Evaluating the Effects of Four VR Locomotion Methods: Joystick, Arm-Cycling, Point-Tugging, and Teleporting

Noah Coomer
Rhodes College

Sadler Bullard
Rhodes College

William Clinton
Rhodes College

Betsy Williams-Sanders
Rhodes College
sandersb@rhodes.edu

Figure 1: Top down view of the four different virtual environments used in this study.

ABSTRACT

In this work we present two novel methods of exploring a large immersive virtual environment (IVE) viewed through a head-mounted display (HMD) using the tracked controllers that come standard with commodity-level HMD systems. With the first method, “Point-Tugging,” users reach and pull the controller trigger at a point in front of them and move in the direction of the point they “tug” with the controller. With the second method, “Arm-Cycling,” users move their arms while pulling the trigger on the hand-held controllers to translate in the yaw direction that their head is facing. We perform a search task experiment to directly compare four locomotion techniques: Joystick, Arm-Cycling, Point-Tugging, and Teleporting. In the joystick condition, a joystick is used to translate the user in the yaw direction of gaze with physical rotations matching virtual rotations. In the teleporting condition, the controllers create an arched beam that allows the user to select a point on the ground and instantly teleport to this location. We find that Arm-Cycling has advantages over the other methods and could be suitable for wide-spread use.

CCS CONCEPTS

• Computing methodologies → Perception; Virtual reality;

KEYWORDS

virtual environment, locomotion, spatial awareness, teleporting

ACM Reference Format:

Noah Coomer, Sadler Bullard, William Clinton, and Betsy Williams-Sanders. 2018. Evaluating the Effects of Four VR Locomotion Methods: Joystick, Arm-Cycling, Point-Tugging, and Teleporting. In *SAP '18: SAP '18: ACM Symposium on Applied Perception 2018, August 10–11, 2018, Vancouver, BC, Canada*. ACM, New York, NY, USA, 8 pages. <https://doi.org/10.1145/3225153.3225175>

1 INTRODUCTION

The *U.S. Consumer Technology Sales and Forecasts* report predicts that number of virtual reality (VR) headsets that will be sold in 2018 will exceed 4.9 million units, representing a 25% increase over 2017 sales [usC 2018]. Moreover, the VR market is estimated to grow from \$2 billion to \$27 billion between 2016 and 2022 [zio 2017]. Although these numbers are promising, these VR systems still have limitations. To locomote or move through the virtual environment (VE) seen through these commodity-level VR systems, users commonly “teleport” [Habgood et al. 2018]. With teleporting, users typically use a VR controller to display an arc that extends from the virtual controller and meets the ground of the virtual world. The users move the controller around to modify the arc to highlight different points in the environment. After selecting a point, the user “jumps” instantly to that position without visual self-motion information (see Figure 2). Despite teleporting’s popularity, research has shown that it has a negative effect on navigation, causing people to be disoriented [Bolte et al. 2011]. However, the fundamental advantage of teleporting is that it reduces the effects of simulator sickness [Christou and Aristidou 2017], which is the major hurdle for the widespread adaptation of virtual reality [Rebenitsch 2015]. Thus, the purpose of this study is to understand more about the cognitive effects as people undergo multiple teleports and to

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.

SAP '18, August 10–11, 2018, Vancouver, BC, Canada

© 2018 Association for Computing Machinery.

ACM ISBN 978-1-4503-5894-1/18/08...\$15.00

<https://doi.org/10.1145/3225153.3225175>

Figure 2: Teleporting: Users select a point on the ground and jump instantaneously to that location in the IVE. The button on the top of the controller is pressed.

Figure 3: Point-Tugging: Users grab a point in 3D space and pull the VE towards (or away from them). In this diagram, the camera indicates the view of the participant with the user pulling the controller backward to move forward in the VE.

Figure 4: Arm-Cycling: When both triggers are engaged, users are translated forward in the direction they are facing according to the absolute value of the displacement of the controllers.

compare teleporting to three other methods of exploring a large immersive virtual environment (IVE): Joystick, *Point-Tugging*, and *Arm-Cycling*.

This paper presents two new methods of exploring a VE that was inspired by prior work [McCullough et al. 2015; Murias et al. 2016; Wilson et al. 2016]. These methods were developed and piloted in our lab by individuals who frequently play VR games. The first

Figure 5: A view of the VE used in this study.

method, *Point-tugging*, works by allowing the user to select a 3D position in space and pull themselves towards that point in space (with their viewing eye height preserved). This method, as depicted in Figure 3, was inspired by the “real” game “tug of war”, and it can be thought of as allowing users to “pull” themselves though an IVE with an imaginary rope. It is important to note that users can tug themselves in any direction. For example, users could grab a point in space on their right hand side and pull themselves to this location. With *Arm-Cycling*, the users press the controller triggers and move their arms in a cyclic motion to explore the environment. More specifically, users can either make an arm-swinging motion similar to how the arms move when walking or move the arms in unison to make a breast stroke swimming-like motion. Users translate forward in the yaw-direction that they are facing (see Figure 4).

A within-subjects design experiment presented in this work compares locomotion across four conditions: Joystick, *Arm-Cycling*, *Point-Tugging*, and Teleporting. In the joystick condition, the joystick is used to translate the users in the yaw direction that their head is facing. To evaluate the four conditions, participants perform a search task ([Riecke et al. 2010; Ruddle and Lessels 2006, 2009]) where they navigate through a part of a town that consists of four “blocks” of buildings intersected by a road to find hidden treasure. Participants had to find eleven treasures hidden in fifteen chests scattered throughout the environment in each of the locomotion conditions. The top down view of the environment can be seen in Figure 1 and view from the street can be seen in Figure 5. Simulator sickness was measured for each participant after each locomotion condition.

2 BACKGROUND

Much like in the real world, humans update their spatial knowledge or spatial awareness with respect to a VE as their relationship to objects in the environment change [Williams et al. 2007]. However, humans are more disoriented in VEs [Darken and Peterson 2014; Kelly et al. 2013]. Thus, navigation, the most common way people interact with a VE [Bowman et al. 2004], causes people to feel disorientated. Exploring a VE by physically walking seems to result in the best spatial awareness [Darken and Peterson 2014], but the size of the space that can be explored using a tracking system is limited without alternate interventions such as teleporting. Much work has looked at how best to explore a VE larger than the tracked

space while maintaining spatial awareness [Hashemian and Riecke 2017; Kitson et al. 2017; Riecke et al. 2010; Suma et al. 2012; Wilson et al. 2016; Zielasko et al. 2016]. These locomotion methods involve real walking, redirected walking, walking-in-place, teleporting, joystick, swimming, arm-swinging and more (for a literature review of these see [Boletsis 2017]). Much of the more recent navigation work has focused on engaging the user in physical movement as it seems to result in better spatial awareness of the VE as compared to using a joystick [Hashemian and Riecke 2017; Kitson et al. 2017; Suma et al. 2012; Waller and Hodgson 2013; Wilson et al. 2016].

Teleporting is a commonly used locomotion method for VR games as it seems to be best for preventing cybersickness [Christou and Aristidou 2017]. Teleporting has been around for many years, but has been known to cause disorientation in VEs [Bowman et al. 1997]. With the recent increase in teleporting popularity, other works have compared it to different locomotion methods. Habgood et al. [2018] present a method of locomotion using predefined “nodes” where users experience rapid, continuous optical flow when moving from node to node. This study measures presence and simulator sickness to compare their method to game controller navigation and teleporting. They find no difference in presence between the conditions. However, they show that their node based system is similar to teleporting in terms of simulator sickness. Sarupuri et al. [2017] present trigger walking where the VR controller trigger pulls result in virtual steps. They perform a usability study to compare their method with walking-in-place, teleportation and joystick locomotion and find that 9 out of 16 participants preferred trigger walking. They also report that trigger walking, walking-in-place, and teleporting are similar with respect to simulator sickness. Christou et al. [2017] compare gaze-directed locomotion, pointing and teleporting. Participants had to walk and collect “Pokémon” tokens as a means of testing their spatial updating ability. They show that pointing and gaze-direction locomotion caused less cybersickness compared to teleporting. In terms of performance, teleporting resulted in faster travel times and seemed to not be disorienting as it was just as effective in allowing users to complete their journey. However, teleporting increased the likelihood of the user missing collectable tokens. Bozgeyikli et al. [2016] present a locomotion technique called Point & Teleport that allows the users to be teleported based on where their finger is pointing. They perform a user study to compare Point & Teleport, joystick, and walking-in-place. The authors report a slight preference of Point & Teleport, but differences in levels of tiredness were found and there were no significant differences on enjoyment, discomfort, and presence between the methods.

This work is inspired by the work of Ruddle and Lessels [2006] who performed a series of navigational search studies where participants were asked to search for eight target objects hidden in 16 boxes. They find performance was substantially reduced when translations were controlled using a button-press interface instead of physically walking. This suggests that both translational and rotational physical motion cues are required to allow for real world-like performance in such search tasks. More recently, several studies have evaluated locomotion methods using a search task [Christou and Aristidou 2017; Fiore et al. 2013; Nybakke et al. 2012; Riecke et al. 2010; Von Kapri et al. 2011; Young et al. 2014]. Nybakke et al. [2012] perform a within-subjects experiment where participants

Figure 6: A view of the HTC Vive controller depicting the trackpad, grip, and trigger buttons and the joystick.

search the contents of 16 randomly positioned and oriented boxes to find 8 hidden targets using four locomotion modes: real walking, joystick translation with real rotation while standing, joystick translation while sitting, and a motorized wheel chair. They find a marginal effect of condition for the number of revisits to the same hidden target, but pairwise comparisons did not reveal differences. They report that the distance traveled was smaller in the walking condition and it took less time to complete the trial when users physically walked. In a similar task, Riecke et al. [2010] find that when the joystick was combined with physical rotations that performance compared to actual walking is similar in terms of search efficiency and time.

3 LOCOMOTION METHODS

This section explains the algorithms used for the four locomotion conditions evaluated by this work. The immersive VE was viewed through a HTC Vive head-mounted display (HMD) which had a resolution of 1080x1200 per eye, a field-of-view of 110° diagonally, a weight of 0.47 kg and an optical frame rate of 90Hz. Orientation was updated using the orientation from the sensor found on the Vive. Vive controllers (Figure 6) that came with the HTC Vive system were used for the teleporting, *Point-Tugging*, and *Arm-Cycling* conditions. In these conditions, the models of the Vive controllers were rendered in the VE and updated as they moved around. The joystick (Figure 6) used in this experiment was a Logitech Extreme 3D Pro. Graphics were rendered using the Unity engine. **Joystick** At each frame, the vertical position of the joystick is checked for a non-zero value. A positive value (or pushing forward on the joystick) resulted in translating the user forward in the yaw direction of gaze while a negative value resulted in moving backwards. The gaze yaw-angle was obtained from the HMD orientation sensor. The maximum joystick translation rate was that of normal walking, 1 m/s (similar to [Riecke et al. 2010]). Participants could also go slower by not pushing all the way forward or backward on the joystick.

3.1 Teleporting

Teleporting is accomplished using the scripts included in the SteamVR Plugin asset found on the Unity Asset Store. To teleport, the participant held down the trackpad on a single Vive controller (see Figure 2). While the trackpad is pressed, a parabolic projection extends from the controller and arcs downward until it intersects the virtual scene, creating a puddle-shaped indicator of where the participant

would teleport. The participant was instantaneously moved to the (x, z) coordinates of this desired location (while preserving the eye height of the user in the y -direction) when they released the trackpad button.

3.2 Point-Tugging

When the trigger of the controller is pressed, the x and z positions of the controller are saved as the “grabbed” point ($grab_x$ and $grab_z$). While the trigger is held, the position of the controller is checked at each frame. At each frame, the user translates in the yaw-direction by the calculated difference between the x, z positions of the current controller (con_x, con_z) and the x, z positions of the grabbed point. In this manner, the user moves along the xz plane and eye height (y -position) is preserved. When the trigger is released, the controller is no longer locked to the grab point. Thus, while locomoting using *Point-Tugging*, the user’s updated position ($NewPos$) is calculated from the current position of the user ($CurPos$) as follows: $NewPos = (grab_x - con_x, 0, grab_z - con_z) + CurPos$. With this method, users are able to freely look around in the environment as they locomote in any direction that they tug. To move through the VE, users have to click to grab a point in space, pull themselves, release, and then repeat.

3.3 Arm-Cycling

With arm-cycling, when the triggers on both the left (L) and right (R) controllers are pressed, the x and z coordinates for the controllers are saved ($oldL_x, oldL_z, oldR_x, oldR_z$). During a frame where both triggers are held down, new positions of the controllers are recorded ($currL_x, currL_z, currR_x, currR_z$). During that frame, the user is translated forward in the yaw-direction of their HMD by the sum of the absolute differences in the movement between frames of the controllers: $Translation\ Amount = (|oldL_x - currL_x|, 0, |oldL_z - currL_z|) + (|oldR_x - currR_x|, 0, |oldR_z - currR_z|)$. Before the next frame, $oldL_x, oldL_z, oldR_x, oldR_z$ are over-written and assigned the values $currL_x, currL_z, currR_x, currR_z$, respectively. The effect is forward movement at a speed determined by the speed of controller movement. When either trigger is released, the controllers cease to control locomotion.

4 EXPERIMENTAL EVALUATION

The experiment presented in this section compares four conditions: Joystick, *Arm-Cycling*, *Point-Tugging*, and Teleporting. In each condition participants had to locomote through a small town looking for treasure in treasure chests. In each condition there were fifteen treasure chests, and eleven of those treasure chests contained treasure. Note that we decided to have only four chests that did not contain treasures to reduce lucky guessing from greatly affecting completion time. The distance traveled, time, and number of visits to chests that had been previously visited were recorded.

Since there were 24 orders of the four conditions, participants were tested in a pseudo-balanced fashion. More specifically, we counterbalanced the orders using a Latin square design. A Latin square is an n by n array, where each cell in the array contains one of the n conditions such that each symbol occurs only once in each column and only once in each row. We had four locomotion conditions and had 10 participants, thus, we used three 4x4 Latin

Figure 7: An example of a treasure chest in the environment.

squares to counterbalance our testing. Half of the participants had experienced VR. Six of the participants reported that they played video games casually and only one of the participants reported that they did not regularly play video games, while the other three considered themselves to be experienced gamers.

4.1 Materials

The VE used for this study consists of four small “towns” as seen in Figure 1, with each town being a rectangle of four blocks. The blocks contain different buildings, plants, fences, and objects, and are divided by perpendicular roads connecting at an intersection in the center of the town. All parts of the town are simple models with light colors, with different roof colors distinguishing buildings. Different vehicles, primarily cars and a bus, are placed on the roads. There is a wall that serves as a boundary of the town that can be seen bordering the town in Figures 1 and 5. In each town, the position and orientation of the town models are different, so that no two towns have the same layout. However, they are similar in nature in that they contain the same building models differing by color and texture. The placement, color, and type of the vehicles are also different in each town.

Fifteen treasure chests (approximately 1m wide, 0.5m deep, 0.5m tall) were arranged in each of the towns, and their relative locations were not repeated in other towns. However, the placement of the chests were similar across the towns. The chests were placed so that they were partially or completely obscured from the location of the other chests. An example of a treasure chest in the environment can be seen in Figure 7. Exactly eleven of the fifteen chests contained “treasures” which were golden spheres located inside the chest (Figure 8).

4.2 Procedure

The experimental procedure was fully explained to the participants prior to seeing the VE. For each locomotion condition, participants’ task was to navigate the VE until they had encountered each of the eleven treasures. To accomplish this, participants had to locomote through the VE to find the eleven chests checking their contents for the golden sphere. To “open” chests to check for treasure, participants pressed the grip button on the controller (in the teleporting, *Point-Tugging*, and *Arm-Cycling* conditions) or the top button on the joystick (in the joystick condition). This rendered the walls

Figure 8: An example of a subject approaching a chest and selecting the reveal button to visit the chest.

of the treasure chest semi-transparent as seen in Figure 8. When users “opened” or revealed the contents of a chest, they could see its contents as long as the button was held down. To visit each chest, the user’s (x, z position) had to be within 1.5m of the (x,z) center of the chest. The treasure only appeared in the chests when the user clicked the button so that they could not cheat and simply look inside the chest without opening it.

During each condition, a message was continually displayed in the upper right hand corner indicating the total number of targets left to find. If the chest revealed by the participant contained an unvisited treasure, the number of targets left to find would decrease by one. If the chest contained a previously visited treasure, the number of targets left to find would remain the same. The program kept track of how many times participants went back and rechecked a chest (by clicking the reveal button). There were four empty chests that did not contain any treasures. For empty chests, participants could check these each once with no penalty toward their total number of revisits. However, the number of empty chest revisits was also accumulated in the total number of revisits.

Participants were advised to do their best to remember each chest that they interacted with in the environment, trying not to recheck any a second time. They were also encouraged to minimize the distance traveled and time needed to complete the trial without starting to rush or move too quickly through the VE. They were instructed to avoid collisions with the objects in the VE and to make sure to hold down trigger or grip button for each chest so they did not accidentally check it twice. Additionally, participants were told to stay within the boundaries of the white wall surrounding the “town.” The trial for each condition was terminated when the participants had found all eleven treasures or five minutes had elapsed.

Prior to each test trial, participants completed a practice trial where participants viewed an example “town” area that was not used for test trials and contained three treasure chests. Participants were encouraged to get a feel for the locomotion method and to practice visiting the treasure chests. This practice trial lasted approximately two minutes. Once the subject felt comfortable with the given locomotion method and task, participants were instructed to close their eyes and then the testing environment was loaded. In each locomotion test trial, participants started at the center of the environment.

Each participant completed one practice trial and one test trial for each of the four locomotion modes. Locomotion modes were blocked and balanced across participants. Before the experiment

and after each condition, participants took off the HMD and filled out a survey. This helped to reduce the likelihood of fatigue and simulator sickness between conditions. For each locomotion test trial, we tracked the total distance traveled by the user, the total number of rotations about the y-axis, the total time to find the treasures, the number of treasures found, and the number of re-visits. After the experiment, participants were debriefed and thanked for their participation. The total experiment time per subject took about 30 minutes.

Prior to starting the experiment, participants were asked to complete a pre-exposure simulator sickness questionnaire (SSQ) which tested for baseline symptoms before undergoing the simulation [Kennedy et al. 1993]. The questionnaire included 16 different symptoms, and participants were requested to provide ratings from 0 to 4 for each one of the symptoms, where 0 represented no symptom and 4 represented severe symptoms at the time of completion of the survey. The same SSQ was administered after each locomotion condition. We also administered an additional survey aimed at gauging the overall usability and user thoughts on each method (see Table 1). We based this survey off of a study that tested the core elements of a video game experience for usability [Bozgeyikli et al. 2016; Lewis and Loewenthal 2015]. Each question corresponded to one of the categories as follows: Questions 1, 4, and 5 tested difficulty in understanding; 2, 9, 11, and 15 tested difficulty of operation; 3, 7, and 12 tested the feeling of being in control; 6, 13 and 19 tested the feeling of tiredness; 8, 10, and 20 tested feeling of enjoyment; 14, 16, and 21 tested feeling of being overwhelmed; and 17, 18, and 22 tested feeling of frustration. The responses were recorded on a 5 point Likert scale (strongly disagree; disagree; neutral; agree; strongly agree).

4.3 Results

Table 1 shows the mean results from our usability survey taken after each method. Table 2 presents this same data collapsed by category. We ran a repeated measures ANOVA on the mean Likert scale data across the participants for each of the categories shown in Table 2. We found a significant effect on control, $F(3,44)=4.5$, $p=.03$, with t-test revealing differences between Teleporting and *Point-Tugging* to the rest of the conditions. Thus, users felt more control in both the joystick and *Arm-Cycling* conditions. We found a significant effect on tiredness ($F(3,8)=1.3$, $p=.02$), where the *Point-Tugging* and *Arm-Cycling* conditions were found to be more tiring than the joystick and teleporting conditions. There is a significant effect of enjoyment as well ($F(3,8)=3.6$, $p=.03$), with t-test suggesting that the

Table 1: Overall Usability Survey

	Joystick	Teleport	Point-Tug	Arm-Cycle
1. I thought this method was easy to understand.	4.7	3.7	4.2	4.1
2. I thought this method was hard to use.	1.5	2.6	3.0	3.0
3. I felt like I had control over my actions.	4.3	3.6	3.4	4.2
4. I did not have a hard time visualizing this movement in my head.	4.0	3.9	3.7	3.8
5. I understood how my movements translated to the environment.	4.5	3.9	4.0	4.0
6. This method made me tired.	1.7	1.4	2.3	2.9
7. I felt like I could go where I wanted to.	4.5	3.1	3.8	4.6
8. I liked using this method.	4.1	3.3	3.1	3.9
9. I had a hard time remembering the controls for this method.	1.2	1.7	1.5	1.7
10. I think that this method added to the virtual experience.	3.5	2.9	3.4	3.9
11. I think this method made the task harder to complete.	1.7	2.2	2.8	2.2
12. I did not get lost as I used this method.	3.5	3.0	3.6	4.0
13. I felt like this method required a lot of energy.	1.2	1.5	2.5	3.1
14. I felt like this method required a lot of effort.	1.4	2.0	2.8	2.9
15. I felt like this method was buggy.	1.5	2.7	2.3	1.7
16. I felt like there was not enough time when using this method.	1.5	2.0	1.6	1.9
17. I felt like this method was unpredictable at times.	1.5	2.8	2.4	2.0
18. I would not like using this method again.	2.3	2.6	3.1	2.2
19. I felt like I needed a break after using this method.	1.6	1.6	2.7	2.6
20. I would like to see this method implemented in a video game.	3.8	3.3	3.3	3.9
21. I felt overwhelmed when using this method.	1.8	1.8	2.5	1.8
22. This method made me frustrated.	1.4	2.2	2.7	1.7

This table reports the mean responses to the questionnaire that participants were given after each locomotion condition. A five-point Likert scale corresponds to strongly disagree (1), disagree (2), neutral (3), agree (4), and strongly agree (5).

Table 2: Survey Results by Category

	Joystick	Teleport	Point-Tug	Arm-Cycle
Understanding	4.4	3.8	4.0	4.0
Difficulty of Operation	1.5	2.3	2.4	2.1
Control*	4.1	3.2	3.6	4.3
Tiredness*	1.5	1.5	2.5	2.9
Enjoyment*	3.8	3.2	3.2	3.9
Overwhelmment	1.6	1.9	2.3	2.2
Frustration*	1.7	2.5	2.7	2.0

This table collapses the survey results from Table 1 across the categories. An (*) denotes a significant effect. The Likert scale is explained in Table 1.

Table 3: Simulator Sickness Results

Pre-Exp	Joystick	Teleport	Point-Tug	Arm-Cycle	This
16	37*	19	80*	13	

table shows the SSQ values summed across all participants for each condition. An (*) denotes a significantly different condition.

joystick and *Arm-Cycling* methods were more enjoyable. Similarly, an ANOVA for the frustration category was significant ($F(3,8)=1.5$, $p=.03$) with t-test suggesting that participants find the teleporting and *Point-Tugging* more frustrating.

Table 3 shows the total cybersickness scores summed across the participants prior to experiencing the VE and then by condition. We analyzed the total cybersickness score as a repeated measures ANOVA on total cybersickness score and find a significant effect of condition ($F(4,7) = 5.7$ $p < .01$). Further pairwise t-tests reveal there was a statistically significant difference between the joystick condition and the rest of the conditions. Similarly, t-tests revealed that *Point-Tugging* was significantly different from the other conditions. There were no differences between pre-exposure, teleporting, and

Arm-Cycling. These results suggest that the participants in the joystick and *Point-Tugging* conditions were more prone to simulator sickness.

In Table 4, the main results of the experiment are presented. It shows the mean distance traveled, accumulated turning angles (rotations), total time to complete the task, and the number of revisits, respectively across the conditions. We ran five different repeated measures ANOVAs to compare this data across the four experimental conditions. We found a significant effect on distance ($F(3, 9) = 9.1$, $p<.01$), time ($F(3, 9) = 5.9$, $p=.03$), rotation ($F(3,9)=2.1$, $p=.03$) and number of revisits $F(3,9)=5.2$, $p=.01$. T-tests revealed that the total distance traveled was different for participants across the four conditions. Similarly, t-tests showed accumulated rotations were statistically different across participants. In terms of time, t-tests revealed that the joystick and *Arm Cycling* conditions were similar and that teleporting and *Point-Tugging* were statistically different. For number of revisits, t-tests revealed a difference between the conditions indicating that participants normally had the lowest number of revisits in the *Arm-Cycling* followed by *Point-Tugging*, joystick, and teleporting. We did not find effects of order.

5 DISCUSSION

In this work we present a navigational search task experiment to test the cognitive effects of locomoting under four different conditions: Joystick, Teleporting, *Point-Tugging* and *Arm-Cycling*. Both *Point-Tugging* and *Arm-Cycling* are novel approaches introduced by this work. They are robust, simple to use, and easy to implement. Moreover, they are easily combined with VR systems currently on the market such as the HTC Vive, Oculus Rift, and Samsung Gear VR.

Overall, participants traveled the smallest distances when looking for treasures in the *Arm-Cycling* condition, with the distances that participants traveled systematically increasing from the *Point-Tugging*, Joystick, and Teleporting conditions. With teleporting, participants moved almost twice the distance on average as compared to *Arm-Cycling*. It should be noted that it was easier for participants to travel longer distances with teleporting as they simply selected points and instantly moved to a new location. Additionally, participants looked around the most in the teleporting condition. The accumulated turning angles averaged across the participants decreased systematically starting with the teleporting condition (12114.2°), followed by *Point-Tugging* (11730.9°), *Arm-Cycling* (10038.3°) and the Joystick (8387.3°). This suggests a qualitatively different navigation strategy for teleporting as participants traveled longer distances and had to look around more to get their bearings. Thus, teleporting led to an increase in rotational orienting motions and an increase in path length. Interestingly, the joystick condition had the lowest amount of head rotations. In a similar task comparing walking to joystick locomotion, Riecke et al. [2010] found significantly less accumulated turning angles in the joystick condition as compared to walking. Joystick allowed users to go backwards which could further explain why there were fewer accumulated rotations.

On average, across all the trials, it took participants 3min 12s to complete a trial. Both the joystick (178.2s) and *Arm-Cycling* (180.6) conditions were best in terms on completion time, followed by

Table 4: Main Results of the Navigational Search

	Joystick	Teleport	Point-Tug	Arm-Cycle
Distance (m)*	1279.7(339)	1571.6(595)	1180.9(252)	896.3(157)
Rotations (°)*	8387.3(3452)	12114.2(4367)	11730.9(3663)	10038.3(3045)
Time (s)*	178.2(68.4)	216.5(72.1)	191.2(58.9)	180.6(66.9)
Treasures	10.9(.3)	10.4 (1.0)	11(0)	10.9(.3)
Revisits*	7.2 (4.9)	9.4(6.2)	4.7(4.7)	3.4 (4.4)

This table shows the main results of the experiment averaged across the participants (with standard deviation). An (*) denotes a significantly effect.

Point-Tugging (191.2) and teleporting (216.5). It is interesting that teleporting took the longest amount of time because participants could move instantaneously across the environment if they wanted to as compared with the other three methods that constrained the speed by which participants could locomote through the environment. In terms of time both the joystick and *Arm-Cycling* conditions were best, but it seems that participants used different strategies. In the joystick condition, people traveled longer distances and moved their heads around less while in the *Arm-Cycling* condition participants rotated their head more and traveled less. This could be because the *Arm-Cycling* method requires significantly more effort as shown by the data in Table 2.

The number of revisits needed to complete the task was highest for the teleport condition (9.4), followed by the joystick (7.2), *Point-Tugging* (4.7), and *Arm-Cycling* (3.4) conditions. Participants in the teleport condition revisited chests significantly more. With teleporting participants traveled the longest distances, scanned the environment more by rotating their heads, took the longest time and made the greatest number of revisits. This supports the body of work that suggests teleporting is disorienting [Bowman et al. 1997; Christou and Aristidou 2017], even when the teleporting method gives visual spatial cues by showing a parabolic curve to help with point selection as shown in Figure 2.

Consistent with the literature [Christou and Aristidou 2017], teleporting does not result in an increase in simulator sickness. However, our method *Arm-Cycling* was also found to not cause any sickness. Both the joystick and the *Point-Tugging* methods seem to cause cybersickness, with *Point-Tugging* being the worst. From this SSQ survey, it is clear that *Point-Tugging* is not a viable method of virtual exploration. We hypothesize why this method caused an increase in simulator sickness. With the *Point-Tugging*, participants are allowed to look around as they locomote through the environment. In contrast, with both the joystick and *Arm-Cycling* conditions, participants move in the direction they are facing. This result could suggest that VR locomotion techniques that involve users moving in the direction of gaze cause less simulator sickness. From our questionnaire summaries shown in Table 2, participants find both the joystick and *Arm-Cycling* movements to be easier to control, more enjoyable, and the least frustrating. However, *Arm-Cycling* seems to be the most tiring with an average “neutral” response to questions about the method being tiring.

In conclusion, our study suggests that *Arm-Cycling* is the best of the four methods we tested. It seems to give users the greatest sense of spatial awareness of the environment as evidenced by the fewer number of revisits, fastest completion time, and the smallest

total distance traveled. The simulator sickness scores were also the lowest, though not statistically different than teleporting. The only advantage that teleporting seems to have over *Arm-Cycling* is that it was reported to be less tiring. We suggest that *Arm-Cycling* be studied further to understand how much energy it requires and its potential to cause cybersickness studied when participants experience the condition for a longer amount of time. Our results showing that *Arm-Cycling* has navigational advantages is consistent with the work of McCullough et al. [2015] who present an arm-swinging method and show that it was similar to walking in terms of spatial updating. Our algorithm for *Arm-Cycling* is slightly different than the arm-swinging method presented by McCullough et al. [2015]. Arm-Swinging involves placing an orientation tracker on your upper arm and tracking the changes in the x-direction of the arm. *Arm-Cycling* involves tracking the changes in distance of hand-controllers. Thus, users can move the controllers in any direction to move forward. In our pilot testing, we found that the *Arm-Cycling* method was robust allowing for different types of movement to move, but more work should be done to compare Arm-Swinging and *Arm-Cycling*.

Other works have looked at using “walking-in-place” and trigger walking [Sarupuri et al. 2017] to explore a VE but an obvious disadvantage of this method in that it forces the user to walk around the VE in whole step increments. From informal pilot testing, we hypothesize that *Arm-Cycling* requires less energy walking-in-place, though more research needs to be done on this topic. *Arm-Cycling* does not suffer from these limitations and is a simple, robust algorithm that has advantages of providing good spatial awareness and is similar to Teleporting in terms of cybersickness. Additionally, the experiment presented in this work points to some interesting conclusions regarding designing navigation strategies. Teleportation changes the navigation strategy, such that participants move and then localize themselves by turning their heads, rather than doing both simultaneously. *Point-Tugging* may have increase sickness reports because participants are able to turn their heads while moving, as the direction of motion is determined by the motion of the controllers, which is not true for other methods.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under grant 1351212. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsors.

REFERENCES

2017. Virtual Reality (VR) Market by Hardware and Software for (Consumer, Commercial, Enterprise, Medical, Aerospace and Defense, Automotive, Energy and Others): Global Industry Perspective, Comprehensive Analysis and Forecast, 2016–2022. Zion Market Research Report. (9 2017). <https://www.zionmarketresearch.com/report/virtual-reality-market>.
2018. U.S. Consumer Technology Sales and Forecasts. Consumer Technology Association. (1 2018). <https://www.cta.tech>.
- Costas Boletsis. 2017. The New Era of Virtual Reality Locomotion: A Systematic Literature Review of Techniques and a Proposed Typology. *Multimodal Technologies and Interaction* 1, 4 (2017), 24.
- Benjamin Bolte, Frank Steinicke, and Gerd Bruder. 2011. The jumper metaphor: an effective navigation technique for immersive display setups. In *Proceedings of Virtual Reality Intern. Conf.*
- Doug Bowman, Ernst Kruijff, Joseph LaViola, and Ivan Poupyrev. 2004. *3D User Interfaces: Theory and Practice*. Addison-Wesley.
- Doug A Bowman, David Koller, and Larry F Hodges. 1997. Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques. In *Virtual Reality Annual International Symposium, 1997., IEEE 1997*. IEEE, 45–52.
- Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2016. Point & Teleport Locomotion Technique for Virtual Reality. In *ACM CHI PLAY*. 205–216. <https://doi.org/10.1145/2967934.2968105>
- Chris G Christou and Poppy Aristidou. 2017. Steering Versus Teleport Locomotion for Head Mounted Displays. In *Augmented Reality, Virtual Reality and Computer Graphics*. Springer, 431–446.
- Rudolph P Darken and Barry Peterson. 2014. Spatial Orientation, Wayfinding, and Representation. (2014).
- L Puchalla Fiore, Ella Coben, Samantha Merritt, Peng Liu, and Victoria Interrante. 2013. Towards enabling more effective locomotion in vr using a wheelchair-based motion platform. In *Joint Virtual Reality Conference*. Eurographics Association, 83–90.
- Jacob Haggood, David Moore, David Wilson, and Sergio Alapont. 2018. Rapid, continuous movement between nodes as an accessible virtual reality locomotion technique. (2018).
- Abraham M Hashemian and Bernhard E Riecke. 2017. Leaning-Based 360° Interfaces: Investigating Virtual Reality Navigation Interfaces with Leaning-Based-Translation and Full-Rotation. In *International Conference on Virtual, Augmented and Mixed Reality*. Springer, 15–32.
- Jonathan Kelly, Lisa Donaldson, Lori Sjolund, and Jacob Freiberg. 2013. More than just perception—action recalibration: Walking through a VE causes rescaling of perceived space. *Attn., Perc., & Psych.* 75 (2013), 1473–1485.
- Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. 1993. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *Inter. J of Aviation Psych.* 3, 3 (1993), 203–220.
- Alexandra Kitson, Abraham M Hashemian, Ekaterina R Stepanova, Ernst Kruijff, and Bernhard E Riecke. 2017. Lean into it: Exploring leaning-based motion cueing interfaces for virtual reality movement. In *IEEE VR*. 215–216.
- Christopher Alan Lewis and Kate Loewenthal. 2015. *An introduction to psychological tests and scales*. Psychology Press.
- Morgan McCullough, Hong Xu, Joel Michelson, Matthew Jackoski, Wyatt Pease, William Cobb, William Kalescky, Joshua Ladd, and Betsy Williams. 2015. Myo Arm: Swinging to Explore a VE. In *ACM Symposium on Applied Perception (SAP '15)*. ACM, New York, NY, USA, 107–113.
- Kara Murias, Kathy Kwok, Adrian Gil Castillejo, Irene Liu, and Giuseppe Iaria. 2016. The effects of video game use on performance in a virtual navigation task. *Comp. in Hum. Behav.* 58 (2016), 398–406.
- Amelia Nybakke, Ramya Ramakrishnan, and Victoria Interrante. 2012. From virtual to actual mobility: Assessing the benefits of active locomotion through an immersive VE using a motorized wheelchair. In *IEEE 3DUI*. 27–30.
- Lisa Rebenitsch. 2015. Managing Cybersickness in Virtual Reality. *XRDS* 22, 1 (Nov. 2015), 46–51.
- Bernhard E. Riecke, Bobby Bodenheimer, Timothy P. McNamara, Betsy Williams, Peng Peng, and Daniel Feuereissen. 2010. Do we need to walk for effective VR navigation? Physical rotations alone may suffice. In *7th Inter. Conf. on Spat. Cogn.* 234–247.
- Roy Ruddle and Simon Lessels. 2006. For Efficient Navigational Search, Humans Require Full Physical Movement, but Not a Rich Visual Scene. *Psych. Sci.* 17, 6 (June 2006), 460–465.
- Roy A Ruddle and Simon Lessels. 2009. The benefits of using a walking interface to navigate virtual environments. *ACM Transactions on Computer-Human Interaction (TOCHI)* 16, 1 (2009), 5.
- Bhuvaneswari Sarupuri, Simon Hoermann, Frank Steinicke, and Robert W. Lindeman. 2017. Triggerwalking: A Biomechanically-inspired Locomotion User Interface for Efficient Realistic Virtual Walking. In *Symp. on Spatial User Interaction (SUI '17)*. ACM, New York, NY, USA, 138–147.
- Evan Suma, Gerd Bruder, Frank Steinicke, David Krum, and Mark Bolas. 2012. A taxonomy for deploying redirection techniques in immersive VE. In *IEEE VR*. 43–46.
- Anette Von Kapri, Tobias Rick, and Steven Feiner. 2011. Comparing steering-based travel techniques for search tasks in a cave. In *Virtual Reality Conference (VR), 2011 IEEE*. IEEE, 91–94.
- David Waller and Eric Hodgson. 2013. Sensory contributions to spatial knowledge of real and virtual environments. In *Human Walking in VEs*. Springer, 3–26.
- Betsy Williams, Gayathri Narasimham, Westerman, John Rieser, and Bobby Bodenheimer. 2007. Funct. similarities in spatial representations between real and VEs. *TAP* 4, 2 (2007).
- Preston Wilson, William Kalescky, Ansel MacLaughlin, and Betsy Williams. 2016. VR locomotion: walking > walking in place > arm swinging. In *ACM VRCAI*. 243–249.
- Mary K. Young, Graham B. Gaylor, Scott M. Andrus, and Bobby Bodenheimer. 2014. A Comparison of Two Cost-differentiated Virtual Reality Systems for Perception and Action Tasks. In *ACM Symposium on Applied Perception (SAP '14)*. ACM, New York, NY, USA, 83–90.
- Daniel Zielasko, Sven Horn, Sebastian Freitag, Benjamin Weyers, and Torsten W. Kühlen. 2016. Evaluation of hands-free HMD-based navigation techniques for immersive data analysis. In *IEEE 3DUI*. 113–119.