University of Nevada, Reno

EVALUATION OF HANDSBUSY VERSUS HANDSFREE VIRTUAL LOCOMOTION

A Thesis Submitted in Partial Fulfillment

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by

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ABSTRACT

To navigate beyond the confines of often limited available positional tracking space, virtual reality (VR) users need to switch from natural walking input to a controller-based locomotion technique, such as teleportation or full locomotion. Overloading the hands with navigation functionality has been considered detrimental to performance given that in many VR experiences, such as games, controllers are already used for tasks, such as shooting or interacting with objects. Existing studies have only evaluated virtual locomotion techniques using a single navigation task. This paper reports on the performance, cognitive load demands, usability, presence and VR sickness occurrence of two hands-busy (full locomotion/teleportation) and two hands-free (tilt/walking-in-place) locomotion methods while participants (n=20) performed a bimanual shooting with navigation task. Though handsfree methods offer a higher presence, they don't outperform handsbusy locomotion methods in terms of performance.

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CHAPTER 1

INTRODUCTION

Where moving around freely has been a fundamental appeal of 3D games, facilitating this in VR has remained a topic of active research [6]. Natural walking input using positional tracking on consumer VR platforms offers a high presence [34] while it is not known to cause VR sickness. However, it doesn't let users travel beyond the confines of often limited available tracking space. To navigate larger distances, users must switch to an artificial locomotion technique (ALT) that is typically activated using a hand-held controller.

Popular ALTs include teleportation using pointing or full locomotion (e.g., steering/rate controller using a thumb stick or trackpad). ALTs that generate optical flow without generating vestibular/proprioceptive afferents may confuse the senses and lead to vection-induced VR sickness [34].

Teleportation discontinuously translates the user's viewpoint and avoids the generation of optical flow. Although this mitigates any sensory conflict, the absence of optical flow cues impedes path integration [5] (i.e., estimating distance travelled) which can lead to spatial disorientation [3].

Because they rely on the use of a controller, both full locomotion and teleportation are considered to have a low presence [8, 34]. With natural walking offering the highest presence [7], various walking-based ALTs have been developed that can be integrated with existing positional tracking systems. Walking-in-place (WIP) [30], arm swinging [22], head bobbing [31], and leaning input [13] mimic some or all of the motor actions of walking. Because they generate some or all of the proprioceptive/vestibular afferents of natural walking, there is some evidence that this can minimize VR sickness [16, 32].

Though controller based ALTs like full locomotion and teleportation are widely used, many VR applications (e.g., games), use controllers for other tasks such as shooting enemies, moving objects, reloading guns, blocking attacks, etc. It has been suggested that overloading the hands with navigation functionality could increase cognitive load and decrease performance [18]. Existing studies that have evaluated the performance of controller-based ALTs [27, 7, 34, 28, 29, 4, 35, 11, 39, 9, 12, 38, 32, 17] have only included participants that perform a navigation task while not performing other tasks with a controller at the same time.

This paper is the first to report on the performance, cognitive load demands, usability and presence of two popular hands-busy (full locomotion/ teleportation) and two hands-free (tilt/ walking-in-place) ALTs with participants performing a navigation task but also a bimanual target selection task (i.e., aiming and shooting) at the same time. This task more closely represents a realistic use case found in current consumer VR experiences, such as games, and provides a better understanding of the performance, usability and suitability of popular controller based ALTs, like teleportation and full locomotion.

CHAPTER 2

BACKGROUND AND RELATED WORK

The capability to navigate beyond the confines of available tracking space while minimizing VR sickness, minimizing cost, and maintaining a high presence is considered a major barrier for the mass adoption of VR [19]. Natural walking offers the highest presence [34], but unfortunately, it doesn't scale up to navigate large environments. Redirected walking techniques rely on rotation, curvature, or translation gains to give users the illusion of walking straight while they are actually moving on a curve [24]. Though they offer a high presence, they require a tracking space (at least 12x12m according to [15]) that exceeds the capabilities of current consumer VR systems (4.5x4.5m) as well as available space in most homes. Using high rotation gains on HMDs can increase spatial disorientation and VR sickness [23].

Gait negation devices like omnidirectional treadmills and low-friction surfaces have been criticized for their high cost, low usability, and lagging responsiveness [37]. Gait negation devices also require users to be strapped into them for safety. This requirement makes them difficult to integrate with existing positional tracking systems, since the user's movement is impeded by limiting the user's ability to bend down and pick up an object [32].

Currently, the most widely used controller based ALTs that enable virtual locomotion at scale –and that can be integrated with existing positional tracking systems without impeding movement– are teleportation [21], full locomotion and vehicle movement. Vehicle movement has users enter a vehicle or platform to move larger distances. The vehicle is either controlled by the user using their controller, controlled by the user with their gaze, or not controlled at all by the user but rather provides an on-rails experience. On-rails experiences offer limited interaction and presence while being more likely to induce VR sickness, as users have no control over the direction of movement [19]. Full locomotion using a controller (e.g., rate control and steering using thumb-sticks or track-pads) is the default navigation technique for non-VR 3D experiences, but on VR, it can cause VR sickness [8, 34].

Teleportation is a popular locomotion technique that instantly translates the viewpoint and doesn't generate any vection. It is therefore less likely to cause VR sickness [7]. However, because it lets users do something that doesn't exist in real life, it is considered to offer a low presence [7]. Teleportation may also cause user disorientation [5] and due to the fact that a user's avatar lacks a continuous representation during its use can significantly alter intended gameplay [21]. Though many VR games launch with teleportation as the default ALT, there is an active community of gamers that develops modifications which add full locomotion to such games [10].

Walking based ALTs closely emulate walking to assure a higher presence. Walking-in-place (WIP) requires users to provide step-like motions while remaining stationary [30]. WIP can be implemented cost-effectively using inertial sensing [33] or using positional tracking. WIP closely approximates natural walking input in terms of performance [26] and presence [27, 34]. Partial WIP implementations include head bobbing [31] and arm swinging [22]. Though WIP and head bobbing are handsfree, arm swinging is often implemented using controllers.

Leaning interfaces are widely used, for example, in popular hoverboards and take advantage of the fact that humans lean their body in the direction that they walk; as to align with the gravitational vertical [13]. Leaning interfaces have been explored for VR locomotion [36, 20, 32]. Like a controller, they offer omnidirectional navigation with the significant difference that leaning interfaces are hands-free. Although controller input is faster, leaning interfaces offer a higher presence [36] because they generate vestibular feedback. WIP generally only allows navigation in the direction of the gaze, but some recent work has augmented WIP with leaning input (head tilt) to allow for omnidirectional navigation [32]. Though walking based ALTs have not been widely adopted, some recent games like the running game Sprint Vector rely on arm swinging for locomotion. Its popularity shows that walking based ALTs have the potential to enable virtual locomotion at scale at a low cost.

Various studies have compared ALTs and we survey the tasks that participants had to perform in the evaluations. Slater et al [27] compared WIP to navigating using a controller with participants that navigate a room and pick up objects. Bowman [7] compared gaze based steering to pointing using a motion controller with participants that navigated towards a target location. Chance et al [12] compared gaze-directed steering, joystick control, and real walking in a path integration task where the participant followed a guide object in a maze that contained targets.

Usoh et al [34] compared natural walking, WIP, and flying. Participants were asked to move an object between two locations separated by a virtual pit. Suma et al [28] compared natural walking, moving where looking (using a controller to move in direction of head gaze), and moving where pointing (using a controller to move in the direction that the controller is pointing). Participants explored a two story 3D maze that was linear in design and then took tests related to recall of various aspects of the maze environment.

Zanbaka et al [38] compared room-scale real walking, limited-space real walking with joystick control, 3 DoF head tracking with joystick control, and joystick control using a monitor. Participants were given a virtual room exploration task. Beckhaus et al [4] compared their novel designs for a Dance Pad and Chair Based navigation interface. Participants used both devices to navigate through market-place aisles, around billboard stands, to a location, and up narrow, serpentine stairs.

Suma et al [29] compared real walking, real world natural walking, and gaze-directed steering with participants that navigated and explored a maze. Kapri et al [35] compared their novel design for a bimanual body-directed locomotion technique with joystick control and a hand directed locomotion technique. Participants were asked to navigate along the ground and pick up virtual coins by moving through them. Cardoso [11] designed a VR locomotion technique for the Leap Motion device and then evaluated it against gaze-directed and gamepad locomotion. For the first task, participants had to navigate to a series of indicated platforms in a path following task. For the second task, participants had to find a red vase located in each of the eight houses. Zielasko et al [39] compared Shake-Your-Head, Leaning, WIP, gamepad control, and two accelerometer pedal methods. Participants were asked to determine the shortest distance between pairs of vertices in a vast 3D graph. Bozgeyikli et al [9] compared their hand directed teleportation method with joystick and Walking-in-place. Participants were asked to navigate to destination locations. Langbehn et al [17] compared joystick control, teleportation, and redirected walking in a task where participants navigated to target locations and were later tested on their cognitive map building. Tregillus et al [32] compared WIP, controller, and head-tilt on mobile VR platforms using an obstacle course navigation task.

All of these related studies had participants perform a single navigation task using a controller. Though a few studies [27, 35] required participants to also interact with objects, e.g., picking them up using a controller, those tasks were not performed at the same time as the navigation task.

CHAPTER 3

HANDSBUSY VERSUS HANDSFREE VIRTUAL LOCOMOTION

The goal of our study was to compare four popular ALTs with participants navigating a virtual environment while simultaneously performing a secondary task using their controller. Such a use case has not been evaluated in prior studies while it resembles more realistic VR usage context that can be found in games. Thus it will provide a better understanding of the effectiveness of handsbusy versus handsfree ALTs.

3.1 Instrumentation

For this study, we used the HTC Vive, a popular PC VR platform that allows full outside-in tracking of the HMD and two controllers using infrared “room scale" technology. The HTC Vive uses a pair of wall-mounted base stations that are placed across the room from each other above head height. The Vive offers 1080x1200 per-eye resolution at 90 Hz and a 110° FoV. An Alienware X51 R3 PC (Intel Core i5, 16GB RAM, NVIDIA GTX 970) was used to run our virtual environment. For our study, we configured our tracking space to have a size of 2.0m x 1.5m. This is the smallest supported room-scale size and the limited amount of walking space assures that our participants use the ALT for navigation.

3.2 Virtual Environment

We created a game in Unity 2017.2.0f3 using the SteamVR plugin version 1.2.3. A δ of 1.0 was used so a 1.0 meter displacement in the real world corresponded to a 1.0 meter viewpoint translation in the virtual environment. We used a game for this study as this may encourage the participants to be more engaged. Our game was inspired by the popularity of popular VR wave-shooters, such as Space Pirate Trainer, where players stand still and shoot at waves of enemies. Instead of a player being stationary, our game allows players to navigate an open area, avoid enemy fire, and pick up ammo by using one of the four ALTs we implemented. We used free assets from the Unity asset store to create our game. The usage of a game for our study was motivated by the idea that the real-time constraints that players are subject to can bring out their best performance. The player shot at flying drones in a circular walled-off arena (68m diameter) by firing the machine guns held in each hand (see Figure 3.1).

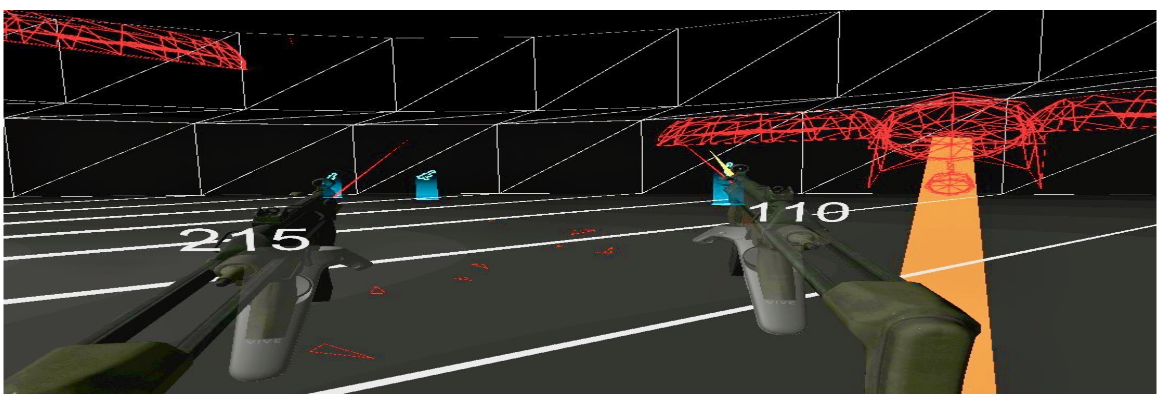

Figure 3.1: Game used for our study that includes two distinct tasks that need to be performed at the same time. Participants hold a gun in each hand while they need to shoot at enemies (in red) that chase and shoot at them. Because guns have limited of ammo (see counter), participants must also navigate to pick up ammo (in blue) in order to survive.

The guns fired 40 bullets per second with a small cone shaped random spray pattern of between 0.025 and -0.025 in game meters. A laser sight was attached to each gun to allow ease of aim by the user. The guns could be continuously fired by holding down the trigger for the respective gun's controller. An ammo counter was mounted on top of each gun to indicate remaining ammo. Neither gun needed to be reloaded and would continue to fire for as long as the ammo counter was positive. Ammo drops spawned randomly throughout the arena whenever an enemy was successfully destroyed and would be picked up when the player moved over it. Picking up ammo replenished 20 ammo in both guns and triggered auditory feedback for the successful pick up. Enemy drones spawned to meet a limit of 3 drones at any one time. A new drone spawned when one was destroyed and each drone was destroyed by 6 bullets. The drones locked on to the user for 2.5 seconds with a transparent orange colored laser after getting within 3 meters of the player and then fired at the locked location with an opaque orange colored laser. If the player is still at the location when the laser is fired, the player receives a hit. The game was designed so that players could not die but, when hit, their screen would flash red. A timer counting down the remaining time in the round was shown above the arena in the sky. All game parameters were determined experimentally using several play-testing sessions.

3.3 Locomotion Methods

For controller-based ALTs, we chose to evaluate the popular techniques of full locomotion and teleportation. For hands-free ALTs, we chose to evaluate WIP and tilt. Though there are other handsfree ALTs that could have been chosen, the implementations of WIP and tilt have the benefit of not requiring any additional instrumentation.

Full locomotion was implemented using the controller's trackpad with direction set by the position of the users finger on the trackpad and velocity interpolated depending on the distance of the user's finger from the center of the trackpad. To implement regular teleportation, we used the SteamVR plugin's teleportation system [2] which lets users select a destination using a teleportation cursor that is tethered to the ground plane and which can be manipulated by pointing the 6-DOF controller.

Tilt was implemented according to a description presented in Tregillus et al [32] where direction of movement is indicated by the direction in which the user's head tilt and velocity is set to an interpolated value depending on the current angle of head-tilt and a maximum tilt value (20°). We measured head-tilt using the HMD's IMU. A dead-zone of 10° is used to allow users the ability to freely tilt their head without translating their position. These values were taken from suggestions made in [32].

WIP was implemented using an implementation presented by Tregillus et al [33] which was available as a Unity plugin called VR-step [1]. This plugin detects steps using inertial data, but we modified it to use the positional Y data from the HMD. We used recommended values for the step detection threshold. To enable 360° omnidirectional navigation, we modified the WIP with head-tilt according to a description provided in [32]. Similar to tilt, we use a dead-zone of 10° and, when a step is detected, the player will move in the direction of their head tilt.

Teleportation instantly translates the viewpoint and is thus significantly faster than other ALTs like full locomotion or tilt. This is a problem for our study because it may skew the performance of teleportation. To allow for a fair comparison, we decided to pair the navigation velocities of every ALT. The virtual locomotion velocity of WIP depends on step frequency but, in order to minimize any differences in performance, the maximum velocity was set to 6m/s, which is reached with a step frequency of 2 steps a second (i.e., average human walking speed). The velocity of full and tilt is interpolated depending on the position of the player's finger on the trackpad and their head-tilt, but we set the maximum velocity also to 6m/s. For teleportation, instead of directly pointing, we use an indirect selection mechanism where a parabolic arch is rendered from the controller to the cursor. By holding down the trackpad on the controller, the arch expands with the teleportation cursor at a speed of 6m/s.

3.4 Participants

We recruited 20 participants (5 females, average age=23.45, SD=5.4) for our user study. One participant was left handed and none self-reported any non-correctable impairments in perception or limitations in mobility. Regarding experience navigating 3D environment and VR, participants rated themselves on a scale of 1 (no experience) to 5 (lots of experience). The average 3D navigation experience was 4.05 player(SD=3.0) while the average VR experience was 3.00 (SD=1.1). Four participants owned a VR headset or smartphone VR adapter. The study was approved by an institutional review board.

3.5 Procedure

The experiment was conducted in a testing lab that was quiet and free of physical obstacles. The experimenter helped the participant equip the Vive headset and adjust it so that the HMD sat comfortably on the head. The participant was guided to use the bottom right knob on the HMD to adjust for the interpupillary distance until they no longer saw double vision. Then, the participant was informed regarding the basic controls on the Vive's controller. It was explained to the participant that the tracking space boundary grid walls (e.g., Vive chaperone) would demarcate the safe zone in which they could freely and safely move around without risk of colliding with any obstacles in the real world. The participant was told that they would navigate to areas in the game that were beyond the available tracking space using four different ALTs. Participants were informed about the features of the game that they would be playing. Then, they were told that their objective in each round was to destroy as many drones as possible within the 90 second time limit. To accustom the participant to each ALT we tested, a training round (no data was collected) was conducted before the experimental round.

To collect information about VR sickness, after each round, participants were asked to provide their level of discomfort from 0 to 10, with level 10 signifying the highest level of discomfort [25]. This was presented to participants using a pop-up panel where they could use their controller to adjust the slider on a continuous scale. Participants were told that when a value of 10 (max discomfort) was selected, the experiment would be terminated.

The locomotion technique that the participant would use each set of rounds was explained right before the training round. At the end of each round, the participant filled out a VR sickness question consisting of a simple floating GUI with a slider and submission button. Participants filled out a VR sickness question for training rounds as well, but the data was not collected. Each participant was randomly assigned to one of 20 unique locomotion technique orderings. The experimenter addressed any questions that the participant had before and after each training and experimental round. Each trial lasted 90 seconds and participants rested for 3 minutes between trials. The entire session took about 25 minutes.

3.6 Data Collection

For performing a bimanual task while navigating at the same time, we and another study [18], expected handsfree ALTs to offer a better performance than using a hands busy ALT because the hands are not overloaded with additional navigation functionality. To assess this, we collected the following data: (1) number of enemies killed; (2) ammo collected; (3) damage taken, aiming accuracy for the (4) left hand and (5) right hand; (6) total virtual distance moved, (7) total positional distance moved, (8) total time participant was moving; (9) total NASA TLX score; and (10) discomfort scores. We calculated the aiming accuracy using total bullets fired and total bullets hit for each controller. A standalone script using OpenVR was used to access the HTC Vive's hardware for positional tracking data of the HMD through SteamVR. The script saved separate CSV files for positional data, tracking space corner positions, and time elapsed. Positional data in the form of an (x,y) pair was collected once every $100ms$. To filter positional movements from sway, we thresholded the data when movement exceeded 1.0 cm. For handsfree ALTs, due to the lower anticipate cognitive load, we expected higher values for variables 1), 2), 4), 5) 6), 8) and a lower value for 3) than for hands-busy ALTs.

After the user study, participants filled in a questionnaire to collect demographic data and provide subjective feedback on each ALT. To collect information about cognitive load, we used the widely used NASA TLX perceived workload questionnaire, with six questions specified for each ALT. The six subscales were Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. The NASA TLX questionnaire is used to rate perceived workload for assessing aspects of performance. It is intended for human operators working on human-machine interface systems. It is known that it may be intrusive for the participant when administered during the task, participants might be prone to correlating their performance with workload ratings, and participants may forget details about the task if administered after the task. We asked participants to rate each ALT in terms of usability using four attributes[14], e.g., efficiency, learnability, accuracy, and likability using a 5 point Likert scale. We also had participants rate each ALT on presence. Questions were formulated as:*"<method> was efficient to use"* and *"<method> offers a high presence"*. Under the presence question, we defined presence as the subjective sensation of being in the virtual world. The five subjective measures were used to assess how participants felt about various aspects of the teleportation techniques to provide insight on to perceived differences between teleportation techniques and handsbusy versus handsfree techniques.

3.7 Results

Table 3.1 lists the average performance results and standard deviation while Table 3.2 lists the average NASA TLX score for the six subscales as well as the average discomfort scores collected after each trial. Following are the analyses for each of the aforementioned variables.

ALT type	WIP	Teleport	Full	Tilt
Enemies	46 (6)	51 (10)	50 (13)	46 (7)
Ammo	706 (185)	1022 (367)	960 (287)	756 (190)
Damage	1.70 (2.6)	2.10 (3.2)	0.55 (0.9)	0.25 (0.6)
Left (%)	36.1 (14.5)	34.4 (12.6)	32.0 (9.4)	35.5 (12.3)
Right (%)	42.3 (13.8)	39.4 (10.5)	39.3 (10.7)	41.5 (10.7)
Time (s)	49.8 (19.4)	20.9 (7.6)	59.3 (22.2)	57.1 (15.5)
Vdistance (m)	288.8 (139)	157.7 (62)	486.5 (182)	342.8 (93)
Pdistance (m)	4.96 (3.6)	1.77 (1.0)	1.48 (1.2)	4.41 (3.5)

Table 3.1: Quantitative measures of performance for each ALT. Standard deviation listed between parentheses.

ALT type	WIP	Teleport	Full	Tilt
Cognitive load (NASA TLX)				
Mental	4.53 (1.2)	4.45 (2.1)	4.08 (2.4)	4.38 (2.0)
Physical	5.73 (1.2)	1.98 (2.0)	1.68 (1.6)	5.05 (1.4)
Temporal	5.13 (1.9)	4.98 (1.8)	4.45 (2.1)	4.83 (1.6)
Performance	4.90 (1.7)	4.45 (2.1)	3.70 (2.3)	5.28 (1.0)
Effort	6.03 (0.7)	4.75 (2.0)	4.08 (2.4)	6.03 (0.7)
Frustration	4.98 (1.8)	3.55 (2.4)	3.25 (2.6)	4.08 (2.4)
Total	31.28 (5.8)	24.18 (8.5)	21.23 (9.8)	28.73 (6.2)
VR sickness				
Discomfort	1.06 (1.5)	0.30 (0.6)	1.62 (1.5)	1.58 (0.8)

Table 3.2: NASA TLX scores and discomfort scores for each ALT. Standard deviation listed between parentheses.

3.7.1 Enemies killed

The results are summarized in Figure 3.2. A one-way repeated measures ANOVA was conducted to determine whether there were statistically significant differences between the four ALTs. There were no outliers. Mauchly's test of sphericity indicated that the assumption of sphericity had been violated ($\chi^2(2) = 16.03$, $p = .007$). A Greenhouse-Geisser correction was applied to the ANOVA but no statistically significant differences between ALTs was detected ($\boldsymbol{F}_{1.972,37.46} = 3.191$, $p > .05$).

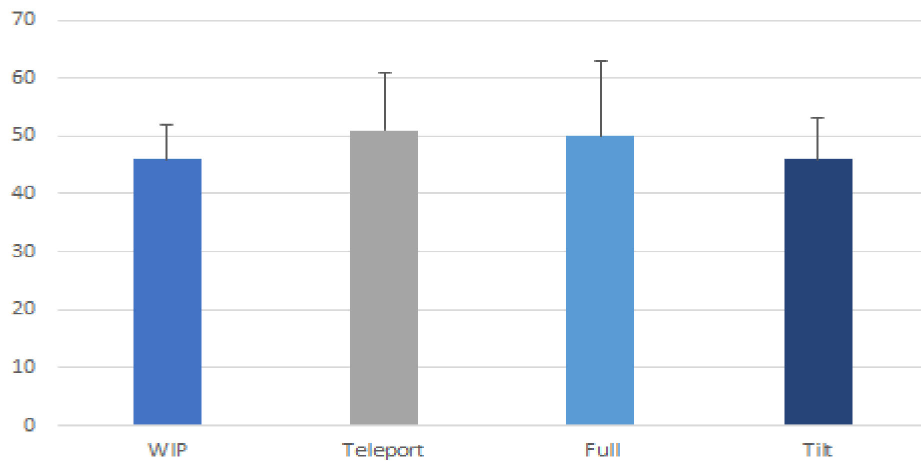

Figure 3.2: Columns show number of enemies killed for each teleportation method. Error bars represent standard deviation.

3.7.2 Ammo collected

The results are summarized in Figure 3.3. There were no outliers and Mauchly's test of sphericity indicated that the assumption of sphericity had been met ($\chi^2(5)$ = 10.903, p = .054). A one-way repeated measures ANOVA found a statistically significant difference between ALTs ($\boldsymbol{F}_{3,57}$ = 10.884, p < .01). A post-hoc analysis with a Bonferroni adjustment revealed that there were statistically significant differences (p < .01) with full higher than WIP, full higher than tilt, teleport higher WIP, and teleport higher than tilt.

3.7.3 Damage taken

The results are summarized in Figure 3.4. A Grubbs test found two outliers (one in Teleport and one in Tilt) that were replaced with the average. A Mauchly's test of sphericity indicated that the assumption of sphericity had been violated ($\chi^2(5)$ = 25.243, p < .01). A one-way repeated measures ANOVA using a Greenhouse-

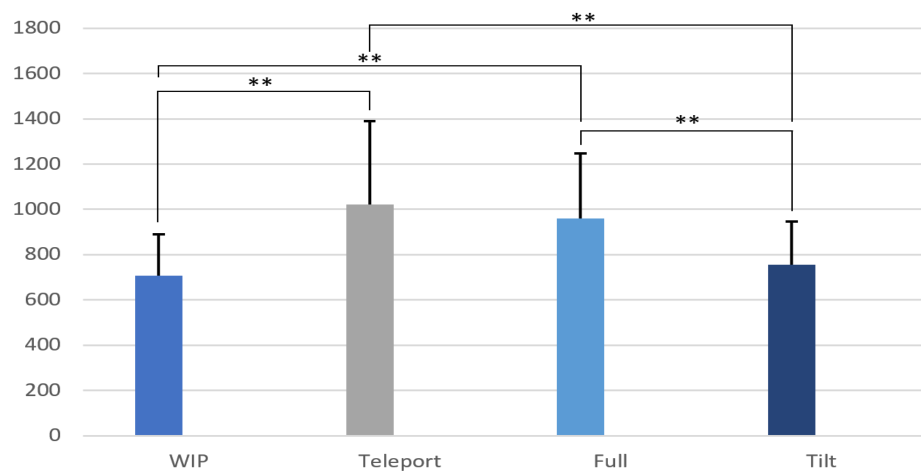

Figure 3.3: Columns show ammo collected for each teleportation method. Error bars represent standard deviation.

Geisser correction found a statistically significant difference between ALTs ($\boldsymbol{F}_{1.758,33.406}$ = 4.612, $p < .05$). A post-hoc analysis with a Bonferroni adjustment revealed that there were statistically significant differences ($p < .01$) with full higher than tilt.

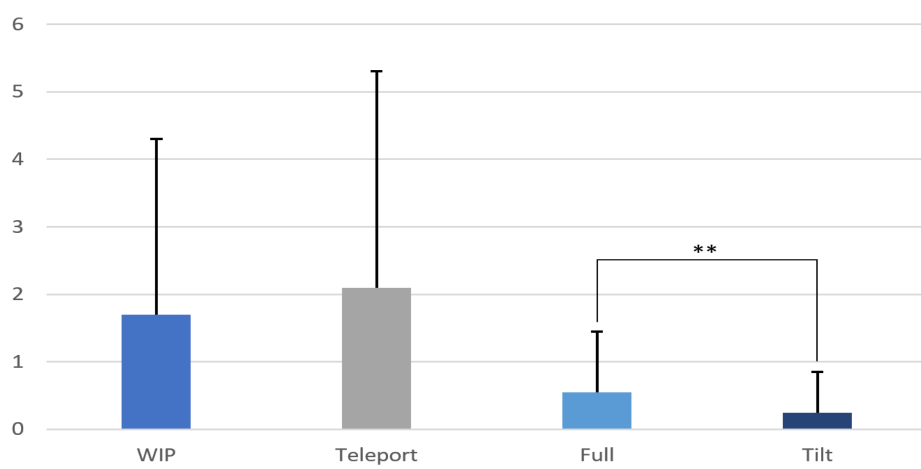

Figure 3.4: Columns show damage taken for each teleportation method. Error bars represent standard deviation.

3.7.4 Aiming accuracy

The results are summarized in Figure 3.5. For both left and right hand, no outliers were detected and Mauchly's test of sphericity indicated that the assumption of sphericity had been met ($\chi^2(5) = 6.030, p = .304$). A one-way repeated measures ANOVA found no statistically significant difference between ALTs ($\boldsymbol{F}_{3,57} = 1.472, p = .232$).

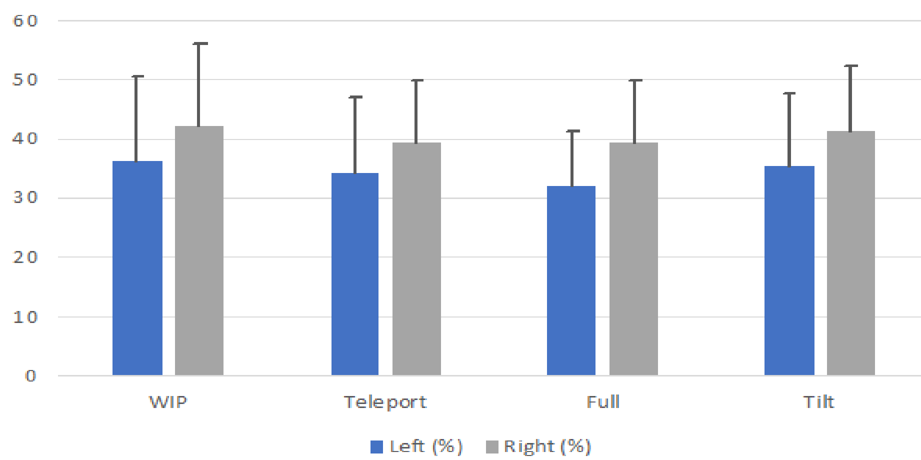

Figure 3.5: Columns show aiming accuracy for each teleportation method. Error bars represent standard deviation.

3.7.5 Total virtual distance

The results are summarized in Figure 3.6. No outliers were detected and Mauchly's test of sphericity indicated that the assumption of sphericity had been violated ($\chi^2(5) = 12.148, p < .01$). A one-way repeated measures ANOVA using a Greenhouse-Geisser correction found a statistically significant difference between ALTs ($\boldsymbol{F}_{2.172,41.259} = 32.989, p < .01$). A post-hoc analysis with a Bonferroni adjustment revealed that there were statistically significant differences ($p < .01$) with full higher than teleport, full higher than WIP, full higher than tilt, WIP higher than teleport, and tilt higher than teleport.

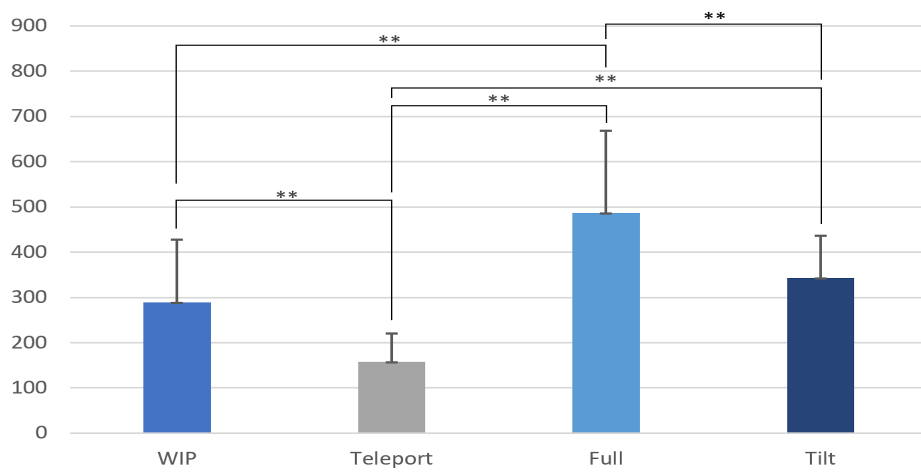

Figure 3.6: Columns show total virtual distance travelled for each teleportation method. Error bars represent standard deviation.

3.7.6 Total positional displacement

The results are summarized in Figure 3.7. No outliers were detected and Mauchly's test of sphericity indicated that the assumption of sphericity had been violated ($\chi^2(5) = 21.783$, $p < .01$). A one-way repeated measures ANOVA using a Greenhouse-Geisser correction found a statistically significant difference between ALTs ($\boldsymbol{F}_{1.959,37.217} = 22.344$, $p < .01$). A post-hoc analysis with a Bonferroni adjustment revealed that there were statistically significant differences ($p < .01$) with WIP higher than full, tilt higher than full, WIP higher than teleport, and tilt higher than teleport.

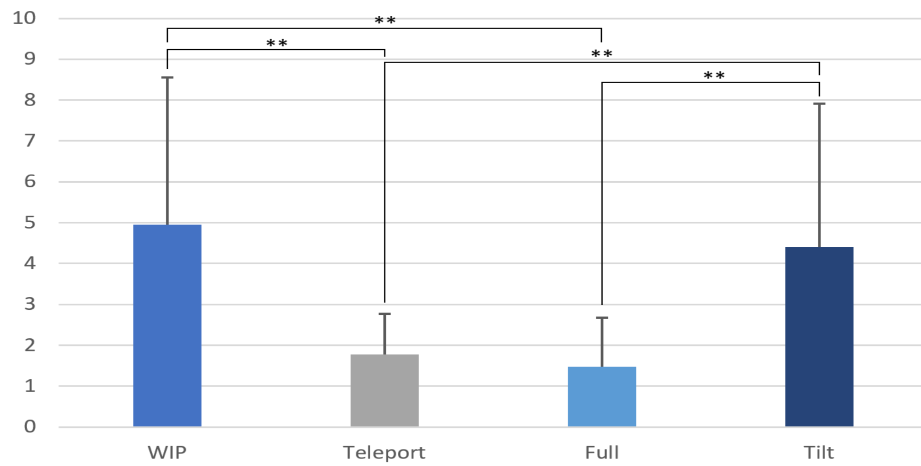

Figure 3.7: Columns show total positional displacement for each teleportation method. Error bars represent standard deviation.

3.7.7 Total time spent moving

The results are summarized in Figure 3.8. No outliers were detected and Mauchly's test of sphericity indicated that the assumption of sphericity had been violated ($\chi^2(5) = 12.070$, $p < .01$). A one-way repeated measures ANOVA using a Greenhouse-Geisser correction found a statistically significant difference between ALTs ($\boldsymbol{F}_{2.298,43.658} = 28.011$, $p < .01$). A post-hoc analysis with a Bonferroni adjustment revealed that there were statistically significant differences ($p < .01$) with full higher than teleport, WIP higher than teleport, and tilt higher than teleport.

3.7.8 NASA TLX scores

The results are summarized in Figure 3.9. No outliers were detected and Mauchly's test of sphericity indicated that the assumption of sphericity had been met ($\chi^2(5) = 8.937$, $p = .112$). A one-way repeated measures ANOVA found a statistically significant difference between ALTs ($\boldsymbol{F}_{3,57} = 9.745$, $p < .01$). A post-hoc analysis with a

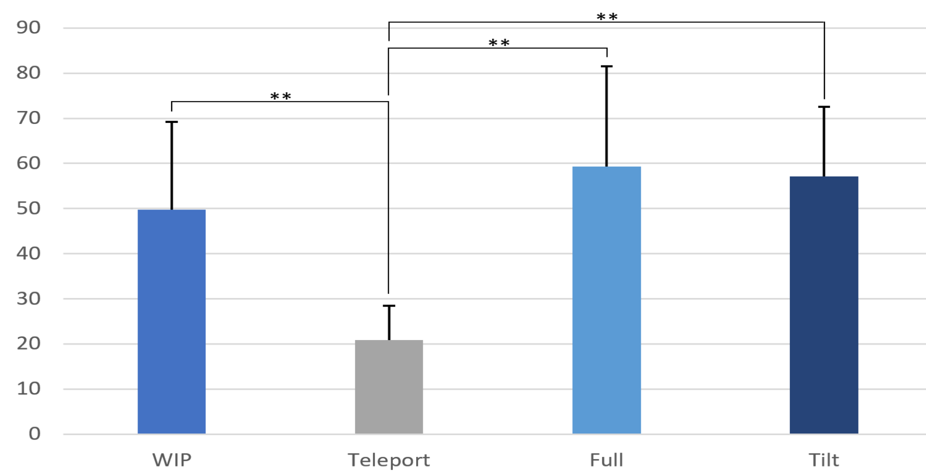

Figure 3.8: Columns show total time spent moving for each teleportation method. Error bars represent standard deviation.

Bonferroni adjustment revealed that there were statistically significant differences ($p < .01$) with WIP higher than full, tilt higher than full, and WIP higher than teleport.

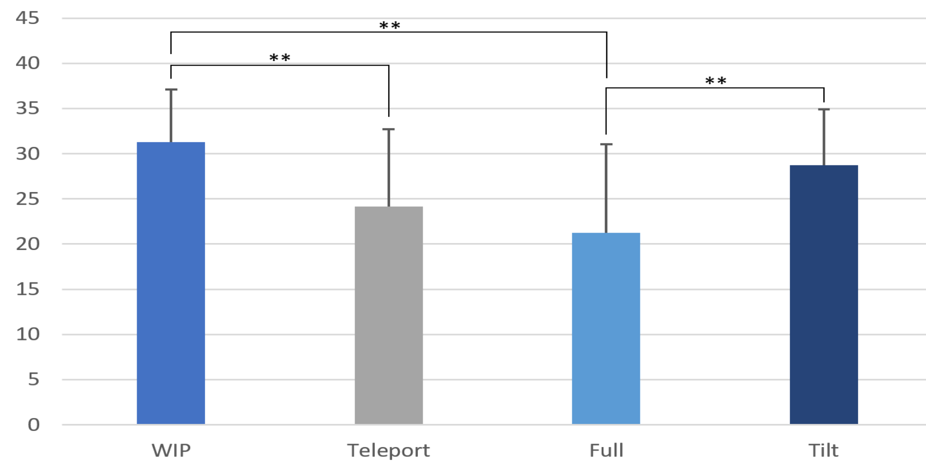

Figure 3.9: Columns show total NASA TLX scores for each teleportation method. Error bars represent standard deviation.

3.7.9 Discomfort scores

The results are summarized in Figure 3.10. No outliers were detected and Mauchly's test of sphericity indicated that the assumption of sphericity had been met ($\chi^2(5) = 6.091, p = .298$). A one-way repeated measures ANOVA found a statistically significant difference between ALTs ($\boldsymbol{F}_{3,57} = 8.232, p < .01$). A post-hoc analysis with a Bonferroni adjustment revealed that there were statistically significant differences ($p < .01$) with full higher than teleport, and tilt higher than teleport.

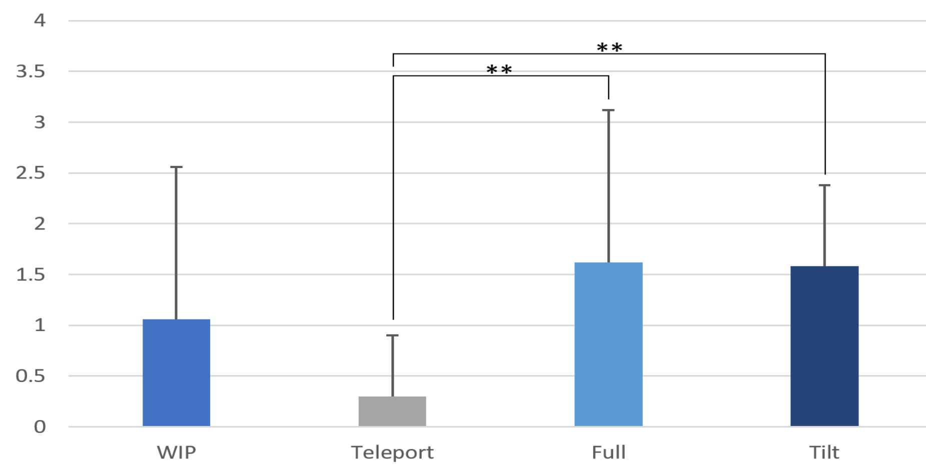

Figure 3.10: Columns show discomfort scores for each teleportation method. Error bars represent standard deviation.

3.7.10 Subjective measures

The results are summarized in Figure 3.11. A Kruskal-Wallis test found a significant difference in Likert scores for efficiency ($\chi^2(3) = 16.19, p = .001$), learnability ($\chi^2(3) = 22.94, p = .0004$) and presence ($\chi^2(3) = 19.91, p = .0002$) but not for accuracy or likeability ($p > .05$). For efficiency, a Mann-Whitney post-hoc tests found a significant difference in Likert scores with full higher than teleport ($p < .05$) and full higher than WIP ($p < .05$). For learnability, a Mann-Whitney post-hoc tests found a significant difference in Likert scores with full higher than all other ALTs ($p < .05$) and tilt higher than WIP ($p < .05$). For presence, a Mann-Whitney post-hoc tests found a significant difference in Likert scores with WIP higher than all other ALTs ($p < .05$) and tilt higher than teleport ($p < .05$).

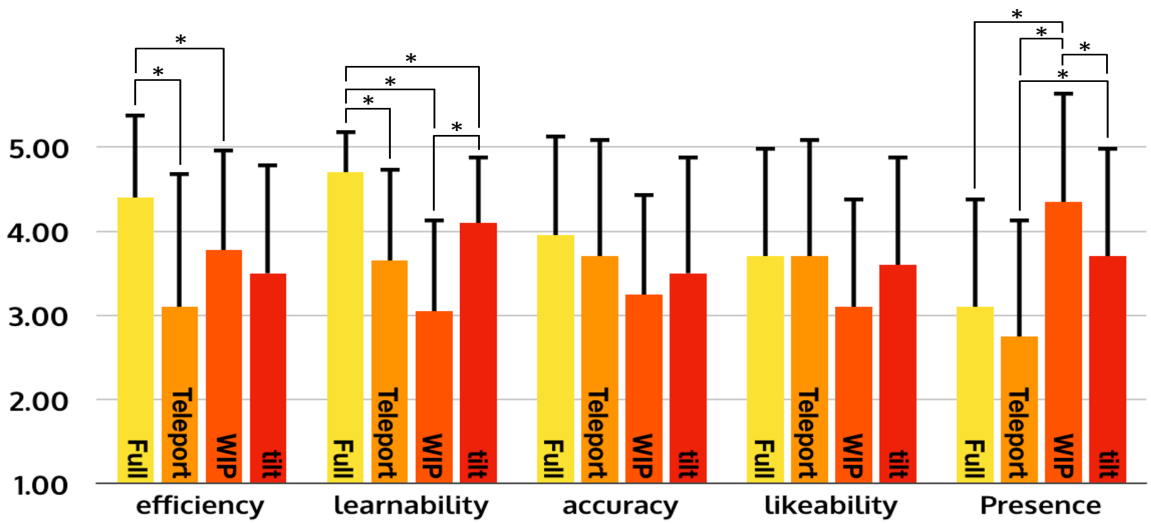

Figure 3.11: Columns show Likert scores (scale 1: strongly disagree to 5: strongly agree) for each teleportation method based on criteria: efficiency, learnability, accuracy, likeability and presence. Error bars represent standard deviation.

3.8 Discussion and Limitations

The results of our study were surprising and somewhat a mixed bag with regards to our expectations, e.g., a higher performance for handsfree ALTs than for hands-busy ALTs. Regarding bimanual target selection performance, we did not find a significant difference between ALTS for total enemies killed or in aiming accuracy between both hands. There were significant differences regarding ammo collected and damage taken that are related to navigation performance. When participants can travel large distances quickly using their ALT, they will have more opportunities to pick up ammo. This seems to be true for full locomotion and tilt, but we observed contradictory results for teleportation. Teleportation had the highest value for ammo collected, but surprisingly also the lowest virtual distance travelled. Teleportation and full had significantly higher ammo collected than both WIP and tilt. They also had lower physical, effort, and frustration scores than WIP and tilt. It seems that ammo collected may correlate with lower self-reported physical, effort, and frustration. It is possible that increases in cognitive load through those categories inhibit the participants' ability to do a secondary task such as collecting ammo while not affecting their ability to do a primary task such as shooting enemies. From the positional tracking, as well as the time spent moving data, one can observe that, using teleportation, participants remained largely stationary . Participants didn't bother travelling short distances using teleportation to try to avoid enemy lasers -which explains that they took significantly more damage than when using full or tilt locomotion.

Full and tilt are similar in that they implement linear directional movement and allow for participants to travel the largest virtual distances, with full locomotion having a significantly higher total distance than the other ALTs. For handsfree ALTs, the total positional displacement was larger than for handsbusy ALTs, but this may also have been caused by participants tilting their head a bit. The minor amount of head tilt is picked up as positional displacement, though preliminary experiments showed that the amount of displacement that is captured like this is fairly small. Using teleportation, participants travel directly to ammo, while using other ALTs participants travel over it as they have momentum and thus travel larger distances. Using WIP, participants were often observed to drift, which is a known side effect of WIP [32].

Given the larger amount of observed positional movement, handsfree ALTs seem to better integrate with positional tracking as they enable more natural walking input - something that was recently corroborated by a related study that compared WIP to using a controller [6]. A lack of integration with positional tracking is especially evident for teleportation, which navigates a user much faster than natural walking and requires such low physical effort that it has been suggested that it encourages players to abandon natural walking input altogether [21].

Regarding cognitive load, measured using the NASA TLX questionnaire, handsfree ALTs had a higher associated cognitive load than when using handsbusy ALTs (e.g., this was only significant for WIP and tilt was higher than full locomotion). Given that handsfree ALTs leave the player's hands free to focus exclusively on aiming, we assumed this would result in a lower cognitive load. Looking at the subscales of the NASA TLX, we only detected a statistical significant difference ($p < 0.05$) between ALTs for physical demands. This makes sense as tilt and especially WIP require physical effort to be used, while teleportation and full require little physical input. Our study also did not find a significant difference in aiming accuracy of each hand between ALTs (though the aiming accuracy for the dominant hand is generally slightly higher), which suggests that overloading the hands with navigation functionality is not cognitively taxing. There are two issues that should be considered though. Several participants had prior experience with full locomotion or teleport, so they were more proficient with it already. Also, the game was designed to have at most three drones visible at all times. If we had increased this number, the game would have been much harder to play and differences in performance between handsbusy and handsfree ALTs might have been observed. We made the game such that players could not die, which would allow for comparing results between participants. We do not believe this limitation affected the performance of each ALT.

Presence is an important quality for VR [7] and, given that navigation plays such a central role in 3D experiences, it is to a large extent determined by what ALT is used. WIP offered a significantly higher presence than any of the other ALTs, while tilt offered a higher presence than teleportation. In general, teleportation is considered to offer a low presence [7] so this result is not surprising. WIP and Tilt generate some or all of the proprioceptive/vestibular afferents of natural walking –which is most natural to us– and therefore they offer a much higher presence than full locomotion and teleportation which do not generate such cues.

The presence of proprioceptive/vestibular cues also have the potential to minimize visual-vestibular conflict [16]. The discomfort scores we acquired in this study were very low likely due to the usage of a high end VR headset with negligible latency. We did detect a statistically significant difference in discomfort scores between full locomotion and teleportation and teleportation and tilt. For full locomotion, eight participants reported a discomfort over 2.0 with two participants reporting a score of 5, which was evidence that it did induce some VR sickness. For tilt, only 5 participants reported a discomfort score between 2.0 and 3.0. Teleport generally doesn't cause VR sickness due to the lack of optical flow in the viewpoint transition of teleport while the other ALTs all generate optical flow, which might have led to a significant difference. However, there was no difference for WIP, and this might be because WIP generates vestibular cues that can mitigate the visual-vestibular conflict that can cause vection-induced VR sickness [32].

CHAPTER 4
CONCLUSION

A limitation of existing studies that have evaluated controller based locomotion methods is that they primarily have participants perform a navigation task. This doesn't represent real world usage of locomotion methods as controller are often user for various other tasks. Our study evaluates two handsbusy locomotion methods, e.g., full locomotion and teleportation and compares to two handsfree locomotion methods, walking-in-place and tilt. Our study is different from existing studies in that participants not only perform a navigation task but also a bimanual aiming task, which more closely resembles VR experiences like games. Overall, our study provided useful insights. Contrary to our expectations that handsfree techniques would perform better, there were no differences in bimanual target selection accuracy while there were significant differences in navigation related tasks (picking up ammo, distance travelled, avoiding enemy fire). Overall, handsfree locomotion methods offered a higher presence but were found to have a higher cognitive load, because -unlike handbusy locomotion methods- they require players to provide physical input. VR game designers should carefully consider such trade offs when choosing a locomotion method. Our study provides some compelling evidence that, at least in terms of performance, handsfree locomotion methods offer the same performance as controller based locomotion methods while they have potential to solve some of the major limitations associated with these methods, e.g., VR sickness (full locomotion), low presence, and discontinuous avatar representation (teleportation).

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