The Evaluation of Gait-Free Locomotion Methods with Eye Movement in Virtual Reality

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(a) Virtual environment (b) Arm Swinging (c) Dash and Joystick (d) Grappling (e) Teleportation

Figure 1: The virtual environment for locomotion (a) and the illustration of the five evaluated gait-free locomotion methods (b)-(e).

ABSTRACT

As VR becomes increasingly popular in the entertainment industry, VR locomotion, a technique that allows users to navigate virtual environments beyond the spatial confines of the real world, is being increasingly studied by developers and researchers. Previous work has examined the effects of locomotion methods on various aspects of users, such as user experience, motion sickness, and task performance. However, how locomotion methods affect users' eye movements that might indicate cognitive load has not yet been investigated, although several relevant works have addressed these effects as being important to study. To contribute to this area of research, in this work we investigate the evaluation of five common gait-free locomotion methods using eye movements during VR navigation. The results show that locomotion methods significantly affect participants' eye movement behavior (i.e., blinks, fixations, and saccades), suggesting that different cognitive responses were elicited with different locomotion methods. Our research provides a viable tool for future studies evaluating locomotion methods, thus providing further in-depth insights for developing more effective and enjoyable VR locomotion methods.

Keywords: Virtual reality, locomotion methods, eye tracking, cognitive load.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality;

1 INTRODUCTION

With the increasing development of commodity-level virtual reality (VR) head-mounted displays (HMDs), VR is being widely used in entertainment and education [19,21], leading thus to a growing interest in the design and development of VR applications. Navigation is one of the most important features in VR applications (especially VR games), allowing users to efficiently and infinitely navigate large virtual environments (VEs) while remaining confined in a room-scale real-world environment. To date, a variety of locomotion methods have been developed and employed in VR applications, such as arm swinging, dash, joystick, and teleportation-like locomotion methods [4, 8, 13, 14, 17]. Since locomotion methods are only tools to help the user move around in the VE, they should not interfere with the user's main task during VR navigation. Therefore, one of the major challenges for VR developers and researchers is to develop advanced locomotion methods that offer an enjoyable experience while imposing a low cognitive load on users and causing less or no VR sickness.

A body of previous work has evaluated currently popular locomotion methods and compared their effectiveness in VR and games. This involved quantifying assessments such as user experience (usability of locomotion methods), sense of presence, motion sickness, and other post-hoc surveys such as user preferences that were usually quantified with questionnaires [6, 17]. However, the real-time user cognitive load induced by the locomotion method and the visual behavior during VR navigation have rarely been studied and compared between different locomotion methods. Some previous studies have examined the cognitive load of users while experiencing different 3D travel techniques (e.g., real walking, steering, and joystick), but used either a post-task or dual-task paradigm to measure cognitive load [12, 15]. The cognitive load induced by the travel techniques alone was not directly measured as additional cognitive tasks were involved. In our study, however, we aim to measure the cognitive load induced purely by the locomotion method. With this in mind, an eye-tracking-based analysis could provide a great opportunity for such evaluation from a new perspective and should attract the attention of researchers. In the literature, eye tracking has been widely used as a non-intrusive and objective measurement of human conscious and unconscious temporal cognitive and visual behavior in various tasks [2, 3, 9, 11].

The aim of this work is to evaluate and compare five commonly used gait-free locomotion methods, namely arm swinging, dash, grappling, joystick, and teleportation. For this purpose, we introduced eye movements as objective measurements of cognitive load for the first time in this research domain. Specifically, we conducted a VR user study using a within-subjects design. Participants per-

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formed a simple search & collection task by navigating the VE using five different locomotion methods. The eye-tracking data providing information about participants' underlying cognitive processes and visual behavior during navigation were collected and analyzed. Our results show that locomotion methods have significant effects on participants' eye movements.

2 RELATED WORK

Previous studies have evaluated a variety of locomotion methods and compared them with respect to different aspects. Coomer et al. [6], for example, examined the effects of four locomotion methods on users, including joystick, arm-cycling, teleportation, and point-tugging. User experience, simulator sickness, and participants' task performance were evaluated. Results showed that arm-cycling was the best out of the four methods, as it performed best on the search task and had better simulator sickness scores than joystick and point-tugging. teleportation, on the other hand, performed worst in the search task but also had better simulator sickness scores than joystick and point-tugging.

Similar to [6], Paris et al. [17] also evaluated four commonly used locomotion methods, including skiing, magic carpet, grappling, and teleporting. Post-hoc questionnaires on user experience, presence, simulator sickness, and path integration performance in the absence of external landmarks were evaluated. Results showed that continuous methods had advantages over discontinuous methods in path integration performance, consistent with the work of Coomer et al. [6]. However, the advantage of discontinuous methods over continuous methods with respect to simulator sickness, generally reported in previous work [18], was not present in [17].

Frommel et al. [7] conducted a user study to evaluate four controller-based locomotion methods, including free teleportation, fixpoint teleportation, touchpad-based (joystick-like), and guided automatic locomotion. Participants' discomfort, presence, enjoyment, affective state, and simulator sickness during VR locomotion were evaluated. Results showed that free teleportation was superior to the other three locomotion methods, eliciting the least discomfort and scoring highest on enjoyment, presence, and affective state. In addition, free teleportation was found to have significantly lower simulator sickness scores than touchpad-based locomotion, which is inconsistent with the literature [18].

Based on different evaluation purposes, the aforementioned works have demonstrated the effects of locomotion methods on different aspects of navigation in VEs. However, the measures used are similar and limited, mostly based on subjective self-reports by users. This inspires our study to explore the feasibility of using eye movements as objective metrics to assess participants' cognitive processing responses during VR navigation.

The finding that eye-tracking measurements correlate with cognitive load is no longer new and has been widely used in previous studies. In particular, it is well known that pupil diameter correlates positively with human cognitive load [22]. In addition, eye movements such as blinks, fixations, and saccades have also been found to be indicative of cognitive load. Specifically, blink and fixation rates were found to be negatively correlated with cognitive load [5]. Conversely, fixation duration was found to be positively correlated with cognitive load [5, 23]. In addition, saccadic measures were also found to be correlated with cognitive load, e.g., saccade amplitude was found to be negatively correlated with cognitive load [16]. These previous works strongly support our current study, which examines the cognitive response of users during VR locomotion using eye movements.

3 LOCOMOTION METHODS

Since our goal in this study is to investigate the feasibility of using eye-tracking technology to measure users' cognitive processing load during VR locomotion, we selected the five most commonly used and representative gait-free locomotion methods as test subjects rather than proposing new locomotion techniques. The HTC Vive Pro Eye HMD was used to display the VE. All scripts of the locomotion methods were written in C#. The user navigates the VE using Vive controllers that come with the HMD. The models of the controllers were rendered and updated as the user moved around the VE. In the Unity coordinate system, all movements occur in the (x, z) plane, and the eye height (i.e, y coordinate) remains unchanged. The distance in Unity is in units (by default, 1 Unity unit is 1 meter). The default scale between the virtual world and the real world is 1:1. Detailed information about the VE design can be found in Section 4.2. Five locomotion methods are illustrated in Figure 1.

3.1 Arm Swinging

Arm swinging converts physical arm movements into player movements in the VE. To navigate, the user holds controllers and swings their arms simultaneously. Once the user holds down the grip button (of right controller), the coordinates of the controllers in the current frame ($Left\_x1$, $Left\_z1$, $Right\_x1$, $Right\_z1$) and in the next frame ($Left\_x2$, $Left\_z2$, $Right\_x2$, $Right\_z2$) are read and stored. Then the differences in the controller positions between two consecutive frames are calculated. The player moves forward in each frame by the sum of the absolute differences in the yaw direction of the HMD. The locomotion stops when the grip button is released or the arm stops swinging.

3.2 Dash

To perform the dash locomotion, the user touches the trackpad on one of the controllers to select the desired direction (thumb on trackpad: up is forward, down is backward, the left side is left, and the right side is right direction). The $2D$ coordinates of the contact point on the trackpad are read and converted to a direction in the Unity coordinate system. Then the user taps the trigger button to perform a dash in the selected direction. The player is then moved 2 units distance in the VE within 0.2 seconds. To perform a continuous movement over a longer distance, the user can hold down the trigger button instead of tapping it. Multiple dashes are then performed continuously, which makes dash a continuous locomotion method. The user can release the trigger button to stop the locomotion.

3.3 Grappling

In grappling, the user uses a grappling hook to pull the player to a desired location in the VE. To navigate, the user presses the trigger button, whereupon a ray is projected from the controller in the direction the controller is pointing. Once the ray hits the desired location (x, z), the grappling hook is extended from the controller to the desired location and the user is then moved to the desired location. The movement speed of the player is automatically adjusted according to the movement state within a minimum of 1 unit per second and a maximum of 4 units per second. Once the player has moved to within one meter of the desired location, locomotion is stopped. Then the visualization of the grappling hook is reset and the movement is unlocked. Locomotion can be ended prematurely by pressing the grip button.

3.4 Joystick

Joystick is a locomotion method that simply relies on the controller's trackpad inputs. Similar to dash locomotion, the user touches the trackpad with the thumb to select the desired direction (see above Section 3.2). The $2D$ coordinates of the contact point are read and converted to a direction in the Unity coordinate system. The player moves at a smoothed speed of 1 unit per second in the VE towards the desired location. Locomotion stops when the user removes the thumb from the trackpad button.

3.5 Teleportation

For teleportation, we directly used the teleportation prefab provided by SteamVR[1] for Unity3D. To teleport, the user holds down the top of the trackpad on one of the controllers. A parabolic projection is then displayed, emanating from the controller and meeting the ground of the VE, visible to the user. The user points the end of the projection to the desired location (x, z). As soon as the trackpad button is released, the player is instantly transported to the desired location in the VE.

4 Experimental Evaluation

We designed an experiment in which participants perform a very simple search & collection task by navigating a VE using five different locomotion methods. We assessed participants' eye movements that might indicate cognitive load during VR locomotion.

4.1 Participants

Fifteen volunteers (10 male, 5 female) between the ages of 23 to 31 participated in our experiment. They were university students, from which six participants reported no experience with video games, four played video games 0 to 5 hours per week, and five played video games for more than 5 hours per week. Eight have no experience with VR, six reported to have some VR experience, and one used VR headsets regularly. All participants provided informed consent. Since all fifteen participants successfully completed the task and the eye-tracking data were valid, no participant was excluded from the study.

4.2 Apparatus and Materials

The HTC Vive Pro Eye HMD was used to display the VE, which has a resolution of 1440×1600 per eye, a refresh rate of 90 Hz, and a field of view of 110°. The HTC Vive Pro Eye is seamlessly integrated with the Tobii eye tracker with a sampling rate of 120 Hz and an accuracy of $0.5° - 1.1°$, which can be used to record eye-tracking data. The HTC Vive controllers served as the input device for locomotion. We used two HTC Vive Base Stations to track a $2m \times 2m$ area. The VE was rendered with Unity engine[2] (version 2020.03.23f) on a computer with a 3.5GHz Core i7 processor and 16GB RAM.

To avoid additional effects on participants caused by the VE and the task, we created a simple VE based on a package from the Unity asset store. The VE was an outer ground plane with several houses and paths and trees in between. In addition, to encourage participants to experience more VR locomotion, we placed the five crystals in different locations (outside the house) in the VE to make these targets easy to find. The top-down view of the VE is shown in Figure 1 (a).

4.3 Experimental Procedure

We used a within-subjects design, where the independent variable of locomotion methods had five levels, i.e., arm swinging, dash, grappling, joystick, and teleportation. Therefore, all participants took part in five trials (locomotion methods). The entire experiment lasted approximately 50 minutes per participant. All participants were informed before the experiment that they could abort the experiment at any time if they felt uncomfortable.

After participants signed an informed consent form, they were asked to complete a demographic questionnaire (e.g., age, gender) and a questionnaire about their previous experiences with video games and VR. Then, the experimenter gave instructions on the experimental task. Next, participants were assigned to one of the five locomotion conditions in a counter-balanced order created using a Latin square. In each trial, participants first practiced the current locomotion method with text instructions in the VE and, if necessary, with the help of the experimenter until they were familiar with it. A standard 5-point eye-tracking calibration routine was then performed before starting the actual data collection. Participants performed the crystal collection task with controllers and they were asked to collect all (five) crystals (see Figure 1 (a)). Note that to avoid additional cognitive load from the task, there was no time limit for performing and completing the task. Eye-tracking data was recorded during the task. After completing the task, participants took off the headset and took a rest. To avoid additional cognitive load from previous experiences, participants were asked to rest for about four to five minutes after each exercise and trial until they felt comfortable to start again. The entire experiment ended after the participant completed all five trials.

4.4 Measures

To evaluate and compare different locomotion methods, different eye movement measures were used. Eye tracking has already been considered a valuable tool for assessing users' cognitive process and visual behavior during interaction with a system [11, 23]. Therefore, in this work, we measured commonly used eye movements such as blinks, fixations, and saccades.

Since the eye tracker integrated into the HMD only outputs pupil size and gaze vectors, and no standard method or software is available for eye movement event detection in VR, eye movements such as blinks, fixations, and saccades had to be detected manually post-experimentally. A blink detection algorithm based on the fluctuations that characterize pupil data as proposed by Hershman et al. [10] was applied in our study.

Before fixation and saccade detection, linear interpolation was performed for the missing gaze vectors. A modified velocity-threshold identification (I-VT) algorithm [1, 9] was used for fixation detection. Specifically, fixations were detected with a maximum gaze velocity threshold of $40°/s$ under the condition of relatively stationary head movement (head moving velocity lower than $12°/s$). In addition, the minimum ($100ms$) and maximum ($500ms$) duration thresholds were used to filter fixation. Saccades were detected using the normal I-VT algorithm [20], with a minimum gaze velocity threshold of $80°/s$, and minimum ($30ms$) and maximum ($80ms$) duration thresholds for the follow-up filtering.

Based on those detected eye movement events, measures such as blink rate, fixation rate and duration, and saccade amplitude were calculated.

5 Results

Dependent variables of eye movements were calculated and compared. The Shapiro-Wilk test was performed to test for data normality. For normally distributed data, the dependent variables across the five locomotion conditions were compared using repeated-measures ANOVA and paired t-test as post-hoc tests for the pairwise comparisons. Friedman test was used as a non-parametric test with Nemenyi as the post-hoc test. Bonferroni correction was applied in the post-hoc tests. The significance level was set at $\alpha = 0.05$ for all tests. The statistical test results are summarized in Table 1 and plotted in Figure 2 to 5, with asterisks in the results indicating significant differences (*, **, *** and n.s. for $p < .05$, $p < .01$, $p < .001$, and no statistical significance, respectively). All statistical analyses were performed using Pingouin[3], an open-source Python[4] package.

Blink rate Statistical tests revealed a significant effect of locomotion methods on participants' blink rate, with $F(4, 56) = 2.65$,

[1]https://store.steampowered.com/

[2]https://unity.com/

[3]https://pingouin-stats.org/

[4]https://www.python.org/

Table 1: Statistical comparison results of eye movement metrics between different locomotion methods. Significant differences are highlighted with *, **, and *** for $p < .05$, $p < .01$, and $p < .001$, respectively.

Metrics	Condition_1	Mean (SD)	Condition_2	Mean (SD)	Significance
Blink rate	Arm Swinging	6.85 (5.35)	Joystick	9.53 (3.68)	$p = .045$, *
Blink rate	Dash	5.05 (3.09)	Joystick	9.53 (3.68)	$p = .004$, **
Blink rate	Dash	5.05 (3.09)	Teleportation	9.06 (6.68)	$p = .018$, *
Fixation rate	Arm Swinging	34.16 (15.67)	Joystick	59.53 (11.85)	$p = .002$, **
Fixation rate	Arm Swinging	34.16 (15.67)	Teleportation	56.17 (14.20)	$p = .012$, *
Fixation duration	Arm Swinging	239.86 (19.54)	Joystick	205.04 (23.67)	$p < .001$, ***
Fixation duration	Arm Swinging	239.86 (19.54)	Teleportation	219.54 (22.92)	$p = .047$, *
Saccade amplitude	Arm Swinging	8.60 (2.21)	Joystick	10.12 (1.53)	$p = .021$, *
Saccade amplitude	Arm Swinging	8.60 (2.21)	Teleportation	10.28 (1.48)	$p = .010$, *
Saccade amplitude	Grappling	9.47 (1.58)	Teleportation	10.28 (1.48)	$p = .017$, *

$p = .042$. As shown in Figure 2, the blink rate ($blinks/min$, abbreviated as b/m) differed significantly between some of the locomotion conditions, with the blink rate in the joystick condition ($M = 9.53b/m$, $SD = 3.68b/m$) is significantly higher than in the dash ($M = 5.05b/m$, $SD = 3.09b/m$) and arm swinging ($M = 6.85b/m$, $SD = 5.35b/m$) conditions, with $p = .004$ and $p = .045$, respectively. In addition, the blink rate in the teleportation condition ($M = 9.06b/m$, $SD = 6.68b/m$) is also significantly

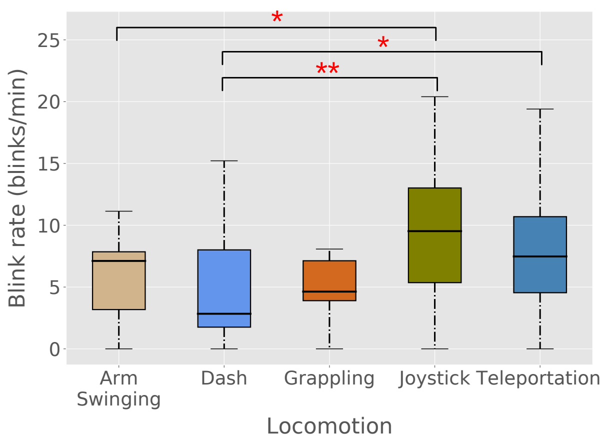

Figure 2: Blink rates in each locomotion condition. Significant differences are highlighted with * and ** for $p < .05$ and $p < .01$, respectively.

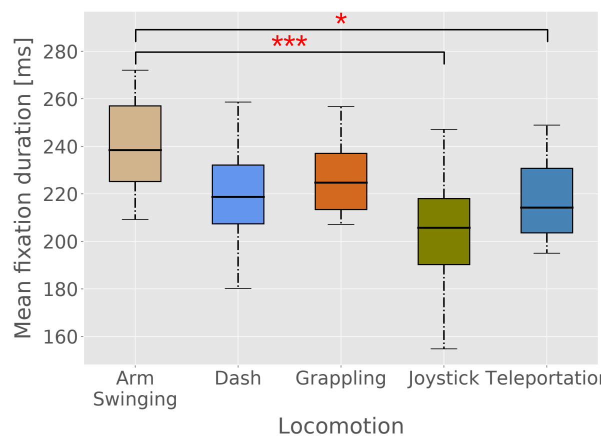

Figure 4: Mean fixation durations in each locomotion condition. Significant differences are highlighted with * and *** for $p < .05$ and $p < .001$, respectively.

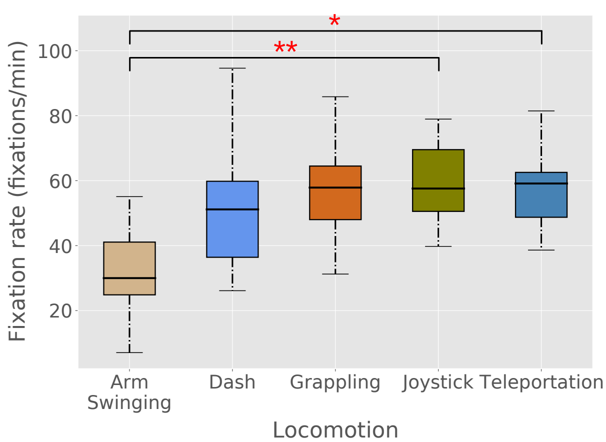

Figure 3: Fixation rates in each locomotion condition. Significant differences are highlighted with * and ** for $p < .05$ and $p < .01$, respectively.

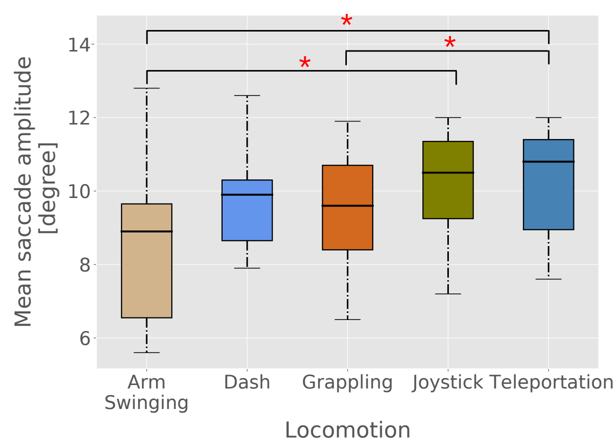

Figure 5: Mean saccade amplitudes in each locomotion condition. Significant differences are highlighted with * for $p < .05$.

higher than in the dash condition, with $p = .018$.

Fixation rate With regard to fixation, statistical tests showed a significant effect of locomotion methods on participants' fixation rate, with $F(4,56) = 8.78$, $p < .001$. As shown in Figure 3, the fixation rate ($fixations/min$, abbreviated as f/m) in the arm swinging condition ($M = 34.16 f/m$, $SD = 15.67 f/m$) is significantly lower than in the joystick condition ($M = 59.53 f/m$, $SD = 11.85 f/m$), with $p = .002$. In addition, the fixation rate in the arm swinging condition is also significantly lower than in the teleportation condition ($M = 56.17 f/m$, $SD = 14.20 f/m$), with $p = .012$.

Fixation duration Not only fixation rate but also the mean fixation duration was found to be significantly affected by the locomotion method. The mean fixation duration in the arm swinging condition ($M = 239.86 ms$, $SD = 19.54 ms$) is significantly longer than in the joystick condition ($M = 205.04 ms$, $SD = 23.67 ms$), with $p < .001$. In addition, the mean fixation duration in the arm swinging condition is significantly longer than in the teleportation condition ($M = 219.54 ms$, $SD = 22.92 ms$), with $p = .047$.

Saccade amplitude Furthermore, statistical tests revealed a significant effect of locomotion methods on participants' mean saccade amplitude, with $F(4,56) = 7.59$, $p < .001$. As shown in Figure 5, the mean saccade amplitude in the teleportation condition ($M = 10.28°$, $SD = 1.48°$) is significantly larger than in the arm swinging ($M = 8.60°$, $SD = 2.21°$) and grappling ($M = 9.47°$, $SD = 1.58°$) conditions, with $p = .010$ and $p = .017$, respectively. In addition, the mean saccade amplitude in the joystick condition ($M = 10.12°$, $SD = 1.53°$) is also significantly larger than in the arm swinging condition, with $p = .021$.

6 Discussion

We found that eye movements, reflecting participants' temporal cognitive processing load, were significantly affected by locomotion methods (see Figure 2 to Figure 5). In particular, the mean blink rate was higher in the joystick condition than in other locomotion conditions and significantly higher than in the arm swinging and dash conditions. In addition, the mean blink rate was significantly higher in the teleportation condition than in the dash condition. Previous work has shown that the blink rate is negatively correlated with cognitive load [5, 23]. Therefore, the blink rate results in this study may suggest that participants had lower cognitive load when navigating the VE using the joystick and teleportation locomotion methods than when using the arm swinging and dash locomotion methods. The finding that the joystick elicited less cognitive load in participants during VR locomotion is consistent with the previous study showing that the joystick is less fatiguing than the arm-cycling and point-tugging, providing a greater sense of control, and is more enjoyable than teleportation [6].

In addition to blinks, our results showed that the mean fixation duration in the joystick and teleportation conditions was significantly shorter than in the arm swinging condition. Previous work has shown that fixation duration is indicative of users' cognitive processing load. It was found that higher cognitive load was associated with longer fixation duration [5, 23]. This may indicate that participants had lower cognitive load and shorter processing time for visual information when using the joystick and teleportation compared with other locomotion methods. In addition, fixation rate was also found to correlate with cognitive load [23]: the higher the load, the lower the fixation rate. This further supports the results on fixation duration, which state that joystick and teleportation elicit lower cognitive load than arm swinging. This is not surprising, as fixation duration was negatively correlated with the number of fixations. The fixation results are consistent with the blink rate results discussed above.

Furthermore, we found that the mean saccade amplitude in the teleportation condition was significantly larger than in the arm swinging and grappling conditions, and the mean saccade amplitude in the joystick condition was significantly larger than in the arm swinging condition. Similar to blink and fixation rate, saccade amplitude was also found to be negatively correlated with cognitive load in previous work [16]. Therefore, these results again suggest that participants had a lower cognitive load when using the joystick and teleportation methods than when using the arm swinging and grappling.

Overall, our results on eye movements (i.e., blinks, fixations, and saccades) are interrelated, suggesting that joystick and teleportation cause less cognitive processing load in participants than other locomotion methods. Although no previous locomotion studies have evaluated eye movements as a measure of cognitive load, our findings were validated by a number of previous eye movement studies suggesting that eye movements are a valuable tool for assessing cognitive load. Furthermore, our findings that joystick and teleportation elicit less cognitive load are also consistent with previous work showing that joystick is an enjoyable locomotion method and teleportation elicits less motion sickness [6, 7, 13]. Typically, participants are assumed to have a lower cognitive load when they have a more pleasant VR experience and less motion sickness. Taken together, our findings provide strong evidence for the effectiveness of eye movements as a proxy for assessing cognitive load in interaction tasks with VR systems (e.g., VR navigation); moreover, eye movements as objective measures can compensate for or even substitute questionnaires. This argues for the use of eye-tracking methods in future studies, as cognitive processing load during VR locomotion has rarely been investigated, providing important avenues for the evaluation of VR locomotion methods.

7 Conclusion

In this study, we evaluated five common gait-free locomotion methods using eye movements to assess participants' cognitive processing load during navigation in VEs. Our results showed that the locomotion methods significantly affected participants' cognitive state, with joystick and teleportation locomotion methods found to elicit less cognitive load in participants. However, no significant differences in eye movements were found between other three locomotion methods, i.e., arm swinging, dash, and grappling.

Our results demonstrate the effectiveness and the feasibility of using eye movements as a proxy to study human cognitive behavior during VR locomotion, which can be used as compensation or potential replacement for questionnaires. Our study offers profound implications for future studies in this research domain that use eye movements as a superior objective measure of users' cognitive load, and thus can be further used as a tool to assess VR locomotion techniques.

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