Travel Kinematics in Virtual Reality Increases Learning Efficiency

Eric Nersesian, Margarita Vinnikov, Michael J. Lee
Department of Informatics
New Jersey Institute of Technology
Newark, New Jersey, USA
{eric.nersesian, vinnikov, mjlee}@njit.edu

***Abstract*—Virtual reality (VR) computer interfaces show promise for improving societal communication and representation of information due to their unique ability to be placed spatially around the user in three-dimensional (3D) space. This opens new possibilities for presentation and user interaction with the target information, and may be especially impactful for the education of science, technology, engineering, and mathematics (STEM) professionals. Simulations and visualizations have been shown in research studies to improve the efficiency of STEM learners compared to the less sensorimotor rich learning mediums of live instruction and textbook reading. Yet, learning science research into immersive computer simulation environments for educational applications remains limited. To address this research gap, we analyzed a fundamental VR interface capability, virtual environmental traversal, and its impact on participants' learning. We altered the traversal ability between two groups of STEM learners within the same virtual environment and compared their performance. Findings point that VR computer interfaces, regardless of environmental traversal, are suitable STEM learning environments, but that environmental traversal can increase learning efficiency.**

***Index Terms*—virtual reality, educational technology, computer science education, STEM education, sorting algorithms**

I. INTRODUCTION

As virtual reality (VR) technologies become more mainstream, educational technologies will increase the use of their capabilities. VR computer interfaces have a unique spatial component that allows them to be embedded into the three-dimensional (3D) virtual environment of the user. Sensorimotor experiences that humans have natural understanding of can be emulated with a higher level of fidelity than the competing technologies of two-dimensional (2D) interfaces on computer monitors. This may enable to new design framework for user experience (UX) designers enabling more natural input and output interfaces for virtual learning environments. Understanding the unique affordances that spatial interfaces can provide learners can define the best use cases for VR educational technologies. This study examines a fundamental component of spatial computer interfaces, environmental traversal. We seek to understand what impact different fidelity levels of environmental traversal have to learning efficacy and usability preferences.

We examine if learning, and engagement of the science, technology, engineering, and mathematics (STEM) field of computer science (CS) improves when learners process educational concepts through a spatial interface within a VR environment with controlled variation to environmental traversal. We explored the traversal methods and their effects with undergraduate CS student participants learning bubble sort—a commonly taught introductory CS algorithm. Students that find educational topics within the STEM fields difficult to learn, may find alternative teaching methods useful to maximize their performance and comprehension. When designing VR educational tools, having the user move through and interact with the virtual environment may help them engage with difficult concepts, and attract a more diverse group to the STEM fields.

When a system interface is displayed spatially in 3D around the user, the traversal fidelity of the interface may have a stronger impact on user performance [1], [2]. This is because the interface elements are not restricted to a 2D monitor that is completely contained within the user's field of view [3]. Interface elements can be placed in any location around and distance from the user. This increases the complexity of the decisions for the UX designer, so it is important to understand how fidelity of an environmental traversal interaction with a spatial interface can impact user performance in an immersive virtual learning environment.

II. BACKGROUND

Learning tasks involving environment traversal have little research in relation to general-based or STEM-based virtual learning environments. Most of this research area involves industrial- or military-based learning scenarios. A recent example is a multiplayer VR game to train workers to navigate complex industrial facilities, developed by Mas et al [4]. Training within a VR environment made it possible to exponentially increase the variety of the learning scenarios enabling a better consolidation of knowledge and skill bases for the learners [4]. Jingxian et al. found simulation of realistic movements found on naval vessels within a VR environment improving the learning efficacy of naval officers in training [5]. These findings may be generalized to STEM education or broader topics as we did not find any prior research examining how spatial computer interfaces may offer unique impacts to learning general- or STEM concepts. We aim to begin addressing this knowledge gap with this study.

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VR applications have different demands for a user interface than monitor-based applications. This led Weib et al. to conduct a quantitative study identifying advantages and disadvantages of 2D, 3D, and speech-based user interfaces for virtual environments [6]. They found that 3D interfaces have higher ratings for natural and intuitive inputs along with better immersion into the experience, but that 2D interfaces are easier to learn and comprehend. This led the design of our study's interface as a mixture of 2D and 3D elements to attempt to gain the advantages and minimize the disadvantages of both techniques. The feeling of "being" in a virtual environment, or presence, was studied by researchers Lorenz et al. They found that presence was impacted by the style of traversal, which altered the level of immersion [7]. They tested two methods of walking. One style was to track the user's natural walking with a Kinect sensor and the other was less intuitive for the user by asking them to stand on a Wii Balance Board. Findings pointed to the more natural walking method as giving a stronger sense of presence.

Traversal tasks within virtual environments can be problematic for users. Kheddar et al. approached these traversal task issues with a proposed traversal control algorithm based on the behavior of how humans move their head while exploring the real world [8]. Their psychology review of how humans process a new environment led to design decisions in the study on how to build the 3D representation of the virtual world. An extensive review of spatial traversal interfaces was conducted by Kruijff & Riecke on virtual environmental locomotion allowances [9]. Travel and explorational themes were explored as factors from psychological theories to build a framework for design ideation. From this process, they devised two traversal methods to build an experimental study with a group using a hand-controller for environmental traversal and the other using natural walking. This successful experimental approach informs us that spatial computer interfaces will need practical solution from well-established pedagogical frameworks to build effective learning environments in VR.

CS pedagogy may prove to be a fruitful education discipline to develop research findings that may be generalizable to general- or STEM-based education. Learner outcomes have shown a positive change when integrating CS concepts with a multidisciplinary approach involving other STEM concepts while simulating constructivist learning principles (e.g., [10]–[13]). CS teaching that injected mathematical calculation or scientific experimentation with algorithmic thinking increases learner engagement in the material and related career paths [14]. Even mixing non-STEM fields within a CS class, such as music, art, and dance, found increased engagement in STEM [15]. Findings, such as these, point to virtual environments promoting constructivism through active learning can increase efficacy within STEM fields [16].

III. METHOD

A. Study Design

The study was a between-group design with two groups—a control and a treatment—that both participated in learning the bubble sort algorithm in VR. The control group had to use hand controls to move their avatar through the virtual representation of the list of elements they sorted its elements. The treatment group was used a natural walking method to navigate the virtual list to sort and review. The control group was assigned the hand controller interaction, since traversing a digital environment with a hand controller is more typical, whereas physically walking to traverse a virtual environment is less standard, i.e., more experimental.

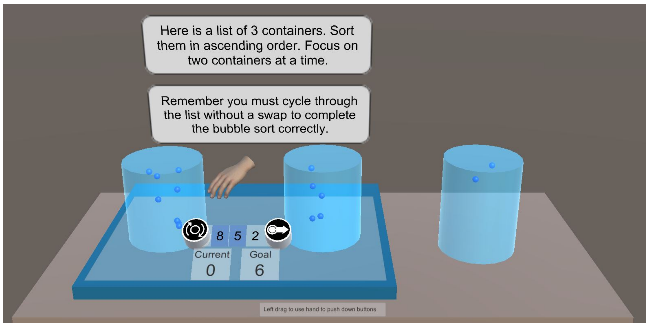
B. System

The design goal of the virtual learning environment was to take advantage of the Oculus Quest VR headset's free roaming feature, which allows the user to move around without entanglement by physical wires [17]. The Oculus Quest is a standalone VR headset that gives stimulus input to the user through a wireless headset and takes output from the user through wireless hand controllers [17]. We used Unity [18] to create the headset software, Autodesk Maya for the 3D models and animations, and Substance Designer to create our textures. For the learning experience, we required the user to be standing and have a free roaming space of 20' x 6' to move around the virtual environment (see Figure 1).

C. Stimuli

In the virtual environment, users saw an empty landscape with a waist-high work station with virtual objects and a text-based user console that provided directions. The presented stimuli was visual and interaction only, there was no audio stimuli. The only part of the user that was represented visually in the virtual environment was their hands since that was their interaction point with the 3D user interface. The bubble sort station was interactive, allowing the user to push their virtual hands through virtual representations of push buttons. All interactions required of the user were presented as a tutorial when the application first started (see Figure 1).

The waist-high work station grew length-wise as each task was completed and room was needed for a larger list to accommodate. The station's virtual objects included a row of translucent cylinders that housed a different number of opaque, floating balls. The current selected pair of cylinders were highlighted with a box, displayed the number of balls


Here is a list of 3 containers. Sort them in ascending order. Focus on two containers at a time.

Remember you must cycle through the list without a swap to complete the bubble sort correctly.

Left drag to use hand to push down buttons

Fig. 1. View of the spatial computer interface for bubble sort activity.

in each cylinder, and included a ”swap” and ”next” button that enabled those actions to the user. Finally the console also included a small 2D representation of the full list (in its current state) for the user to track their progress.

D. Participants

Participants were gathered from the researchers' undergraduate classes for 5% extra credit. The participants were 42 undergraduate Information Technology (IT) students, of which 14.3% were female and 85.7% were male. Participant ages ranged from 18-36 years old (median 21). Demographics were gathered from a pre-assessment survey asking for participants' age, gender, ethnicity, and experience with VR.

E. Procedure

Before starting the sessions, all participants were informed on the purpose and design of the study and asked to fill out the pre-assessments including forms that measured assessment, demographics and consent. The learning assessment was designed to be taken in under 10 minutes since it needed to be taken five times over the course of the experiment. All assessments were administered using digital forms to make the pre, post, and three retention assessments easy for the participants to complete, and the researchers to analyze. The participants were randomly assigned to one of the two groups, and came in for their learning sessions on separately assigned one hour time slots in one of five experiment days to avoid participant interaction between groups during the study.

For both conditions, participants were taught to use the VR equipment called “Oculus Quest”. They were fitted with hand and head controls. 25-30 minutes was allowed for lessons to the participants, where they interacted with the sort station and the console by pushing their virtual hands through virtual representations of push buttons, which was part of the tutorial presented to the participant when the application first started (see Figure 1). Control group participants were trained to use the thumb stick to move their avatar through the virtual environment containing the list meant to sort with the bubble sort algorithm. Treatment group participants were trained to move naturally with the virtual environment, since the sensors on the head and hand mountings would track them as they learned the bubble sort algorithm.

F. Measurements

The measurements were designed to gather data on the learning, retention, and task time metrics of the two groups. Learning measurements were taken as a pre-assessment, an immediate post-assessment, and three more retention post-assessments at later dates. Task time measurements were taken during the treatment sessions to examine task time metrics.

The learning assessment had four multiple choice questions to test the understanding and application of the bubble sort algorithm on progressively longer lists of elements. We selected two questions each from two popular CS educational websites [19], [20], and pilot tested and refined them with five undergraduate CS students prior to the full study.

IV. RESULTS

A. Pre to Post Learning Differences between Conditions

For all of our analyses, we used the non-parametric Mann-Whitney test (with a confidence of $\alpha = 0.05$), as our data was not normally distributed. We analyzed the data to see if there were any learning differences between conditions. Participants from both groups started without a significant difference between their pre-test scores $(W = 437.5, n = 42, p = \textit{n.s.})$, meaning that all participants began the activity with similar inexperience with the bubble sort algorithm (see Figure 2).

After the learning activity, there was an increase in all scores, but no statistically significant difference in participants' post-test scores between conditions $(W = 481.0, n = 42, p = \textit{n.s.})$. This suggests that both traversal interfaces were comparably effective in teaching the bubble sort algorithm. Examining the boxplots of the two conditions (see Figure 2), shows that the control participants knew a small amount more about the bubble sort algorithm in the pre-test but performed slightly worse in the post-test compared to the treatment participants. Upon further analysis, we found a statistically significant difference between the learning improvements from the pre-test to the post-test of the two groups. The treatment group participants performed significantly better than the control group participants when comparing the differences between their pre-test and post-test learning assessments scores $(W = 535.0, n = 42, p = 0.037)$.

B. Task Time Differences between Conditions

We analyzed the task time differences between each condition to see if there was difference in completion time by condition. Outliers (that were two standard deviations away from the mean—a threshold that can be considered “unusual” [21]) were removed from the task time data-sets prior to statistical analysis [22]. For thoroughness, we performed our

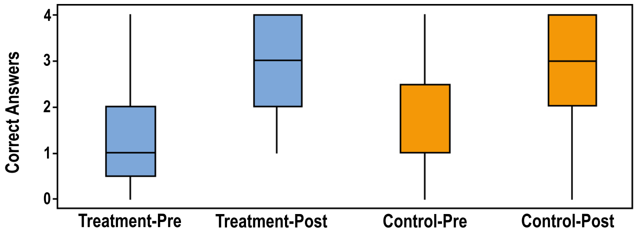


Fig. 2. Pre-test and post-test learning assessment differences per condition.

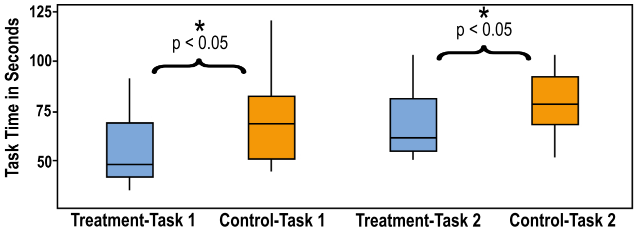


Fig. 3. Task 1 and 2 completion time comparisons per condition.

analyses with and without removing outliers as recommended by Bakker & Wicherts [23], and we found that the overall results were the same using both methods.

The treatment and control group participants had a mean session time of 11.42 minutes, and 12.65 minutes, respectively. We found a significant difference in Task 1 completion time by condition ($W = 308.5, n = 41, p = 0.018$), with the treatment condition participants completing the task faster than their counterparts (see Figure 3). This was the same for Task 2, ($W = 286.5, n = 37, p = 0.025$), with treatment condition participants completing the task faster than their counterparts (see Figure 3). This suggests that the virtual learning environment with the natural walking traversal interface helped the participants complete their bubble sort algorithm tasks faster than with the hand controller traversal interface.

V. DISCUSSION

A. Interpretation of Learning Assessment

The results of the learning assessments showed that the participants from both groups learned the bubble sort algorithm through the virtual learning environment and that the treatment group performed better than the control group. This suggests that the virtual learning environment could be used as alternative teaching tools in CS education, supplementing traditional teaching methods and possibly enabling new learning methods for students in the classroom and at home. The results also suggest that the more natural an environmental traversal interaction is (i.e., a stronger kinematic symmetry), the better they will do on tasks of learning on that topic.

B. Interpretation of Task Time

The results from the task time analyses showed that that the treatment group participants finished Tasks 1 and 2 significantly quicker than their control group counterparts, with the latter having a mean completion time over a minute more than the mean completion time of the former (see Figure 3). A factor for this faster time by the treatment group may have been the relatively short length of the lists in these two tasks, which may have been easier/faster to traverse through with natural walking rather than with the hand controller. We will perform further tests to better isolate the factors contributing to this outcome, and also test users with progressively longer lists to sort to see if that changes the task completion time.

C. Implications for Other Algorithm/Topic Design

This study demonstrates that visualizing algorithms with list components, and being able to walk through this list can be beneficial to learners. While this study is limited to looking specifically at the bubble sort algorithm, we are confident that the ability to move about inside a virtual space positively affects users' learning and engagement [24]–[26]. For example, in our prior works, we found that the ability to move (with a controller, and) interact with objects within a VR space can lead to positive, measurable learning outcomes for other computing-related algorithms such as binary counting [27], and learning about other STEM topics such as chemical compositions [26]. The qualitative participant feedback from this study and prior studies indicate that the design of educational VR systems' user experience should help users immerse themselves in visualizing the steps in an algorithm to help them with their computational thinking. Once that is achieved, designers can reinforce learning by designing interactions that focus on expressing these algorithm steps as body motions and interactions with physical objects (e.g., [28]), which can be an impactful for users to internalize the knowledge [29].

VI. LIMITATIONS AND FUTURE WORK

We acknowledge several limitations to our work which may affect the generalizability of the findings. First, there was a selection bias for our participants, as all were registered undergraduate computing students at a technical, higher educational institution. Next, our system only provided instruction on one algorithm: bubble sort. To address these concerns, future studies can recruit from a wider pool of participants, including younger (K-12) students and older adults, and those with varying levels of experience with different CS concepts. Future studies could also include additional algorithms for participants to learn (perhaps those also requiring different types of visualizations and traversal methods), providing further insight into the unique aspects and requirements for the system design, user experience, and learning outcomes.

VII. CONCLUSION

This study explored the effect of varying the traversal method within an VR learning environment on user performance. The two traversal methods compared were of a style that tracked with equipment allowed the user to walk naturally with their legs and one that allowed the hand controls to move the avatar without the participant moving their legs. The traversal methods and their effects were explored on undergraduate CS students learning CS concepts known as sorting algorithms, and the most simple is known as *bubble sort*. User testing confirmed that the treatment group that learned to bubble sort a list using the natural walking traversal method showed statistical improvements in learning, and task time compared to the control group that used the hand-controller traversal method. This demonstrates that the traversal method should be taken into consideration when designing as VR alternative teaching tools in STEM education. Students that find educational topics within the STEM fields difficult to learn, may find alternative teaching methods useful to maximize their performance and comprehension.

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