Non-Visual Locomotion Techniques for Mobile Virtual Environments

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ABSTRACT
It has already been established by numerous studies that blind individuals can greatly benefit from virtual reality for additional sensory information input for navigating unknown environments. However, for a fully beneficial experience, efficient and natural locomotion techniques must be implemented. Although this field has been thoroughly studied, there is a lack of research regarding non-visual locomotion in mobile virtual reality. We attempt to fill this gap by designing and implementing three different techniques for non-visual locomotion, a virtual D-Pad, a virtual D-Pad with physically-aware orientation and a tilt-to-walk physically aware technique. Our goal is to determine how physical orientation and different inputs (3D gesture versus touch input) influence user's navigational efficiency in virtual reality. For this purpose, we conducted an exploration and navigation evaluation for each technique which showed no significant differences in the performances of each technique despite a significant number of participants preferring the Directional D-Pad with physically-aware orientation. After reviewing participants feedback we conclude that our results are not decisive and were influenced by the simplicity of the evaluation's virtual environment.

Keywords
Blind, Locomotion, Virtual Reality, Smartphone.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous; See http://acm.org/about/class/1998 for the full list of ACM classifiers. This section is required.

INTRODUCTION
Spatial orientation and navigation is the result of a combination of sensory and cognitive skills in which we form a mental mapping of our surrounding environment based on the information that our sensory channels provide us [6]. Most of the information of our surroundings comes primarily from the visual channel. People that are blind lack this information and therefore rely on compensatory channels to fill the gaps of information caused by the absence of sight. Unfortunately, even with compensatory channels, navigation in unknown environments by blind people can be as difficult as it is unsafe often leading to injury or loss of possessions. For years, the primary aids for blind people have been the white cane and the guide dog but recent advances [18] and studies in virtual reality provide us with evidence that blind people can benefit from a virtual environment to gather sensory information and create an accurate mental mapping of an unknown environment in a safe and reliable way by using 3D sound as well as haptic information [7].

However, in mobile contexts virtual navigation and locomotion can become problematic. If the means of navigation and locomotion do not effectively transmit a natural sense of motion, then the exploration as well as the mental mapping of the virtual environment are compromised due to cognitive overload. Presently, the lack of research into non-visual virtual locomotion techniques in mobile contexts, particularly in input techniques, make it difficult to develop efficient virtual mobile navigational aids for blind people.

Therefore, in our work we attempt to fill this gap by designing and implementing 3 non-visual locomotion techniques for mobile virtual reality. We design each technique by considering the approaches presented in our related work research with the goal of providing an immersive virtual experience to blind users. Research into sighted locomotion tells us that physically oriented locomotion approaches offer greater immersion than non-physically oriented approaches for sighted people. However, there are no studies to prove that this is true for blind people, therefore we aim to determine if physically aware characteristics offer greater immersion for blind people. Another of our goals is determining if different input's influence blind people's navigation and exploration performance in mobile virtual reality. And so, our 3 solutions for non-visual locomotion are comprised of a virtual D-Pad, a virtual D-Pad with physically-aware orientation and a tilt-to-walk physically aware technique.

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RELATED WORK

Several works have been developed regarding virtual reality for blind people. These works usually focus on adapting virtual worlds, that did not have blind people as their target users, by providing accessibility features. Other works, on the other hand, provide some interesting approaches and solutions that attempt to combine virtual reality with other technologies in order to support blind people in collecting spatial information about unknown environments.

In this section, we discuss previous work concerning these approaches as well as other approaches for visual virtual locomotion.

Adapted Virtual Worlds

Nowadays virtual worlds are used in a wide variety of fields such as gaming, communication and education by allowing users to explore and navigate an emulated environment. The representation of this environment is done by conveying information to the user's senses, with visual rendering being the primary method to communicate the state of the virtual world. In nearly all approaches, haptic and audio communication are mostly used as a secondary method to complement the visual information provided by the virtual world.

However, although virtual worlds were inaccessible to the blind community for a long time, recently developed virtual worlds are being released with a set of accessibility options that enable visually handicapped individuals to enjoy a virtual reality experience.

Accessible navigation and movement in a virtual world is a troublesome topic when working on making virtual worlds accessible to blind people. Most virtual worlds depend on visual cues for effective movement and orientation throughout the virtual environment such as looking at the user's objectives at distance. Due to the absence of vision in blind individuals it becomes difficult to give them a sense of movement in a virtual world while also maintaining their orientation when navigating towards their objective.

In the work performed in PowerUp by Trewin & Cavender [15], a keyboard approach was adopted with the arrow keys controlling the orientation and the WASD keys controlling the movement of the avatar. But for a more effective navigation simply controlling the avatar through the keyboard was not enough so a controlled walk function (Ctrl+W) was implemented in which the player's avatar keeps its target objective in focus (focused through the find function) while walking towards it. In order to give a sense of movement to the blind user footstep sounds were added during the walk and audio feedback when an event causes the controlled walk to end such as arriving at the target objective or bumping into other players.

In Terraformers [17], a simpler approach for movement and navigation was used with the ASWD keys being used for avatar movement and the numeric keyboard for avatar direct orientation in 8 directions with numeric key ”2” being assigned to the north direction. Again, footsteps sounds were provided for giving a sense of movement to the users while navigating the virtual space. The users were also supplied with a 3D sound sonar for a rough perception of the distance to objects in front of them, and a 3D sound compass for orientation in the virtual space. The success with this simpler approach was probably due to the several tools available to the users, which focused on the representation of the virtual space, that supplied enough information for efficient navigation of the virtual environment.

While these approaches make use of sound output mechanisms such as 3D sound sonars and spatial sounds in order to distinguish a limited number of objects, in most virtual worlds these approaches do not scale well due to the large number of objects and avatars such as the case of the Second Life virtual world. Therefore, more scalable approaches have also been developed such as TextSL[5], a command-based virtual world interface that works with Second Life by using synthesized speech. When using TextSL, blind users interact with the virtual world solely using written text to query about the state of the virtual environment.

Navigation using TextSL can be achieved by using the arrow keys but this approach comes with the inconvenience and time-wasting task of finding a path that is not obstructed, even with TextSL notifying the user every time a collision occurs. Although users can always circumnavigate obstacles using the arrow keys and the feedback provided, TextSL also provides a module that enables collision free navigation where the blind user can just make use of a written “move” command, for example “move north 100”, for TextSL to plot a collision free route to the objective.

These works in blind accessibility of visual virtual worlds provide us with some ideas for accurate and easy to use virtual locomotion approaches, such as the PowerUp controlled walk and the powerful but typing intensive TextSL interface.

Virtual Reality Approaches for Blind Navigation and Exploration

Under the assumption that by supplying enough compensatory perceptual information about an environment could provide the means for an effective acquaintance of an unknown environment by people who are blind, virtual reality approaches for blind people's navigation and exploration have been increasingly studied and explored. These approaches divide themselves in navigational preplanning aids and in-situ aids.

Preplanning aids for unknown environment exploration and navigation offer the blind user the possibility of acquiring spatial information about an environment prior to the arrival at said environment. This approach consists of a safer way of exploration by the blind user although providing a lower spatial information resolution of the environment.

The BlindAid [13] was one of such approaches, which provided a multi-sensory virtual environment (MVE), that attempted to provide information about unknown environments via haptic and auditory stimuli to blind users. The BlindAid system can run on personal computer providing virtual reality environments which blind users can explore with a haptic device and stereo headphones. This approach succeeded in producing a preplanning aid that could be used in rehabilitation of newly sighted individuals but is not scalable enough to make available to the whole blind community.

In-Situ virtual reality aids provide additional spatial information to the blind user while exploring the environment. Most examples of in-situ aids resort to obstacle detectors [11] and embedded sensors in the environment such as Bluetooth Low Energy beacons [1] or Radio Frequency Identification tags [4]. But these blind aids also have some limitations that make them less likely to be used by the blind community. One of the limitations, when using obstacle detectors, corresponds to the fact that while using these aids, the blind user must be the one to gather spatial information about the explored space by a trial and error method which does not improve the blind user's lifestyle since this is much like when he uses the white cane. Another problem with in-situ aids concerns safety of use, for most of these aids make use of sound to convey spatial information to the blind user via earphones which could distract the user from his surroundings giving way for accidents to happen.

MOBILE VIRTUAL LOCOMOTION

Until recent years, virtual reality was mostly associated with the use of expensive and bulky devices which were not normally available to the average consumer [2]. However, currently with the introduction of low-cost virtual reality head mounted displays (HMD), this notion is gradually dying and being replaced with a nomadic-like virtual reality concept where a user is able to use a mainstreamed smartphone adapter such as Google Cardboard or Samsung's Gear VR to transform any smartphone into a head mounted virtual reality display.

Although being innovative, this new approach also comes with some new challenges such as input techniques for task execution in the virtual environment, which becomes harder since the smartphone is located inside the adapter and therefore its touchscreen is unavailable to the user [3]. Virtual locomotion is one of such challenges and it is considered a key aspect that influences virtual reality immersion [10].

One solution for virtual locomotion is the use of smartphone inertial sensors as conduit to provide a sense of semi-natural locomotion. VR-STEP [14], is a walking-in-place implementation that uses the smartphone's accelerometer for step detection. Whenever the accelerometer value passes a certain threshold it detects a possible step. In order to provide a greater sense of immersion and to decrease virtual stopping latency, the authors also implemented stride speed by measuring the time between steps. In their work the authors point out that stopping and starting walk latency present great challenges for providing an immersive and fluid virtual experience.

We find another semi-natural locomotion technique based on the natural walking metaphor in the work of McCullough, Morgan, et al [8] where an arms-swinging method was devised to enable virtual locomotion. The movement of the arms is equal to the one users already perform when walking in a physical environment. For arm movement detection, the authors made use of the Myo armband, a device which has four sensors, a EMG sensor, a three-axis gyroscope, a three-axis accelerometer, and a three-axis magnetometer. Locomotion speed was also implemented which only required the user to swing his arms faster, like in a running motion, to walk faster. The authors evaluated this method by comparing it to the joystick locomotion and real walking approaches in navigation tasks and found that their locomotion technique was superior to the joystick approach and presented similar results to the real walking.

Comparisons between semi -natural and natural locomotion techniques have also been researched. Wilson, et al. [19] conducted a study in order to compare the arm swinging and the walking in place approaches. The authors also found that it would be interesting to compare these 2 approaches with the approach that is considered the best for immersion and spatial awareness in virtual environments which is physical walking. As expected, physical walking returned the best results of the 3 techniques in every aspect evaluated since this technique offers a more immersive experience and therefore the users are naturally comfortable with it. In regards to the other 2 techniques, walking in place was shown to be better than arm swinging in terms of turning error and mean walking latency.

Overall, regarding virtual locomotion the current trend is set on techniques that mimic real world locomotion. The challenge is that these mimicking approaches must aim to be as immersive as possible or they will, very easily, present an inferior navigational performance when compared to low fidelity techniques, such as the joystick approach, or the real walking technique, even though this technique is predicted to always be better than any semi-natural approach [16, 9]. Nevertheless, new approaches should strive to be as immersive as real walking.

NON- VISUAL LOCOMOTION TECHNIQUES

As we can see, most solutions that use virtual reality for blind user's navigation and exploration of unknown environments are based on non-mobile hardware. Also, most virtual locomotion solutions are aimed at visually focused virtual worlds and therefore depend on the visual channel which blind people do not have access to. Consequently, non-visual virtual locomotion research in mobile devices has not been explored to its full extent.

In this section, we present our approach for non-visual virtual locomotion in mobile virtual reality., with the goal of finding a virtual locomotion method that blind users can easily use without leading to cognitive overload while providing a good navigation and exploration performance. Therefore, in our work, our objective is to differentiate and evaluate different techniques that can be used for blind user's navigation in mobile virtual reality. And so, we have designed 3 techniques for virtual locomotion in mobile contexts, 2 D-pad based techniques that leverage the device's screen (with and without physically aware orientation) and a tilt-to-walk technique with physically aware orientation (Table 1).

Input / Virtual Orientation	Physically aware orientation	Non-Physically aware orientation
Virtual Input	2-direction D-Pad	Multi-directional D-Pad
3D Gesture Input	2-direction tilt-to-walk	No implementation considered due to limited wrist rotation

Table 1. Our virtual locomotion techniques. A non-physically aware tilt-to-walk is not considered in this study due to its limitations regarding unnatural wrist rotations and virtual movement precision

We make this differentiation in order to study if using the user's physical orientation translates into a more immersive and natural virtual locomotion and if it influences navigational performance. Also, we aimed to compare touch and 3D gesture (tilting gesture) input for virtual locomotion regarding virtual reality immersion and navigational efficiency.

We excluded a non-physically aware orientation approach for the tilt-to-walk technique due to limited wrist rotation [12], which makes it unfeasible to turn the smartphone while providing little precision for the virtual movement.

For the D-Pad technique, we transformed the smartphone's touchscreen into a virtual D-Pad that the user can use to move himself in the virtual environment. For the tilt-to-walk technique we used accelerometer values to translate the forward and backward inclination of the smartphone into virtual movement.

Multi Directional D-Pad

In our non-physically aware orientation design of the D-Pad, the virtual avatar's movement and orientation are fully controlled with a multi directional virtual D-Pad (Left side in Figure 1). The user is able to initiate the D-Pad by placing his finger anywhere on the smartphone's screen which will then be the center of the D-Pad. Then the user needs only to slide his finger in the direction he wants move in to initiate the virtual movement (Right side of Figure 1). To increase the virtual movement speed the user only needs to slide his finger further in the direction he is moving.

In order to provide users with feedback regarding their current movement speed, synchronized footstep 2D sounds are used, which play whenever the user's avatar's feet touch the ground. To stop moving, the user needs to slide his finger back to the neutral position or remove his finger from the smartphone's screen. Note that the user's orientation is always aligned with his movement direction, for example, if the user slides his finger 90 degrees to the right from the direction he was moving in, we update his virtual avatar's orientation to 90 degrees in the right direction as we can see in Figure 1.

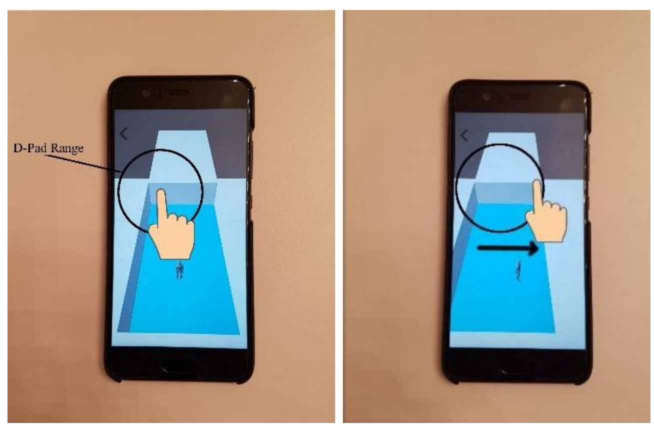

Figure 1. Multi Directional D-Pad.

Physically Aware 2-Directional D-Pad

In order to evaluate the importance of physical orientation in navigation and exploration performance of blind people in virtual environments we designed a physically aware D-Pad.

For this implementation of the D-Pad, we take into account the physical user's orientation (which is measured using the smartphone's gyroscope) and update it in the virtual scene. In this implementation, the virtual avatar's orientation only changes when the smartphone's physical orientation does also. With orientation being physically managed, the D-Pad has only 2 directions, forward and backward movement

(Figure 2). As with the non-physically aware implementation, to initiate the virtual movement the needs to place his finger on the smartphone's screen and slide up or down to move forward or backwards respectively with locomotion speed being determined by how far the user has slid his finger in a given direction. In order to halt his virtual movement, the user has to slide his finger to the neutral position or remove his finger from the smartphone's screen.

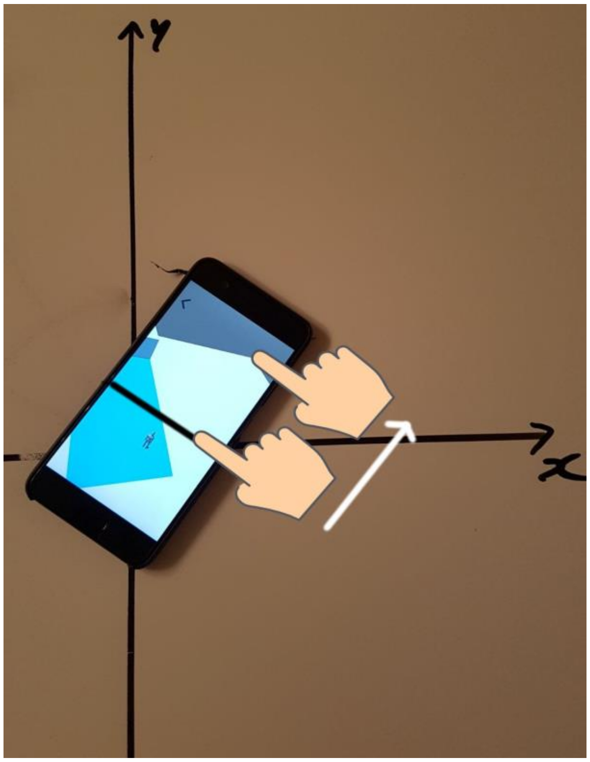

Figure 2. Physically Aware 2 Directional D-Pad. The user places his finger on the screen and slides forward or backwards to initiate virtual movement.

2-Directional Tilt-to-Walk

To also compare the influence that different inputs provide regarding virtual reality immersion and navigation efficiency, we designed a Tilt-To-Walk technique for comparing touch input with 3D gesture input.

Similarly to the physically aware implementation of the D-Pad technique, in our Tilt-to-Walk implementation, the virtual avatar's orientation is determined by the smartphone's physical orientation. However, instead of using the screen to obtain input for virtual movement, we use the smartphone's accelerometer to determine the angle of inclination between the smartphone and the floor and we use those values to determine the direction and magnitude of the virtual movement.

In this technique, to remain stationary the user needs to keep the smartphone in an angle between 30 and 60 degrees with the floor (Figure 3). To initiate the virtual movement the user needs only to tilt the device in an angle of less than 30 degrees (for forward movement) or in an angle of more than 60 degrees (for backward movement). These threshold values for remaining stationary were determined by conducting preliminary tests with the goal of finding a comfortable angle range to hold the smartphone device.

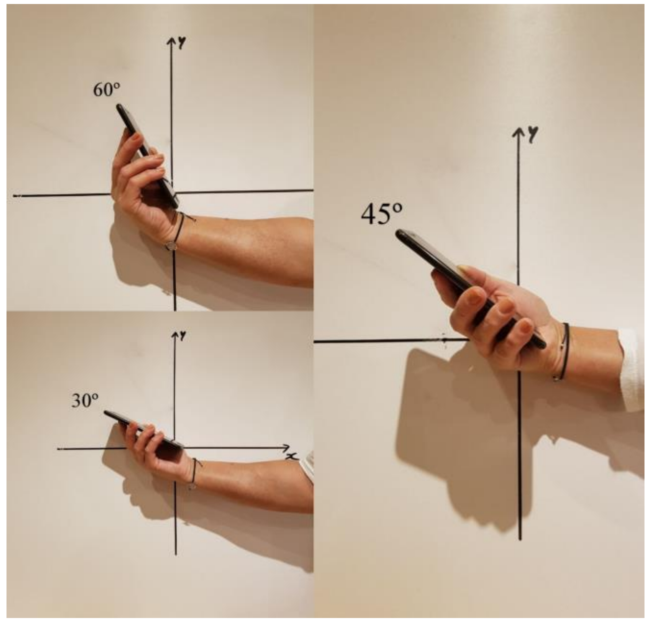

Figure 3. Neutral position's tilt angle (45º) and virtual locomotion thresholds (30º and 60º).

Increasing the tilting angle will also increase the virtual movement’s speed. The max speed is reached at 0 degrees for forward movement and at 90 degrees for backward movement (Figure \ref{fig:maxSpeed}).

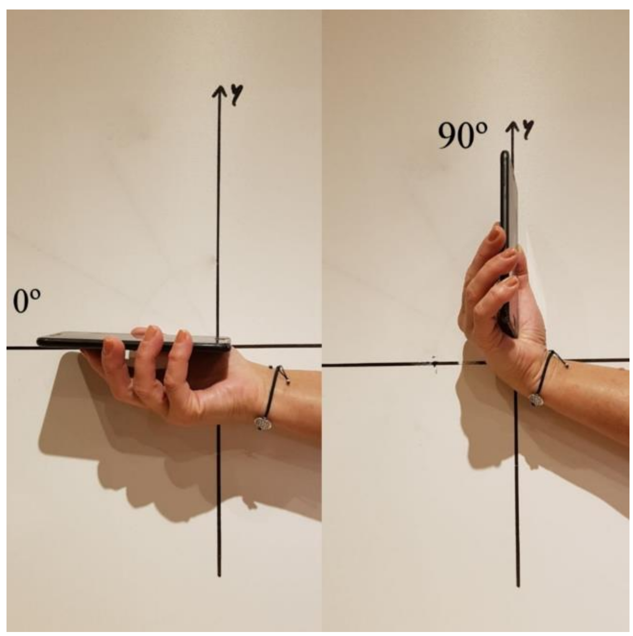

Figure 4. Tilt angles for max locomotion speed.

PROTOTYPE VIRTUAL ENVIRONMENT

In order to conduct user tests with each technique we implemented a mobile application using the Unity Game Engine. Our mobile application renders 6 virtual scenes and provides spatialized audio and haptic feedback to the user while using each technique. We make use of the 3D sound engine as well as the cross-platform libraries included in Unity to provide the spatial audio and haptic feedback.

We make use of Unity's standard assets package of which we import a Third Person Character prefab, audio clips for footstep sounds and Mobile Single Stick Controller prefab. The Third Person Character prefab serves as our user's avatar when using the mobile application and the Cross Platform Mobile Single Stick Controller serves an interface to provide our character and environment scripts with touch input from the user.

We use cross-platform libraries to register input provided by the user via smartphone such as finger touch positions and number of fingers on screen as well as the smartphone's gyroscope and accelerometer values to pass onto each of our techniques scripts.

Each virtual scene is composed of 3 elements, a Structures game object which contains all of the wall objects of the scene, a Third Person Character which serves as the user's avatar in the virtual scene and a Canvas object that is used as an interface to retrieve touch input from the device.

In this section, we go into detail about the characteristics of our virtual environment’s sensory feedback.

Haptic Feedback

To provide the user with a better sense of direction and orientation we added a simple compass with haptic feedback to our techniques similar to the Terraformers approach [10]. We implemented the compass so that when the user is aligned with one of the cardinal points (North, South, East and West) the smartphone will produce a short vibration to inform the user of his orientation. Note that these cardinal points are calculated locally and therefore correspond to the cardinal points of the virtual scene, which are the X-Y axis, and not the real world's.

For the Multi Directional D-Pad, due to its non-physically aware behaviour, we implemented the compass by producing the vibration whenever the Third Person Character is moving in one of the cardinal directions.

For the Physically Aware techniques, we use the gyroscope values to find the rotation angle between the smartphone's orientation and the Y axis. For each frame, we store the previous and current rotation angle and use the Cosine and Sin functions to determine the quadrants of each angle. In the case that the angle's quadrants differ, we emit a vibration to inform the user that his rotation is aligned with one of the cardinal points.

In order to prevent cognitive overload from successive vibrations when aligned with one of the cardinal points, we created a flag that requires the user to make a 35 degrees deviation from the cardinal point before allowing another vibration to occur upon alignment with that same cardinal point.

Audio Feedback

Audio feedback is a key component for providing spatial information to blind people. However, if too much audio feedback is provided, the cognitive load increases and it becomes increasingly difficult to form an accurate spatial map. For these reasons, we opted for a simplistic approach for the audio feedback provide in by our implementations.

In order to effectively transmit a natural sense of motion, we added 2D footstep sounds to each of our techniques. However, instead of simply playing the sounds at a continuous rate, we synchronized 4 AudioClip objects of footstep sounds with the Third Person Character of Unity's standard assets using animation events. By doing this we make sure that the user only hears a footstep sound when his avatar has certainly taken a step forward.

We also provide 3D spatial sounds for our collisions to provide users with audio cues about the position of the obstacle they collided with. For this, we attached AudioSource objects with a simple knock AudioClip to the wall objects of our virtual scenes. We defined the AudioSource component with a 3D spatial blend. We also added a script to our Third Person Character which checks for a collision every frame and plays those sounds whenever a collision occurs between the Third Person Character and a wall object.

EVALUATION

For evaluating our implementations, we decided on conducting user tests using our prototype mobile application. In order to evaluate the exploration and navigation performance provided by each technique when used by blind people in virtual reality, our user testing was comprised of 2 phases, an exploration phase and a navigation phase.

Apparatus

For the evaluation process, we used a Huawei P10 smartphone as the running device for our mobile testing application with our techniques's implementations. As an audio listener we provided users with a Sony ZX220BT Wireless Headphones. We decided on these Bluetooth headphones for commodity of our participants, allowing them to focus on the virtual task while having a better sound feedback from our application and a better isolation from possible outside distractions.

We also provided participants with different tactile maps. The tactile maps 1, 5 and 7 in Figure 5, correspond to the 3 virtual exploration scenes and one of them was presented to each participant, along with 3 other wrong tactile maps, upon completion of each exploration task to evaluate the participant's mental mapping of the area explored.

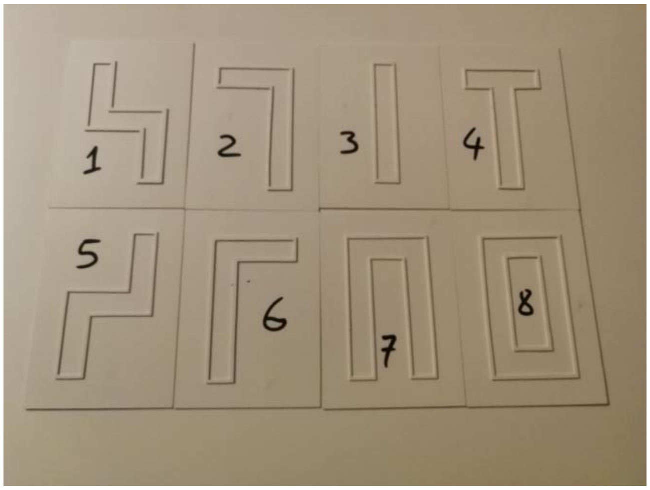

Figure 5. Tactile Maps for the Exploration Evaluation.

Participants

Our study was comprised with a total of 10 participants, 6 males and 4 females, with ages ranging from 25 to 58 years old (M = 50,1; SD = 10,5). Of the 10 participants, 7 were introduced to us by the Raquel and Martin Sain Foundation.

All 10 participants reported using mobile phones on a daily basis, with 5 participants (4 males, 1 female) owning a smartphone. All 5 participants that reported having a smartphone, used them for calling purposes. Of those 5 participants, 4 used them for messaging purposes with 3 of them using other convenience applications such the calculator or the alarm clock. Only 1 of the participants that owned a smartphone used social media.

Of all 10 participants, only 2 participants reported to understanding and having had prior experience with virtual reality.

Measures

For each phase of our evaluation we gathered several metrics from log files provided by our mobile application prototype.

For the exploration phase, we report the number of long (< 10 seconds) and short (4 – 10 seconds) pauses [7], total task duration and distance covered. Ultimately, we report the results of an evaluation of the mental mapping provided by each technique through tactile map selection.

For the navigational phase, we report the total task duration, number of collisions and the relation between optimal distance and the distance covered by each participant.

Procedure

For our evaluation procedure, we began each session with a simple introduction followed by a few profiling questions for the participant. After which, we talked to the participant about the goal of the session and explained the virtual environment and feedback that would be provided in our prototype application (audio and haptic feedback).

Participants were presented with the first technique and explained its functionalities before beginning a 5-minute training session, in a simple rectangular virtual room, to allow the user to familiarize himself with the locomotion technique. In order not to favour any technique by the order they were presented, we established a semi-randomized presentation order for each participant which was decided prior to the beginning of the session. After concluding the 5-minute training session, we then proceeded to conduct an exploration evaluation followed by a navigational evaluation. Upon completion of the 2 evaluations we moved on to the next technique's training and evaluations.

For the exploration evaluation, participants had a 7 minute of free exploration of a virtual scene composed of 3 straight corridors (with the same length). At the end of exploration session, participants were presented with 4 tactile maps and asked if any one of the presented tactile maps corresponded to the virtual scene explored (the option "None of the 4" was also allowed)

The navigation evaluation took place after the exploration evaluation. This evaluation was composed by 2 virtual scenes, both with a straight corridor, one containing an obstacle in the center and another with a unobstructed straight path.

For this evaluation, participants were asked to try and reach the end of the corridor in front of him, circumnavigating around any possible obstacles. For this task we set a time limit of 5 minutes.

At the end of the session, we inquired participants regarding their technique preference as well as to classify each technique in relation to the difficulty they provided in the completion of the tasks using a 7-point Likert scale. We also asked each participant about any critic or suggestion regarding the techniques as well as the virtual environment provided.

RESULTS

Using the information gathered from our log files we analyzed the results produced from both the navigation and exploration evaluations.

We divide the analysis of these results into exploration tasks, navigation task and user feedback analysis.

Exploration Evaluation

In order to determine if there were significant differences between technique implementations regarding exploration time and distance travelled needed to form a spatial mapping of a virtual scene, we analyzed the total task duration and distance covered with each implementation during the exploration tasks.

Our results showed that our participants had a mean average of 303.5 seconds (SD = 79.9) when using the Multi directional D-Pad implementation, 262.4 seconds (SD = 121.5) when using the 2 directional D-Pad implementation and 319.9 seconds (SD = 147.9) when using the Tilt-To-

Walk implementation. We conducted a Shappiro-Wilk normality test, which showed us that our sample had a normal distribution. After which, we conducted a Repeated-Measures ANOVA test to determine if there were any significant differences between each implementation. Results of the ANOVA test showed that differences between each implementation's mean average exploration time were not significant ($F(2,18) = 0.689$, $p = 0.515$).

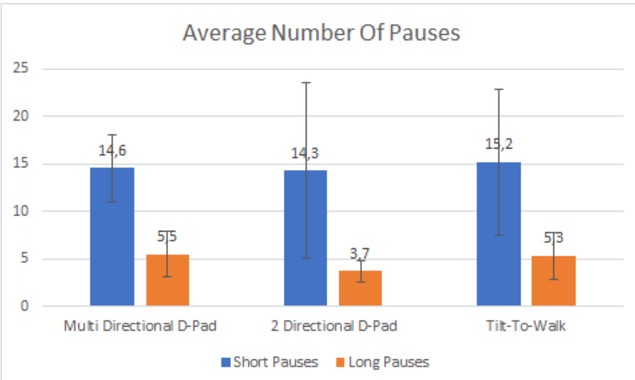

Figure 6. Average Number of Pauses of Exploration Tasks. Error bars denote 95% confidence intervals.

Regarding distance covered, our results showed a mean average of 854.5 meters (SD = 381.9), 933.5 meters (SD = 606.7) and 958.7 meters (SD = 561.8) for participants using the Multi Directional D-Pad, the 2 Directional D-Pad and Tilt-To-Walk implementations, respectively. We again performed a Shappiro-Wilk normality test which classified our sample with a normal distribution. Followed by an ANOVA test which lead us again to conclude that no statistical significant differences were found between the mean average distanced travelled between each implementation ($F(2,18) = 0.097$, $p = 0.908$).

To evaluate the cognitive overload of each implementation we recorded and analyzed the number of pauses that participants made during the exploration tasks. We divided pauses into 2 categories, short pauses (4-10 seconds) for technical adjustments, and long pauses (more than 10 seconds) supposedly for cognitive processing[7].

Regarding short pauses, results showed that participants made a mean average of 14.6 short pauses (SD = 4.9) when using the Multi directional D-Pad implementation, 14.3 (SD = 12.9) when using the 2-directional D-Pad implementation and 15.2 (SD = 10.8) when using the Tilt-To-Walk implementation (Figure 6). Upon conducting a Shappiro-Wilk normality test, we learned that our sample for short pauses had a normal distribution. After conducting a Repeated-Measures ANOVA test, we determined that there were no significant differences between the mean average of short pauses for each implementation ($F(2,18) = 0.034$, $p = 0.966$).

For our sample of long pauses, our results showed an average of 5.5 long pauses (SD = 3.3) when using the Multi directional D-Pad implementation, 3.7 (SD= 1.6) when using the 2-directional D-Pad implementation and 5.3 (SD = 3.4) when using the Tilt-To-Walk implementation (Figure 6). A Shappiro-Wilk test followed by a Repeated-Measures ANOVA test, also determined that there were no significant differences between the mean average of long pauses across all implementations ($F(2,18) = 1.454$, $p = 0.260$).

These results lead us to assume that there were no significant differences regarding the cognitive load of each implementation.

To determine the accuracy of each implementation in providing a correct mental mapping of the virtual scene upon exploration, we evaluated participant's using tactile maps. Our evaluation showed that 30%, 70% and 50% while using the Multi Directional D-Pad, the 2 Directional D-Pad and Tilt-To-Walk implementations, respectively (Figure 7). A Cochran's Q test was used to determine if there was a statistically significant difference between each implementation's results. The results of the test showed no statistically significant difference in the proportion of participants that chose the tactile map correctly while using each implementation ($\chi^2(2) = 3.000$, $p = 0.223$), however our results show a clear tendency for the 2 Directional D-Pad producing better results in exploration tasks.

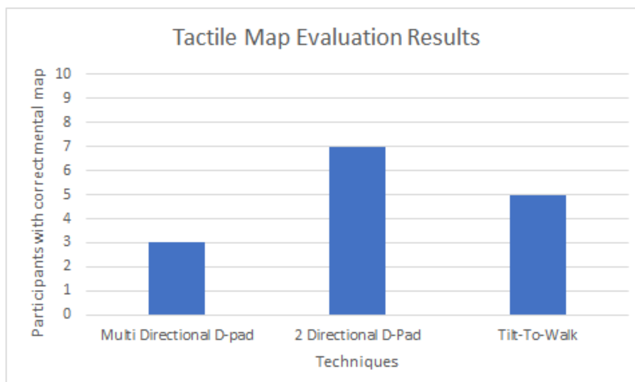

Figure 7. Tactile Map Evaluation of Exploration Tasks.

Navigation Evaluation

For the navigation evaluation, we recorded the total task duration and distance metrics to help us determine the efficiency of each technique when performing simple navigational tasks.

For the total task duration, our results showed that the mean average time for participants to complete the first navigational task was of 17.3 seconds (SD = 17.6) when using the Multi directional D-Pad implementation, 10.8 seconds (SD = 9.5) when using the 2 directional D-Pad implementation and 7.3 seconds (SD = 4.7) when using the Tilt-To-Walk implementation. A Shappiro-Wilk test determined our sample did not have a normal distribution. Upon learning this, we conducted a Friedman test, which concluded that there were no statistically significant differences between implementations regarding the mean average completion time of the first navigational task (χ^2(2) = 3.935, p = 0.140).

For the second navigation task, our results showed a mean average completion time of 69.7 seconds (SD = 43.5), 97.9 seconds (SD= 63.4) and 101.2 seconds (SD = 75.6) when using the Multi Directional D-Pad, the 2 Directional D-Pad and Tilt-To-Walk implementations, respectively. However, despite the Multi Directional D-Pad having a shorter mean time, we found no statistically significant differences between each implementation's mean average completion time for the second navigational task (F(2,18) = 0.840, p = 0.448).

Regarding the distance covered by each of the participants during both navigation tasks, we decided to compare the relation between the optimal distance and the distance covered by participants upon completion of navigational tasks with each implementation.

Since the first navigation task consists of an open corridor we aimed to evaluate the steering performance of each implementation when moving forward. For the first navigation task, our results showed a mean average of 1.28 (SD = 0.5) for the Multi directional D-Pad implementation, 1.05 (SD = 0.1) when using the 2-directional D-Pad implementation and 1.03 (SD = 0,1) when using the Tilt-To-Walk implementation (Figure 8). With these results we see that, on average, the physically aware implementations provided a better steering than the Multi Directional D-Pad due to their mean averages being closer to 1. However, after conducting a Friedman test we learned that there were no statistically significant differences between the mean averages between implementations (χ ^2(2) = 1.600, p = 0.449).

For the second navigation task, the relation between optimal distance and the distance served to evaluate each implementation regarding the navigational ease in circumnavigating obstacles. Our results showed a mean average of 2.61 (SD = 1.7), 3.02 (SD = 1.6) and 2.99 (SD = 2.8) for the Multi Directional D-Pad, the 2 Directional D-Pad and Tilt-To-Walk implementations, respectively (Figure 8). As we can see, in the task of circumventing obstacles, the physically aware implementations, results show that, on average, participants covered 3 times more distance than the optimal to reach the objective. In order to determine if these results were significant, we conducted a Friedman test, which concluded that the differences between the averages of each implementations where not statistically significant (χ ^2(2) = 0.200, p = 0.905).

To determine if there were significant differences between techniques regarding the avoidance of obstacles, we also measured the number of collisions that participants made during each navigation task.

For the first navigation task, our results showed an average of 1.6 collisions (SD = 2.7), 0.2 collisions (SD = 0.6) and 0.7 (SD = 1.6) for the Multi Directional D-Pad, the 2 Directional D-Pad and Tilt-To-Walk implementations, respectively. A statistical analysis conducted using Shappiro-Wilk test followed by a Friedman test concluded that there were no statistically significant differences between the mean collision average for each technique in the first navigational task (χ ^2(2) = 2.941, p = 0.230).

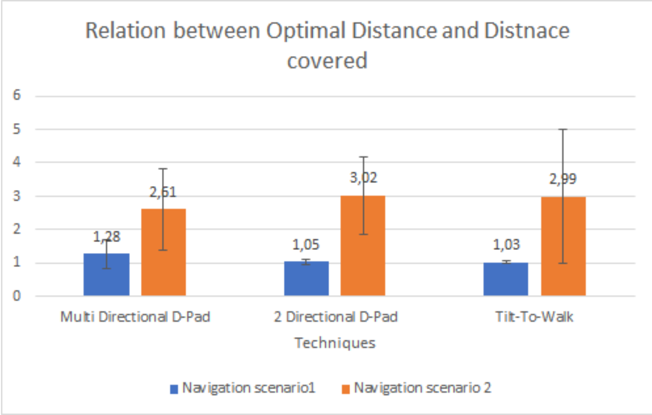

Figure 8. Relation between Optimal Distance and Distance Covered. Values closer to 1 show better navigational performance. Error bars denote 95% confidence intervals

In the second navigation task, involving the circumnavigation of an obstacle, results showed an average of 13.6 collisions (SD = 8.5) for the Multi directional D-Pad, 11.7 collisions (SD = 7.2) for the 2 directional D-Pad and 11.8 (SD = 10.9) for the Tilt-To-Walk implementation. However, results from a Friedman test determined that there was again no statistically significant difference between the mean collision average for each technique in this navigational task either (χ ^2(2) = 0.800, p = 0.670).

Overall, we were unable to statistically prove if any implementation surpasses the other 2 in terms of navigation performance.

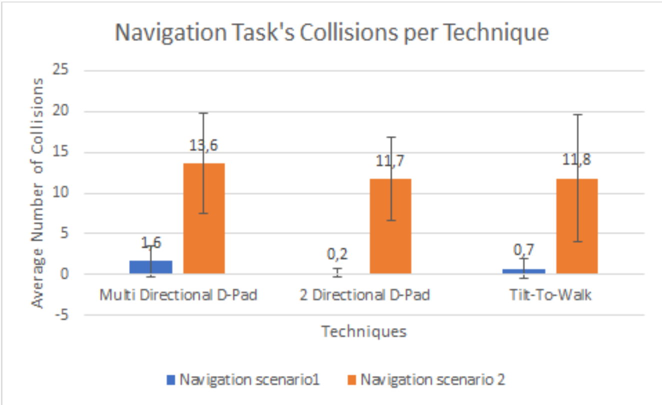

Figure 9. Number of collisions per Technique During Navigation Tasks. Error bars denote 95% confidence intervals.

Participant Feedback

We asked users to rate each implementation on 7-point Likert scale based on the difficulty or ease that each technique provided when conducting both exploration and navigation tasks. In this Likert Scale we considered 1 point as the task being near impossible to complete and 7 points as the task being trivial.

Participants agreed that the 2 Directional D-Pad implementation (Median = 6, IQR = 3.25) helped them perform the navigation and exploration tasks more efficiently than the Multi Directional D-Pad implementation (Median = 4 , IQR = 2.25) and the Tilt-To-Walk ((Median = 5 , IQR = 2.25)). To determine the statistical relevance of these results we applied a Friedman test to the data which determined that there was no statistically significant difference between implementations in regard to the difficulty perceived by the participants when using each implementation.

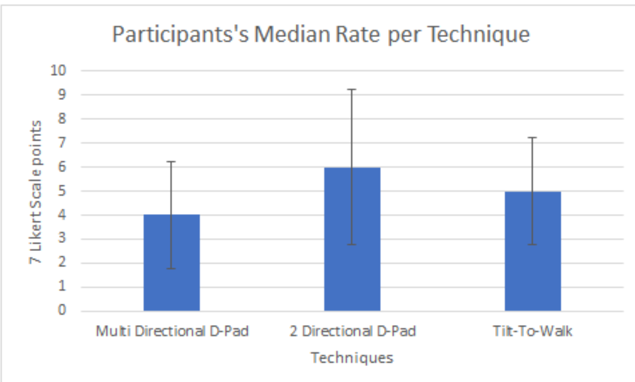

Figure 10. Participants' rating of evaluation tasks' ease per technique. Error bars denote 95% confidence intervals.

However, when asked which technique they would prefer to use in a mobile virtual environment, 70\% of participants chose the 2-Directional D-Pad implementation, 20\% chose the Tilt-to-Walk implementation and 10\% chose the Multi Directional D-Pad implementation. Upon measuring the confidence intervals using a 95\% Adjusted Wald method, we were able to find statistically significant differences between the 2 Directional D-Pad implementation and the other 2 implementations (Lower Interval = 39%, Upper Interval = 89%). We were then able to conclude that the 2-Directional D-Pad technique was significantly preferred over the other 2 implementations.

DISCUSSION

Although, the 2 Directional D-Pad technique had better averages across most metrics, our statistical analysis was unable to find significant differences between the navigation and exploration performances with other techniques. In terms of user feedback, we found a significant preference for the 2 Directional D-Pad across our participants, even though no significant differences were found when participants were asked to rate each technique regarding the ease they provided when completing the tasks. Therefore, with our results, we can only conclude that the 2 Directional D-pad was the most preferred technique among our participants.

Finally, we can only conclude that there are no significant differences in navigational and exploration performance between our 3 implementations when applied in a simplified virtual environment such as the one provided. However, user feedback results suggest that a significant number of participants (8 participants) considered physically aware characteristics crucial to virtual movement. As such, the 2-Directional D-Pad technique was significantly preferred among all 3 techniques by blind people.

CONCLUSION

We have designed and implemented 3 non-visual virtual locomotion techniques. Our aim was to evaluate the influence of physically aware orientation and input method on navigation and exploration performance of blind people in virtual environments. Therefore, our 3 techniques consisted of a Multi Directional D-Pad (Non-Physically Aware with Virtual Input), a 2-Directional D-Pad (Physically Aware with Virtual Input) and a Tilt-To-Walk implementation (Physically Aware with Gesture input).

After conducting exploration and navigation evaluations we found no significant differences between each technique's performance. However, a significant number of participants preferred the 2-Directional D-Pad implementation over the others.

However, these results might have been influenced by a number of factors that we noted upon a crosschecking of results, participant's profile and participant's feedback.

When participants were asked about any suggestions or criticism regarding the techniques, most of their feedback focused mainly on the environment provided by our prototype application. After performing evaluations, 2 out of the 10 participants said that there was a lack of sensory feedback in the virtual environment when they were stationary and suggested that a static spatial sound in one point of the virtual scene could have helped them perform both tasks more easily. Also, 1 participant suggested that the haptic feedback feature be extended to provide feedback upon alignment with intercardinal points also. These suggestions and criticism focus more on the virtual environment provided and less on the actual virtual locomotion techniques. Therefore, further work is needed with these techniques on a richer virtual environment in order to better differentiate each technique.

We also believe that the selection criteria for future work should be refined. In our work we required participants to be totally blind, older than 16 years old, with an onset of blindness of at least 5 years and with no auditory problems. When crosschecking evaluation results with participants' profiles we found that participants who owned a smartphone performed better than the ones that did not own a smartphone. Virtual reality experience also seems to be an important factor. In our evaluation, 8 participants did not have virtual reality experience and therefore performed worse than the other 2 participants that did have experience. So, for future work, we believe that refining the selection criteria, to require participants to be smartphone users, would produce more precise results when comparing locomotion techniques.

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