times, whereas experts who work in pairs could afford to move objects significantly fewer times. The only significant result obtained was a main effect of Group, \( F(1,21) = 4.33, p < .05 \), revealing that singles indeed moved more objects than pairs. There was no main effect of Expertise, and no Group x Expertise interaction. The average results are presented in Figure 7.
The next measure was a combination of the latter two. Movement frequency ($MF$) was defined as the ratio between number of moves and move time ($MF = \text{moves/move time}$). This quantity had the potential to tease apart certain design strategies. For instance, handling a lot of objects in a short period of time would result in large movement frequency, whereas handling a few objects in the same (short) amount of time would be described with a low movement frequency. It was hypothesized that the most efficient way to perform the design task would be indicated by a high movement frequency, most likely exhibited by experts. There was no specific prediction about how singles versus pairs would fare in terms of movement frequency. The average results are presented in Figure 8. There was a Group x Expertise interaction, $F(1,21) = 4.86, p < .04$, suggesting that expert singles moved more objects per unit of time than novice singles. No difference between expert pairs and novice pairs was observed. There were no main effects of Group or Expertise. Expert singles had the highest movement frequency, as predicted by our hypothesis.

![Figure 8: Movement Frequency as a Function of Expertise and Group Type](image)

A study by Maher et al [11] observed three forms of collaboration in a computer mediated architectural design: 1) “mutual collaboration” which involves designers equally working together on the same aspect of the task; 2) “exclusive collaboration” is when designers work on separate aspects of the same problem with occasional time for consultation; and 3) “dictatorial collaboration” when by appointment or naturally there emerge a “designer in charge” who makes all the design decisions. In the experiment that was conducted, the groups that were monitored mostly fell under the “mutual collaboration” category, though occasionally leaned towards “exclusive collaboration.” As we allow for different forms of communication in the future we expect to see a broader spectrum of collaborative styles.

In summary, the effects of collaboration have the potential to be just as complicated as any other form of human interaction. One thing that became evident is that people have a strong tendency to prefer working in groups in architectural design tasks. Perhaps this is because it was a difficult and new task for them. In the future we plan to continue to investigate the cognitive processes of individuals under various conditions with various tasks.
Discussion

We sought to investigate the influence of 1) level of expertise and 2) the presence or absence of opportunity to collaborate on performance in a virtual architectural design task. The technology employed was a CVE that allowed for real time interactions among design partners. Performance was assessed with several kinematic and enumerative measures. Our general hypothesis was that subjects would abide by the principles of economy of action, that is, they would converge towards efficient time management and towards minimizing trial and error strategies. This simply meant doing less, in shorter time, using fewer steps in the design process. It was predicted that experts would be more likely to exhibit such behavior. Our measures were set up to investigate what factors contribute to successful real time collaboration.

We found that experts explore the workspace more extensively, but spend about the same time as novices. As a consequence, experts were found to work faster. Working in pairs was faster than working alone, because pairs explored the same amount of space (as measured by total path length) as singles in less time. The benefits of collaboration were facilitated by level of expertise in that experts who worked in pairs were the fastest designers. Interestingly, the advantages of collaboration were manifested mostly in temporal savings, but not so much in how much of the workspace was explored: overall singles explored the same amount of space as pairs. Future experimental work is needed to investigate how spatial and temporal aspects of performance are influenced by level of collaboration and expertise. One possible way to investigate this would be to impose either explicit time constraints (mimicking deadlines from everyday experience) or explicit spatial exploration limits (mimicking limitations of viewpoint and software computing power) in order to increase task demands.

The economy of action was also reflected in the enumerative measures (move time, number of moves, and movement frequency). Overall, pairs and experts spent less time manipulating objects. This suggests efficient use of software tools, knowledge of how to handle objects, etc. All of this cut down on the extra time taken to explore and try out the objects and figure out how they can be handled. Interestingly, experts’ performance was described as having a higher frequency of movement, but only when working alone. This may be consistent with the principles of economy of action and reflect the benefits of collaboration in the following manner: pairs may afford to do more in less time as singles, because they can divide task responsibilities among themselves.

Overall, interesting tradeoffs were observed between various behavioral aspects of design activities (such as handling objects and time management), but also compounded benefits of expertise and team work.

Conclusion

The results and observations obtained from the experiment suggest the benefits of working collaboratively within a CVE outweighed working individually in a standalone VE. Our findings indicate that collaboration within a CVE has great potential to increase the productivity at which designs are assembled, reduce the number of errors in design, provide a constructive learning environment, reduce the overall stress levels, and increase positive thinking and a group mindset for subjects.
Future work on collaboration in VEs should look at the differential benefits of various technologies, such as software solutions for CVE, and also the ergonomic aspects of human-computer interactions by utilizing haptic, visual and auditory aspects of interactions in the CVE. Monitoring performance over an extended period of time would provide insight about the development of expertise. This can have implications for designing novel educational tools such as interactive real time CVEs for online courses tailored to the demographics of the students (from pre-K to college and beyond). On the psychological side, future work is needed to explore the influence of demographics such as age and gender on collaboration. Social components of group behavior, such as leadership roles, division of labor, and group management are also important factors that need to be submitted to rigorous empirical investigation.

In future, we intend to closely analyze more of the psychological effects of working in a CVE. We also intend to compare the productivity of additional subjects working individually as compared to those working in groups of twos or threes. It is our hope that a larger sampling size of subjects can help us predict more accurately the benefits of collaboration in a VE. We expect to also see a broader spectrum of human interactions and collaborative styles. Our initial findings seem to suggest that males adapt to the navigational controls of the VE slightly faster than females. Does this relate to video game use or is there a deeper spatial reasoning behind this? We still have many unanswered questions which we expect to fully explore in future research.

**Issues and Improvement**

The primary issue we wish to improve is the difficulty involved in learning to navigate the VE. The keyboard and mouse setup is often confusing for subjects who do not have much experience with computer games. Many commands such as entering “editing mode” are often counter intuitive and require a quick-reference guide of commands to perform.

Subjects had a strong tendency to move to a single location and stay there for a prolonged amount of time using the top down view to manipulate the scene as a whole. This often resulted in objects being slightly misaligned. We believe this is largely due to the difficult control schema created by the mouse keyboard layout.

In the future we plan on experimenting with using game pads which may prove easier to become accustomed to. Another alternative which may be more widely available in the not too distant future is ready-to-go video based motion capture devices (such as the one used in Microsoft’s Project Natal) which may allow subjects to bypass a clunky interface altogether and simply move objects “by hand.”

Additionally, we would like to try out new tasks for subjects to complete which may provoke different collaborative styles. How would subjects react to designing their own building or making changes to an existing one? Virtually any scenario which involves subjects creating a 3D world is up for analysis. We hope to create engaging scenarios that create realistic situations for subjects to collaborate on.
References


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