

Characterizing User Mobility within an Immersive Virtual Environment

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One of the unique characteristics of Immersive Virtual Environments (IVE's) is that they allow users to control their viewpoint by simply moving their head. Most configurations include a tracking system which tracks the position of the user's head, hands, and other body parts within a limited tracking range. During previous experiments dealing with object manipulation in IVE's we have observed two groups of (novice) users who have trouble walking around virtual environments. The first group of people seems very reluctant to walk around, they usually stand still throughout the session, extending and reaching their arms out in order to interact with virtual objects. They make heavy use of other provided "artificial" navigation techniques (gaze-directed or object focused point and click techniques), even when a simple step forward could achieve the same navigation goal. We have also observed another group of people with the opposite behavior; they are very willing to walk around an environment, so much so that they often find themselves outside tracker range. Users who leave tracker range often become confused and frustrated by the increased tracking "jitter". In order to improve the general mobility of participants we need to provide something in the virtual world which simultaneously encourages mobility in users who are reluctant to walk around, while also preventing other users from walking outside tracker range. One way to keep users inside tracker range is to construct a barrier or gate around the valid area, however in this paper we go further, by showing that by representing this barrier in the virtual world we can also improve mobility in users most reluctant to walk around. Further, we present evidence that the virtual representation of the barrier, without a corresponding physical one, still prevents many users from leaving tracking range.

1 Introduction

One of the unique characteristics of Immersive Virtual Environments (IVE's) is that they allow users to control their viewpoint by simply moving their head. Most configurations include a tracking system which tracks the positions of the user's head, hands, and other body parts. Unfortunately, most tracking systems have a limited range and once a user gets outside this range the positions returned from the system become erroneous, often causing the user to become confused and disoriented and make object manipulation tasks in the environment nearly impossible to complete. Most (experienced) users have little trouble dealing with tracking systems; they walk around freely within tracker range while being careful not to stray too far. However, during previous experiments dealing with object manipulation in IVE's we have observed two groups of (novice) users who have trouble walking around virtual environments. We observed that these difficulties often negatively affect their performance, complicating the evaluation of different manipulation techniques.

The first group of people seems very reluctant to walk around, they usually stand still throughout the session, extending and reaching their arms out in order to interact with virtual objects. They make heavy use of other provided "artificial" navigation techniques (gaze-directed or object focused point and click techniques), even when a simple step forward could achieve the same navigation goal. This lack of mobility leads to inefficiency in completing a given task and fatigue caused by users continually extending their arm. It also leads to placement and manipulation errors since the user is often too far from the object they are manipulating to see it from all angles.

We have also observed another group of people with the opposite behavior; they are very willing to walk around an environment, so much so that they often find themselves outside tracker range. Users who leave tracker range often become confused and frustrated by the increased tracking "jitter". At best, this tendency to walk out of range slows users down, since they need to stop what they are doing and adjust their position in both the real and virtual world. In the worst case, we have also observed users simply giving up on a manipulation task, not realizing that their difficulties are caused by the limited tracking range.

In order to effectively evaluate different interaction and object manipulation techniques we recognized that there is a need to improve the general mobility of the participants in our experiments. Specifically, we wanted to provide something in the virtual world which would simultaneously encourage mobility in users who are reluctant to walk around, while also preventing other users from walking outside tracker range. An obvious way to keep users inside tracker range is to construct a barrier or gate around the valid area, however in this paper we go further, by showing that by representing this barrier in the virtual world we can also improve mobility in users most reluctant to walk around. Further, we present evidence that the virtual representation of the barrier, without a corresponding physical one, still prevents many users from leaving tracking range.

2 Related Work

There has been considerable research on navigation in virtual environments, particularly focused on enabling users to explore and traverse virtual worlds which are larger than their real-world surroundings (the laboratory), making physically walking inadequate. The more common techniques allow users to specify a direction to travel by pointing with or at an object or by looking in the direction they wish to move. In order to actually travel, users usually need to perform a hand gesture or press a button on an input device to initiate the movement. Another popular navigation technique makes use of the World in Miniature paradigm (Pausch, 1995, LaViola, 2001), where users are presented with a small virtual model of the world and can select their destination, letting the system perform the movement for them. (Bowman, 1997) provides a survey and taxonomy of these popular navigation techniques and discusses which techniques lend themselves well to specific interaction tasks. Researchers have also identified the benefits of making navigation as natural as possible by simulating or allowing walking (Bowman, 1997, Slater, 1995), specifically due to its straightforwardness, simplicity, and because it helps preserve the user's sense of presence. Following this premise, (Usoh, 1999) has developed a technique which allows users to walk in place in order to cover large distances. All of this research primarily focuses on large scale (macro) navigation and way-finding however, in our research we are primarily concerned with "micro-navigation", where users are working on objects within or slightly outside arm's reach. In this situation, physically walking is usually the most practical and efficient method. We are unaware of any research that has investigated this; typically it is assumed that users will walk without hesitation in these situations while also making sure they do not leave tracking range. We have observed that this is often not the case when dealing with novice users.

A number of studies have shown that virtual environments can illicit physiological and psychological responses from users. (Slater, 1995, Meehan, 2002) demonstrated that users are very hesitant to physically walk over or near virtual cliffs, occasionally refusing to do so entirely. (Hodges, 1995, 1996) has effectively used virtual environments to help users with fears of heights and flying through exposure therapy; showing that virtual environments can elicit similar anxiety responses in users as real world situations. Our use of a virtual barrier to indicate the "safe" walking area draws on the same principles, however instead of eliciting anxiety responses from users we are attempting to provide the necessary feedback to a reluctant user in order to make them feel *confident* walking around the environment.

3 Experiment Description

Our solution for the mobility problems we observed in novice users stems from intuition, in that some people are reluctant to walk around while wearing a Head Mounted Display (HMD) because they are concerned about their surroundings. When wearing an HMD users can no longer see where they are in the laboratory, and it takes experience in order for the user to be able to judge where they are at any given time. There are a number of reasons this may be a concern for users; they may worry about walking into nearby walls or furniture, or perhaps they are concerned they may stretch and/or break the wires connected to the HMD and other trackers. In general, there is any number of reasons that users may find walking around unsettling, and they all stem from the fact that once the user puts the HMD on they can no longer accurately judge their position in the real world because they can only see the virtual world. Examining this problem, we felt that if we represented the tracker area within the virtual world users may be able to use this as a point of reference corresponding to the real world, which in turn would make them feel more comfortable walking.

In order to address the problem of users walking outside of tracking range we felt that the best solution might be to construct a physical barrier around the tracking area in order to keep the users in. We felt this barrier would also be a good object to replicate inside the virtual environment in order to give users (reluctant to walk) a point of reference. Thus we chose to erect a gate (Figure 1) surrounding the valid tracking range and to put a virtual gate which directly corresponds to the physical one inside the environment so users would always know where they were in relation to it while performing tasks inside the virtual environment. This virtual representation can be seen in Figures 2 and 3. Note that the virtual and

physical barriers are aligned as precisely as possible, so when users reach out to touch the barrier their virtual hand intersects the virtual barrier just as they come into contact with the physical one. In order to determine the optimal size of the barrier we took measurements to determine precisely where the trackers began to lose accuracy and built the gate slightly smaller, in order to allow users to reach over the gate without losing accuracy if they desired.



Figure 1: Photo of physical gate

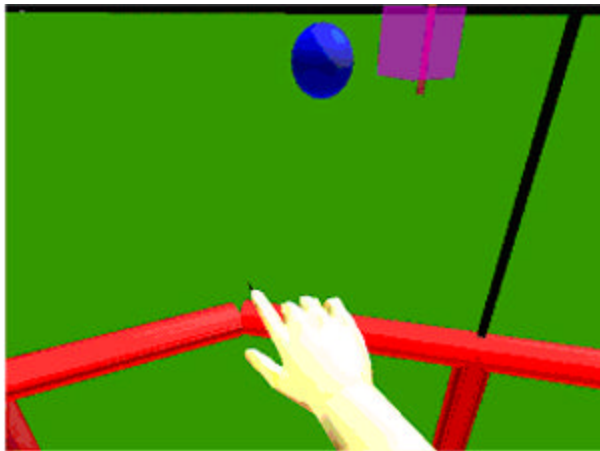


Figure 2: Screen shot of virtual gate

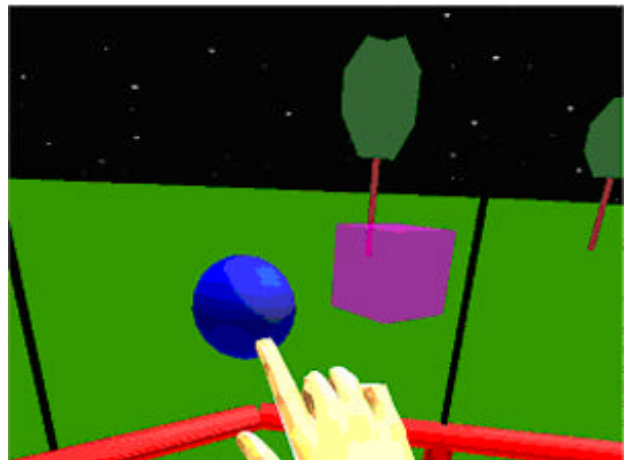


Figure 3: Screen shot of participant moving virtual sphere.

3.1 Experiments

In order to see if our barrier helped both groups of people we designed two experiments which involved very similar tasks. In both experiments users were presented with five virtual cubes and five spheres. The users were asked to center each sphere inside a cube as precisely as possible via direct manipulation with a tracked stylus in their dominant hand. The cubes and spheres were exactly the same size, so if placed accurately the sphere would not protrude from any of the cube's six sides. For both experiments, users performed the task three times, once with no virtual or physical barrier, once with a virtual barrier only, and once with a virtual and physical barrier. The users were given 3 minutes to center all five spheres and were not told that we were interested in their mobility.

In Experiment 1 the five cubes were placed approximately 0.70 meters away from the user, arranged in a pentagon around the user. At this position the cubes were slightly out of arms reach for most people but still within tracking range. The

users were not provided with any other navigation technique; they needed to physically walk to get closer to the target cube. We chose this arrangement (shown in Figure 3) so the users were not required to walk if they didn't want to, however the task was much easier if they did.

Experiment 1 was designed to give us an idea if the virtual and/or physical barriers made users more comfortable walking around the environment. Since all the cubes and spheres were inside tracking range, we knew that it was unlikely many users would have problems staying inside that area however. In order to see how the virtual and/or physical barrier affected users who tended to go outside of tracking range we conducted a second experiment. In Experiment 2 (performed immediately after Experiment 1, with the same users), the task remained exactly the same, however this time the cubes and spheres were placed approximately 2 (virtual) meters away from the user. If users tried to walk directly to the cubes in this experiment they would end up well outside of tracker range. Unlike in Experiment 1, this time users could point their stylus in the direction they wanted to move and hold down the stylus button in order to travel. Users were told they could use any mix of physically walking and stylus directed travel they wished. Once again they performed the task three times (once for each barrier treatment) and were given 3 minutes to complete each trial. In addition to seeing how well the barriers kept users inside tracking range, we were also curious to see if the same trends we might observe among users reluctant to walk in Experiment 1 were seen in this experiment.

3.2 Experimental Procedure

We recruited 18 participants via email and posters around campus; all the participants reported little previous experience with virtual environments. No demographic data was collected from the participants, however nearly all participants were either undergraduate or graduate students. Each participant performed Experiment 1 and 2 in succession, which totaled to 6 separate trials (1 for each barrier treatment for each experiment). The order of barrier treatments was randomized in order to avoid any learning effects. The participants were told to place all spheres as precisely inside the cubes as possible and were offered a reward if they were the most accurate at the end of the entire experiment. The equipment used in both experiments included a four port Polhemus 3SPACE FASTRAK electromagnetic tracking system, a Virtual Research Systems V8 HMD, and a Pentium 4 PC. The software used to drive the virtual environment was the Simple Virtual environment toolkit (Kessler, 2000). Experiments 1 and 2 each took approximately 15-20 minutes to complete, requiring a 40 minute commitment from the participants. At the end of Experiment 2 participants were also given an exit survey in which they were asked to give their opinions about how they felt the barriers affected their mobility.

4 Analysis & Results

Throughout each trial, the user's waist, head, and dominant hand position was tracked and recorded in order to determine a measure of mobility during the trial. In addition we also recorded the accuracy in which the users placed each sphere, in order to see if the barriers had any effect on their performance. In order to calculate the overall mobility of the users in a trial we used the position data gathered corresponding to the user's waist movement. We felt that the user's waist position was a better measure of mobility since the position of their head might vary without the user actually walking (the user could lean in a certain direction, which we didn't want to mistake as walking). To get a concise measure of their mobility, we summed the distance moved between each sampling interval (each frame) and came up with a number representing the total waist movement of the user over the course of the trial. To determine how much time users spent manipulating spheres while outside the tracking range we totaled up a separate sum of waist movement that occurred while their dominant hand (the one used to manipulate the sphere) was outside of tracking range (our trackers are reliable out to approximately 0.8 meters, as determined by the measurements taken when building the barrier). This sum was divided by the total movement during the trial to give us a percentage of movement occurring while interacting outside tracking range.

4.1 Effects of the Barriers on Mobility

With respect to mobility our hypothesis that the presence of a barrier (virtual and/or physical) would simultaneously encourage reluctant users to walk more while also restraining users from leaving tracker range seems to be correct. From our 18 participants, the data suggests three distinct groups, users who had low mobility without a virtual or physical barrier, users who moved around *within* tracker range without a barrier, and users who tended to drift outside of tracker range without a barrier present. In order to present our data more clearly we ranked the participants in ascending order by their total mobility in the treatments with no virtual or physical barrier. We distinguish three groups: "Timid Users", which are the 6 users with the lowest mobility scores, "Bold Users", which are the 6 users with the highest mobility scores, and finally "Normal Users", comprised of the middle 6 users. Table 1 shows the average increase in mobility for these groups in the

Virtual Barrier and Virtual & Physical Barrier treatments. Table 2 shows the percentage of movement that occurred outside tracker range in each treatment in the both experiments.

Mobility Compared to Treatments without Barriers		
	Experiment 1	
	Virtual Only	Virtual & Physical
Timid Users	54% Increase	47% Increase
Normal Users	4% Reduction	No Effect
Bold Users	No Effect	20% Reduction
Experiment 2		
	Virtual Only	Virtual & Physical
Timid Users	24% Increase	37% Increase
Normal Users	5% Reduction	14% Reduction
Bold Users	6% Reduction	30% Reduction

Percentage of Movement Outside Tracking Range		
	Exp 1	Exp 2
No Barrier	0.79%	8.66%
Virtual Only	1.47%	4.86%
Virtual & Physical	1.15%	1.01%

Table 2

Table 1

4.1.1 Restraining the Bold

In order to judge how the barriers affected users with respect to moving outside tracking range we examined the percentage of time spent outside of range in each trial. As we suspected, most users did not leave tracking range for any significant amount of time during Experiment 1, since the objects they needed to manipulate were all relatively close to them. In Experiment 2 however we saw that a significant portion of users left tracking range when no virtual or physical barrier was present. Figure 4 shows a graph of the percentage of movement while outside tracker range for each user. Participants are represented along the x axis and are ranked in ascending order according to how much they moved outside tracking range in the No Barrier treatment.

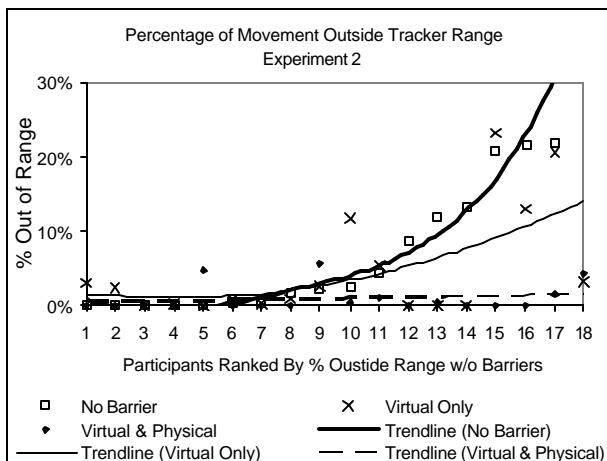


Figure 4: Percentage of Movement Outside Tracker Range for Experiment 2

It is clear from the graph that movement outside tracking range was substantially reduced by the presence of a virtual and/or physical barrier among those users who had trouble with the No Barrier treatment. Clearly this result is expected with the Virtual & Physical treatment, since the users were physically restrained from straying too far, however we also see that the presence of a virtual barrier alone also had restraining effect, although not as profound. In adding up the percentages for all participants combined, 8.66% of movement in the No Barrier treatment occurred outside tracker range as compared to 4.86% and 1.01% in the Virtual Barrier and Virtual & Physical treatments respectively.

4.1.2 Encouraging the Timid

We now turn to the mobility data of each user in order to see if users who didn't walk around much without a virtual and/or physical barrier moved more when a barrier was present. We see evidence that the barriers helped in both experiments, however the increases in mobility are greatest in Experiment 1. In figures 5 and 6 we present graphs showing the mobility of users in the Virtual Barrier and Virtual & Physical Barrier treatments represented as the percentage point increase in mobility from the No Barrier treatment. The x axis represents users, ranked in ascending order according to their mobility in the No Barrier treatment. In these graphs, data points above 0% should be interpreted as an increase in mobility, and those below a reduction.

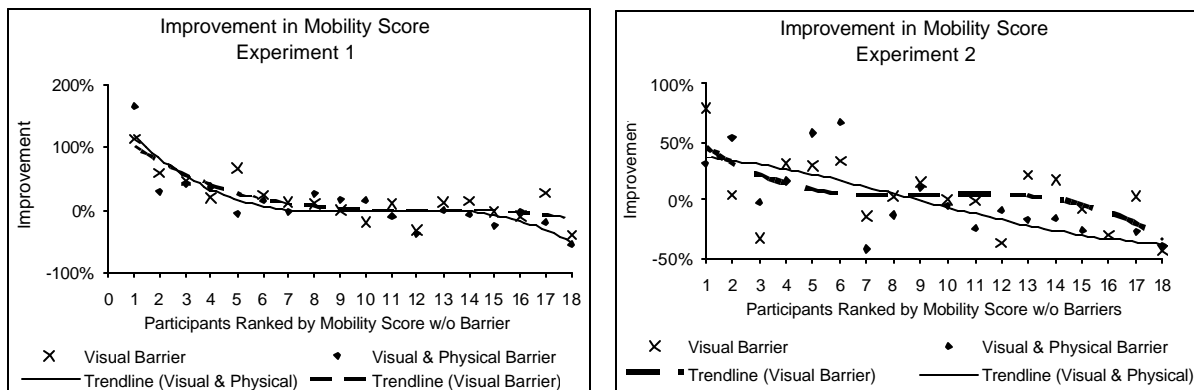


Figure 5 and 6: Mobility of users in the Virtual Barrier and Virtual & Physical Barrier treatments represented as the percentage point increase in mobility from the No Barrier treatment.

In each experiment, the percentage increase in mobility forms an S shaped curve, with the highest increases in mobility among users who moved around the least (the left side of the graph), a segment close to 0% increase (or no effect) in the middle (users who moved around a moderate amount), and finally a curve slipping below 0%, representing a decrease in mobility for those users who moved around the most in the No Barrier treatment. This decrease is to be expected, since these users are the same users who tended to move outside of tracker range the most; and as the previous section describes, mobility for these users was curtailed by the barriers. Among the users who moved the least (participants 1 – 6 in the graphs), there was an average mobility increase of 54% and 47% for the Virtual Barrier and Virtual & Physical Barrier treatments in Experiment 1 and a 24% and 37% increase in Experiment 2 (See Table 1 for further details).

4.2 Effects of Mobility on Accuracy and Fatigue

As we noted in the beginning of this section, in addition to recording the position of the user's waist we also recorded their hand positions and their accuracy in the placement of the spheres during the trials. By looking at the user's hand and waist position at each interval we can get an idea of how far their arm was stretched while manipulating the spheres, which can be used as a measure of expected arm fatigue the user experiences. We felt we might see a correlation between mobility and this fatigue measure, but we did not see any evidence to suggest this. We feel that although we don't see evidence of a correlation in this experiment we are confident from our past experiences that mobility does reduce user fatigue during prolonged use of virtual environments. We also felt we may see a correlation between accuracy and mobility but that didn't seem to be the case either. Our experiment was designed to be quite challenging and in fact most users complained that placing the spheres exactly inside the cubes was far too difficult. We feel that mobility plays a positive role in performance in general, however it did not play a significant enough role in this experiment for us to see a real correlation.

4.3 User Feedback

We were quite interested in how the participants thought the barriers effected their behavior in the environment and whether or not they liked them. Overall user responses were quite mixed; most users who seemed reluctant to walk around indicated that the barriers made them feel more comfortable, and our data suggests this. Surprisingly, users who frequently went outside of tracker range almost uniformly disliked the barriers. Most users in this group stated that they ignored the

virtual barrier and that they disliked the physical barrier because it got in their way. We were surprised by this because these participants also expressed frustration when outside of the tracker range. As we will discuss in the conclusion of this paper, this most likely suggests that the physical barrier is necessary (because some users ignore the virtual one) and that users need more explanation about tracking limitations before taking part in experiments in order to limit frustration. Participants who performed well in the experiment (walked freely but within tracker range) had mixed opinions about the barriers.

5 Conclusions

Our motivation for these experiments was rooted in the fact that we felt user mobility played a role in task performance during interaction and object manipulation experiments we have performed in the past. Specifically, we felt that users who were reluctant to walk around or had trouble staying within tracking range had difficulty performing the manipulation tasks we asked of them, complicating any results we obtained concerning the different interaction techniques we were developing. Our goal was to improve mobility in both groups of people simultaneously and we feel we achieved this with our virtual and physical barriers. The virtual barrier alone seems to have helped the more timid users feel comfortable walking around the environment. For users who had trouble staying within tracking range the virtual barrier alone reduced the problems in some users; however it might not be enough, only the physical barrier seemed to stop the most mobile users. There are advantages and drawbacks of using a physical barrier; while the physical barrier can be used to hold on to and force users to stay within range, it is time consuming to build, takes up space in the laboratory, and might frustrate more experienced users. In general we feel that with proper explanation of tracking limitations the virtual barrier may be sufficient however given the resources the combination of a virtual and physical barrier is probably more desirable. In this specific experiment we did not see a statistical correlation between accuracy and mobility; however from past experience we still believe that there is indeed a connection under certain circumstances. In more complex manipulation tasks users need to see objects from all angles and from up close, and a reluctance to walk to the object will lead to inefficiency and errors. Also, in our experiment users generally had plenty of time to complete the task, however in other situations when completion time is a more pressing issue users who waste valuable time by walking outside of tracking range will see their performance decrease. We believe we have identified two groups of people who have trouble navigating in virtual environments, and since our data suggests that a virtual barrier alone helps both groups we feel that the underlying problem is most likely due to the fact that each user has a different degree of spatial ability or awareness in the virtual environment. Users who walk freely within tracker range without straying too far seem to naturally have the ability to keep track of their position in the real & virtual world simultaneously. We feel that by placing a visual construct of the real world tracking range in the virtual environment we provide users who would otherwise have difficulty orienting themselves the ability to feel more comfortable.

6 Future Directions

Although the presence of a virtual barrier around the tracking area certainly improved mobility among users reluctant to walk, only the presence of the physical barrier brought movement outside tracker range down to a minimum. As discussed in the conclusion, there remain some users who will ignore the virtual barrier and leave tracking range. Compounding the problem, we observed that when these users began to experience “jitter” they were often unable to rectify the situation. Ideally the user should step backwards, back into tracking range, and then to use another navigation technique (in this case, stylus directed movement) to get back into (virtual) position and continue interacting. Unfortunately this wasn’t immediately clear to many users and we expect this to be a common problem. In order to make this situation easier for users to remedy we plan on detecting alerting users when they are near the edge of tracking range and providing a mechanism for the to step back into tracking range and *bring the virtual world with them* as they do this. By translating the virtual world with their movements we can eliminate the two step solution described above, allowing users to get back into tracking range and immediately continue working with the objects they were manipulating as if they have never moved. Finally, we feel that the two groups experiencing mobility problems can also be related to their sense/experience of presence. Users who have difficulty staying within tracker range most likely are experiencing a very high sense of presence in the environment, so much so that they forget about their real world constraints. Users more reluctant to walk around might be experiencing a low sense of presence – they are concentrating on their real world surroundings more than most people. In future studies it may prove useful to study more accurately the relationship between mobility and presence.

7 References

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