Mobile Devices for Interaction in Immersive Virtual Environments

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ABSTRACT

Gamepads and 3D controllers are the main controllers used in most Virtual Environments. Despite being simple to use, these input devices have a number of limitations as fixed layout and difficulty to remember the mapping between buttons and functions. Mobile devices present interesting characteristics that might be valuable in immersive environments: more flexible interfaces, touchscreen combined with onboard sensors that allow new interaction and easy acceptance since these devices are used daily by most users. The work described in this article proposes a solution that uses mobile devices to interact with Immersive Virtual Environments for selection and navigation tasks. The proposed solution uses the mobile device camera to track the Head-Mounted-Display position and present a virtual representation of the mobile device screen; it was tested using an Immersive Virtual Museum as use case. Based on this prototype, a study was performed to compare controller based and mobile based interaction for navigation and selection showing that using mobile devices is viable in this context and offers interesting interaction opportunities.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Interaction paradigms*; Virtual reality• **Interaction devices**→ Touch screens

KEYWORDS

3D interaction, Immersive Virtual Reality, mobile devices

1 INTRODUCTION

The development of immersive Virtual Reality (VR) experiences is significantly facilitated due to the available optimized and easy to use software and the affordable hardware, namely Head-Mounted Displays (HMD). However, one of the challenges to create compelling VR experiences is the interaction of the user with the virtual world. A common option is to use gamepad or 3D controllers to perform the universal interaction tasks for Virtual Environments (VEs): navigation, selection and manipulation [1]. Although these devices (such as the Wiimote) are easy to setup, simple to use and easily available, they also present some limitations due to their fixed layout, the necessity for the user to remember the mapping between buttons and functions, issues related with the location where to display additional menus or information and the indirect manipulation of virtual objects using buttons. As an alternative, mobile devices (smartphones and tablets) are not limited to a single layout configuration providing more flexibility thanks to touchscreens and enabling a wider range of interaction possibilities. Some important advantages of these mobile input devices are the possibility to perform direct interaction on the items and providing a highly customizable user interface. These devices also have some limitations, for example the lack of feedback when pressing a button; however, this problem may be mitigated using proper visual or haptic feedback.

This paper intends to determine the extent to which mobile devices can be a valid input device for interaction in immersive virtual environments and whether this type of interaction is usable and preferred by the users in comparison with 3D controllers. With this goal in mind, we developed a VR system that supports mobile devices as interaction device and created a Virtual Museum prototype to compare and evaluate simple 3D controllers (Wiimote) and mobile interaction for navigation and selection in immersive virtual environments. The reminder of the paper presents related work in section 2, the proposed system in section 3, the user study comparing input devices for selection and navigation in section 3, and finally conclusions and future work.

2. USE OF MOBILE DEVICES IN VIRTUAL ENVIRONMENTS

In this section we present some previous work related to the use of mobile devices in Virtual Environments (VE). Virtual Reality (VR) systems are often classified as non-immersive and (semi- or fully-) immersive. In non-immersive systems the virtual environment is viewed through a standard monitor with a reduced feeling of presence whereas in semi and fully immersive VR systems the user is immersed inside a virtual world giving them the felling that they ”stepped inside the synthetic world” [2]. In this section we present works related to the use of mobile devices as interaction devices first in non-immersive and then in immersive environments.

2.1. Use of Mobile Devices in Non-Immersive Virtual Reality systems

Mobile devices have already been used to interact with non-immersive VR systems. Hori and Katzakis [3] showed that mobile devices can be used effectively as a wireless 3-DOF controller while manipulating virtual content in digital shops, museums and similar scenarios. These authors also suggested that conventional input devices as the mouse and keyboard are not suitable for 3D manipulation tasks and that multi-touchscreens and embedded sensors such as accelerometers and magnetometers available on modern mobile devices can be used to further expand the range of interactions with the objects and turn 3D interaction significantly faster and more natural. Likewise [4] proposed the use of mobile phones for 3D manipulation to simplify complex 3D tasks by mapping specific touch and orientation gestures performed on the mobile device. This technique can also be applied to immersive VR applications that use HMDs, CAVEs or other type of immersive displays.

Thus far, several studies have also tested the usefulness of mobile devices to interact with large displays [5–7]. In this context, an interesting application is the Handymenu [8] that turns Smartphones into VR controllers for menu selection. The touch interface is divided into an area for menu interaction and another for VR tasks such as selection, manipulation or navigation. The authors of this work also analyzed how the Handymenu compares to the standard ray menus and investigated the best layout to perform menu interactions.

Besides manipulation and selection tasks, mobile devices have also been used for navigation inside non-immersive VEs [9,10]. Bergé et al. [9] suggested that Smartphones are an attractive and stimulating solution for interaction with 3D VEs after comparing smartphone-based interaction with interaction using two common devices: the keyboard-mouse and a 3D mouse (Space-Navigator). Another work that explores the benefits of using a smartphone as the interaction device in a VE was performed by Chuah and Lok [11]. Their study used a smartphone as interaction device in two experiments: a mixed reality game that involves placing an object in a specific location on a game board and the Virtual Reality Eye Exam used by medical students to observe symptoms and diagnose cranial nerve damage. Both studies suggest that smartphones can reduce the user need for training and button memorization.

2.2. Use of Mobile Devices in Immersive Virtual Reality systems

Medeiros et al. [12] proposed the use of a tablet-based tool to perform the main 3D interaction tasks in immersive VEs in engineering applications. The mobile device was used to display additional information and aggregate all the major universal interaction tasks as navigation, selection and manipulation. In this work, users could navigate using an in-screen joystick. The selection technique used an adaptation of the Eyeball-in-Hand (EiH) metaphor [13] where an additional virtual camera (EiHCam) provided visualization from the viewpoint of the tablet that the user is holding. The tablet’s touch screen was used to perform selection and manipulation through scale and rotation gestures. The system was validated using the SimUEP- AmbSim training simulator for oil platforms [14]. The study suggests that mobile devices are a viable option to interact with virtual engineering content and authors emphasized that this kind of devices are a complete tool for use in VEs.

Although smartphones and tablets allow display a flexible user interface, a strong limitation of these devices is that users cannot easily locate the virtual widgets without looking at the device screen. To overcome this limitation, Krum et al. [15] propose the use of 3D printed panels overlaid on multitouch mobile devices to provide passive tactile feedback allowing users to easily locate the controls without looking at the screen. Steed et al. [16] focused on interaction with VEs using mobile devices’ touchscreen as an unseen touch panel in a VR system. The main goal was to build a mobile VR system based on an iPhone 4S combined with a Sony Glasstron LDI-D100BE HMD. The set of possible actions was limited and the system presented limitations regarding the tracking and data fusion between the iPhone and the HMD sensors. Despite the limitations, the concept presented great potential and the pilot trial suggested that the interaction technique was simple to learn and that users had no problem navigating in the environment.

Overall, these studies provide evidence that mobile devices offer advantages as interaction devices in Virtual Environments. When compared to a traditional controller-based interaction several studies showed a reduction of the required level of training and memorization. The availability of several different sensors on tablet and smartphone like devices (touchscreen, compass, accelerometer, etc.) is also valuable since it opens the possibility to use and combine different interaction styles with a single device. One of the main limitations is the lack of feedback when using touchscreens, however some simple solutions, as the use of 3D printed panels can help overcome this limitation. In our work, this problem is overcome by presenting a representation of the tablet screen and of the user hands in the virtual world allowing direct manipulation.

3. IMMERSIVE VIRTUAL REALITY SYSTEM WITH TABLET-BASED INTERACTION

The immersive VR system we developed is based on the following two principles: possibility to configure different virtual environments and integration of tabled-based interaction. The system used as inspiration pSIVE - Platform for Setting Up Immersive Virtual Environment developed in previous works [17,18] but the original platform (developed in OpenSceneGraph) was completely redesigned in Unity to support more recent Hardware. The platform allows customize the models in the virtual scene as well as the associated content as text information, PDFs or videos without the need of programming skills. The main novelty of the work presented in this paper is the introduction of a mobile device to test a different range of interactions and visualization of the virtual content. In previous work, a limitation of the system was the location where to display the additional information (video, pdfs, etc.). The solution was to present it in front of the user which resulted intrusive disrupting the VR experience. This motivated the use of a mobile device to implement the “Pen & Tablet” metaphor giving a better control to the user of where additional information is presented. To ease the interaction the physical tablet device and the user hands are both tracked and have a visual representation in the virtual environment. A 2D interface is displayed on the virtual tablet screen with which the user interacts by touching. Given the generalized use of mobile devices, tablet-based interaction is expected to be natural and easy to learn thus improving the interaction within the virtual environment.

3.1. System Architecture

Figure 1 gives an overview of the whole system architecture. The selected game engine was Unity, a fully featured and popular game engine with extensive support to third party hardware (in our case Oculus) and software (Vuforia for AR tracking). It also provides high quality documentation as well as an active and helpful community.

Tablet and Wiimote are the two interaction devices supported; in a session only one of the devices can be used at a given time. A Leap Motion Controller, mounted on the HMD, is used to track the hands allowing show their visual representation to ease the interaction with the tablet representation in the virtual world. The main application (Unity) receives the hand tracking data sent by the Leap Motion Controller. When the Oculus Rift DK2 is connected to the computer the output will be automatically redirected to the HMD with head-tracking activated.

Unity’s Unet Transport Layers (specifically Low-Level API - LLAPI) allows for the creation of a network system sending and receiving messages that are no more than simple commands (strings) with data from the tablet application indicating for example which button was pressed or tracking information. Depending on interactions within the main application, commands can also be sent to the tablet application to change the interface shown. As explained earlier, one design principle on which the platform is built upon is to allow the virtual content to be easily configurable. This is achieved using XML configuration files read by the Unity application at the start-up defining the main configurations. Unity does not provide an out of the box feature to access the data of the Wiimote, but this problem was easily solved with Unity Wii Remote API.

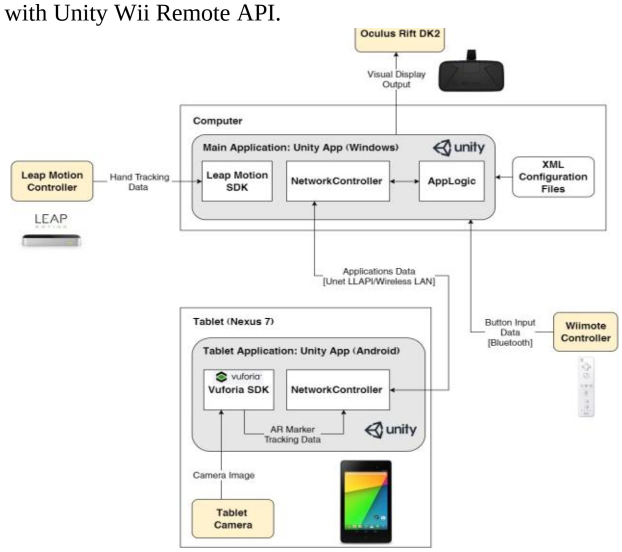

Figure 1: System Architecture

3.2. Input and Output Devices

The system is designed to support other interaction devices, but we focus on the tablet (Nexus 7) and the Wiimote since we want to compare the effectiveness of tablet-based against controller-based interaction. The main components of the system are presented in Figure 2 and described next.

Tablet: when using the tablet to interact with the system the tracking of the device position and orientation is done using the Vuforia SDK 2 as will be explained later in section 3.3. The tablet application exchanges information with the main application. With the Vuforia SDK we obtain the tracking data that is sent whenever there is a touch on the screen or on a specific UI button. This information is also sent to the main application.

Wiimote: was supported by the framework and was the configuration used as reference for later comparison in usability studies with the tablet interaction. Other input devices such as the Playstation Move [19,20] or the Xbox Controller [21] were also viable options but the Wiimote was selected since it is commonly used for 3D user interfaces [22] , low cost, and does not require any additional tracking systems neither additional calibrations (such as additional cameras needed for example for 3D trackers as the HTC Vive or Oculus systems). The infrared tracking available in Wiimote was not used (replaced by HMD gaze steering) since it would have limited the interaction when pointing to the LEDs or make the setup complicated with several infrared bars all over the user.

Figure 2: Hardware setup. 1) Computer running the main application; 2) Wiimote controller; 3) Tablet (Nexus 7) running the tablet application; 4) Leap Motion Controller; 5) Augmented Reality marker attached to the 6) Oculus Rift DK2 HMD

Oculus Rift DK2: was the used HMD. It has 6 DoF but our application only makes use of 3-axis rotational tracking since only head tracking was necessary.

Leap Motion Controller: is used for hand and finger tracking. The role of the hand tracking in the developed platform is to provide additional visual feedback to the user while using the tablet-based interaction within an immersive VE.

3.3. Tablet Tracking

One of the main challenges of our work is to provide a reliable tablet tracking to ensure a correct alignment between the real tablet and its virtual representation in the VE. Several alternatives were tested, namely the use of a 6 DOF magnetic tracker - WinTracker III with one of the receivers attached to the back of the tablet, but this solution suffered from interferences due to the tablet and increased complexity with an additional tracking device. Some experiments were also performed with Google Tango SDK: a tablet device running Android combined with a depth sensor, but the solution was abandoned since it requires additional hardware and needs a calibration process to align the tablet and the HMD in the same coordinate system. A third approach was to use Augmented Reality software (Vuforia SDK for Unity) to get the position and orientation of the tablet camera relatively to an AR marker. This approach does not need any additional device attached to the tablet since the tablet camera was used to track the marker located on the HMD (Figure 3). This solution provides directly the position of the tablet relatively to the HMD without the need of any additional calibration and ensures that when the user is looking at the tablet screen the device camera is pointing to and tracking the marker on the HMD. The image target/AR marker can be easily customizable and just needed to be printed out on regular paper which is a great advantage when compared to an external tracking device both in terms of set up and cost making a lot easier for anyone to use this tracking mechanism.

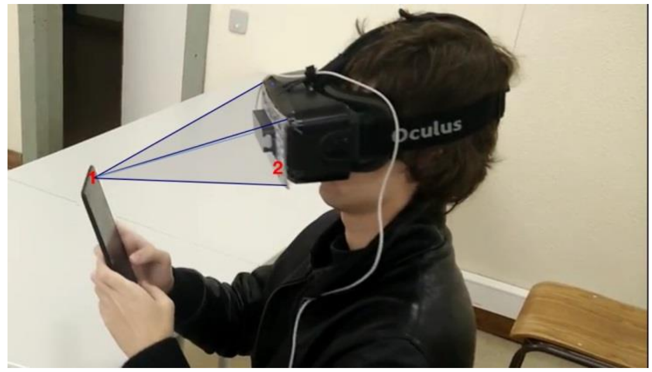

Figure 3: Tracking the tablet device. 1) Tablet front-camera tracks the AR marker 2) on the front of the Oculus Rift.

3.4. Hand-avatar

A relevant aspect when using mobile devices is the ability to see the hand while interacting with the screen. The presence of a hand-avatar in our set-up might improve the user experience by providing self-embodiment and visual feedback during tablet interaction. The existence of a virtual body (or self-avatar) while experiencing a VE may be rather compelling even if its visual characteristics (as shape and color) are not very realistic [23,24] and self-avatars have been used to interact with the environment and objects in games and simulations with different degrees of realism [25]. Their influence on user performance in VEs has also been explored, for instance Ries et al. [26] studied the effects of a self-avatar in estimation of egocentric distances, and their results showed that users performed better while having an avatar.

Based on these findings, we performed a study to evaluate the influence of the user's hands virtual representation on the performance of a button selection task in a tablet-based interaction within an immersive VE. Two different virtual hand representations, a realistic and a translucent hand model, were compared with a no-avatar condition while the users were selecting a series of buttons on the virtual tablet screen. The results of this study [27], performed with fifty five students, suggest that having a virtual representation of the hands may improve the user experience in a tablet-based VE interaction and that users were slightly less prone to make selection errors when using the translucent hand. As a result, the translucent hand was the condition adopted in our system.

3.5. Virtual Museum application

The system was validated using a prototype application under development: The Virtual Museum. It is a virtual room that replicates a real room of the Museum of the City of Aveiro (Figure 4). The main concept of the Virtual Museum is to allow visiting a VR replica of the existing room while interacting with its contents. As further explained in section 4 the user can navigate in the Virtual Museum and select items such as portraits of Aveiro personalities. After selection the user can access through a menu additional contents linked to the museum items: biographies or other text information, 3D Models and/or 360° panorama views. This seems to us an interesting use case to evaluate navigation and selections tasks.

Figure 4: View of the Virtual Museum (left) and real room in the museum (right).

4. USER STUDY

The main goal of the study was to assess the usability of each interaction method (tablet-based vs controller-based) for immersive VR basic tasks of selection and navigation. An experiment was conducted using the Virtual Musem as scenario; the Wiimote was used as representative of a typical low cost/ easy to setup controller-based interaction; the tablet used was a Nexus 7. The interaction techniques for selection and navigation were selected after an exploratory user study. The tasks included in the experiment represent typical tasks of the Museum scenario.

4.1. Interaction and tasks

The following selection and navigation techniques and tasks were used with the tablet and the controller:

Selection: Participants had first to select a predefined item in the virtual museum (e.g. a portrait on the wall). With the Wiimote, selection is performed by looking at the portrait (gaze input) and pressing the A button (Figure 5-left). In tablet interaction, users indicate selection by putting the virtual tablet in front of the desired item and pressing a select button available in the tablet screen (Figure 5-right). In a second stage, participants were asked to select two options on the menu presented after selection: first the Biography option, return to the initial menu, and then the Location option. The menu navigation with Wiimote was performed using the up/down keys of the directional pad and the A button for selection, whereas direct manipulation was possible in the tablet: users simply press the desired option in the touch screen (Figure 5-right).

Navigation: participants had to navigate through a series of yellow markers (six in total) on the floor of the virtual room (Figure 6). The participant started the experiment at a given location and needed to move to 6 predefined positions represented by a marker on the floor (yellow square, Figure 6). On reaching a marker, the next marker would appear. The six markers locations were predefined and equal for all the participants. In the controller method the user could navigate using Wiimote's directional pad buttons and gaze.

For the tablet interaction we decided to evaluate two different navigation strategies: one similar to the controller using a virtual joystick and one that could benefit from the device touchscreen by providing teleportation capabilities (that may benefit from the display of a 2D map on the touch screen) although this interaction was not possible to replicate with the controller. Both tablet methods use a map of the room displayed in the upper part of the screen (white area in the second and third images in Figure 6). The map displays the location of the next marker (represented by a yellow square) as well as the user current location of the user in the room (represented by a red square). Users can move in the environment with the tablet using the lower part of the screen (grey area in Figure 6) as a virtual joystick (the position of the finger indicates the direction of the movement). An alternative consisted in a teleport mechanism where the user can select any location in the museum room to be teleported to by clicking on the map area. In the teleport technique the lower part of the mobile screen displays a grey area as in the tablet-mode (visible in the lower part of the mobile screen in Figure 6-right) where the user may use the virtual joystick as in the first mechanism.

Figure 5: Selection phase. On the left: Menu interaction when using the Wiimote. On the right: Menu interaction when using the tablet.

Figure 6: Navigation phase: On the left: Wiimote mode. On the center: tablet mode. On the right: tablet with Teleport mode.

4.2. Experimental design

The experiment followed a within-subjects design with two experimental conditions: controller-based interaction and tablet-based interaction and was composed of two phases: selection and navigation. In both phases the participants performed the tasks with both experimental conditions.

We considered the interaction method as the independent variable (with two levels: Wiimote and Nexus 7). The following dependent variables were automatically logged during the process:

Selection

1. Portrait selection errors: number of errors when selecting a portrait.
2. Menu selection errors: number of errors when selecting a menu option.
3. Task completion time (seconds): time taken to perform the whole selection task.

Navigation

1. Marker time (seconds): time taken to reach each marker.
2. Task completion time (seconds): time taken to travel the specified route through all 6 markers.

At the beginning of the experiment, each participant was briefed about the equipment and the selection and navigation phases. The selection and navigation tasks were performed sequentially, meaning that each participant performed 5 different tasks: selection with Controller (1) and Tablet (2), and navigation with Controller (3), Tablet (4) and Tablet with Teleport (5). To mitigate learning or fatigue effects the order of the conditions was randomized among participants.

In the follow-up phase, participants were asked to fill an online questionnaire with demographic data as well as preferences and opinion related to the usage of the controller and the tablet while performing the tasks, thus complementing the times and errors allowing a better assessment of the usability.

4.3. Results

A total of 43 students (aged from 19 to 24 years) from our Department participated in the experiment and 34 (30 males / 4 females) completed the questionnaire. Most participants (26 out of 34) use a smartphone or tablet device regularly and 11 had never experienced VR before.

Selection: Figure 7 presents the box plots corresponding to the selection times with both conditions: Controller and Tablet. It is to be noted that a few participants were considered as outliers since they performed significantly worse due to some tablet tracking issues. While the mean selection times were slightly higher with the Tablet, a pairwise T-test did not reject the equality of means (p=0.08), and thus the difference observed between the two conditions is not significant.

Regarding errors, both methods had a similar number of portrait and menu selection errors since most of the subjects completed this stage without any selection errors in both conditions (the average number of selection errors was below 1 with both methods).

Navigation: Figure 8 presents the mean task completion times for the three conditions: Controller, Tablet and Tablet with Teleport. The Controller task completion time was on average lower than with the other two methods. However, it is interesting to note that the fastest completion times were achieved with tablet methods (23 seconds for the Tablet and 10 seconds for the Tablet with Teleport) when compared with the Controller (31 seconds).

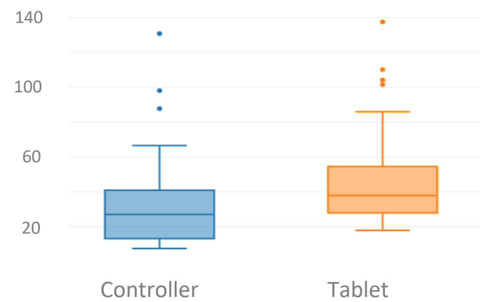

Figure 7: Box plots of the selection task completion time considering the interaction device used. The outliers are marked as individual dots.

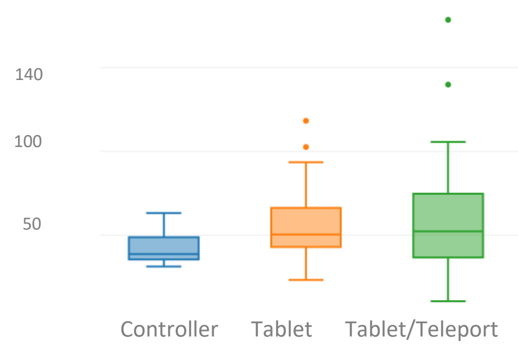

Figure 8: Box plots of the navigation task completion time considering the device and navigation method used. The outliers are marked as individual dots.

The mean completion times for the thee methods were considered significantly different by an ANOVA: F(2,80)=13.21, p_value=0.001. Partial Eta squared=0.248 representing a large effect (i.e. confidence in the statistical result).

Pairwise comparisons adjusted according to the Bonferroni method detected significant differences between Controller and Tablet (p_value=0.000) as well as Controller and Tablet with Teleport (p_value=0.002); no significant difference was detected between Tablet and Tablet with Teleport.

We also analyzed the evolution of the navigation times between markers. Since the tablet-based interaction is affected by tracking errors which caused outliers, we used median times to reduce the effect from outliers. Table 1 shows that there is a clear trend of decreasing the difference between the times obtained with the controller and the times obtained with the two tablet navigation methods. This reduction is particularly significant between marker 0 and marker 1 (with a clear reduction of the relative change to the controller for the tablet conditions) but keeps decreasing in the following markers with the tablet with teleport being the fastest method in two cases (markers 2 and 4).

Questionnaire

Table 2 presents a summary of the questionnaire regarding selection. Answers to questions 2 to 4 ("It was easy to perform the selection task"; "This selection method is intuitive"; "This selection method requires training") were given in a 5-livel Likert-like scale. It appears that the controller was the preferred and most intuitive method for the selection task and the participants felt they would need additional training to use the tablet selection.

Table 3 presents the results of the questionnaire for the navigation task. Even though the results for the controller are overall better than the other methods the participants still preferred the Tablet with Teleport (15) with the Tablet method having a similar preference to the controller (10 and 11).

Analyzing the less preferred method, Tablet with Teleport was selected only by 6 participants, while the Controller and the Tablet were each selected by 14 participants as the less preferred. Several participants justified that although the teleport mechanism requires some training, it allows an advanced user to move faster. This shows that the tablet interaction can provide interesting and faster ways to move than using controllers as the Wiimote. The ability to easily show information like a map with relevant locations of the virtual environment and without obstructing the view of the user is a potential advantage of the tablet methods. It is also noteworthy that the teleport mechanism was tested in a small virtual room and already showed in some cases better results than the other methods. This suggests that using the Tablet with Teleport method would be even more advantageous in larger and more complex VEs although disorientation issues might be considered and studied in such a case.

Table 1: Median times between each marker considering the Navigation Task.

Marker ID	Distance to Marker (m)	Controller median time (s)	Tablet median time (s) [Relative change to Controller]	Tablet with Teleport median time (s) [Relative change to Controller]
0	6.45	3.5	6.8 [96%]	8.1 [131%]
1	11.40	4.8	7.1 [48%]	8.1 [68%]
2	17.1	8.9	11.9 [33%]	8.7 [-2%]
3	15.5	6.7	8.2 [22%]	7.8 [16%]
4	16.7	7.2	8.5 [18%]	6.7 [-7%]
5	16.0	7.1	8.6 [21%]	7.5 [5%]

Table 2: Summary of the questionnaire answers for the Selection Task. The answers to questions 2 to 5 were given in a 5- level Likert-like scale.

ID	Question (scale)	Controller	Tablet
1	Preferred mode (nº of users)	21	13
2	It was easy to perform the selection task.	5	2
3	This selection method is intuitive.	5	2
4	This selection method requires training.	3	4

1 Strongly Disagree, 5 Strongly Agree

Table 3: Summary of the questionnaire answers for the Navigation Task. The answers to questions 2 to 5 were given in a 5- level Likert-like scale.

ID	Question (scale)	Controller	Tablet	Tablet with Teleport
1	Preferred mode (nº of users)	11	10	15
2	It was easy to move to the desired position.	5	4	4
3	This navigation method was intuitive.	5	4	4
4	This navigation method requires training.	1.5	3	3

1 Strongly Disagree, 5 Strongly Agree

4. DISCUSSION

The Virtual Museum Application was used as testbed to perform a study comparing controller-based (Wiimote) and tablet-based interaction for selection and navigation tasks. The study presents some limitations since we are mixing different devices and interaction methods (for example the teleport was not implemented in the controller-based navigation). We also had issues with the tracking of the tablet (with Vuforia) and the users' hands (with Leap Motion) that might be solved with next generations of hardware. Still, the results show that users were able to perform selection and navigation tasks with the mobile device in a VE. The results also suggest that using this kind of devices might require additional training when compared with controller-based methods.

5. CONCLUSION AND FUTURE WORK

In this paper we explored the use of tablets as interaction devices in immersive Virtual Reality systems and how they compare to controller-based interaction. The literature already suggests that mobile devices present several advantages over 3D controllers. We developed a fully immersive VR system allowing both controller and tablet-based interaction. The system provided an easy way to configure a VE linked to virtual content (videos, images and text information) through XML configuration files.

One of the challenges of the work was the tracking of the tablet devices. Several methods were considered and experimented: 6 DOF magnetic tracking device (WinTracker III), Vuforia SDK, Leap Motion sensor and Google Tango. The method based on the Vuforia SDK was selected since it does not require any additional hardware (besides the AR marker placed on the HMD) and offers a reasonable tracking capability. To evaluate the system a Virtual Museum prototype was developed allowing explore a virtual replica of an existing room in the museum of Aveiro and interact with additional contents for the portraits displayed at that room.

The performed study suggests that tablet interaction, successful in the real world, somewhat seems equal or even better in terms of how quickly the action is performed compared to controllers. One significant advantage of mobile devices in the possibility to present useful information about virtual contents without reducing or obstructing the user's field of view.

Future work should focus on optimizing the tracking of the tablet and the hands to consequently improve the performance of the tablet-based interactions. Another possible line of work is to explore the use of mobile devices to perform manipulation in 3D. The effect of having a virtual representation of the user's body in an immersive VE is yet another area that needs further investigation.

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