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# A Comparative Study of 3D Navigation Techniques Using Trackpads in Desktop VR

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**ABSTRACT – The limited input capabilities of trackpads compared to traditional mice hinder smooth 3D navigation, impacting productivity and user experience in design and gaming software. This research investigates the effectiveness of current trackpad-based 3D navigation methods. By comparing task performance user feedback, and identifying the strengths and weaknesses of various techniques, the study aims to guide the development of more intuitive trackpad navigation solutions.**

**KEYWORDS:** Trackpad, 3d Navigation, Interactive, User experience, System usability scale

## 1. Introduction

Trackpads are ubiquitous input devices on laptops, but their limited control variety hinders their usability compared to mice for general tasks. Mice are indirect, relative input devices with two degrees of freedom (DoF) and three states: constant or isometric weight, which corresponds to mouse movement on the x and y axes, and three states: hovering, tracking, and dragging. In contrast, trackpads are direct, absolute, isometric input devices with two DoF and two states. [1]. Fitts' law, which predicts the time it takes for a user to reach a target area, has been extensively studied in comparing mice and trackpads. It relates the time it takes to click on a target object to the distance from the object and the size of the target object. It has been continuously used in UI design for various elements on websites and applications [2][3][4]. The restricted control capabilities of trackpads often lead to unintuitive interactions with 3D content, resulting in challenges for performance and user experience. These limitations are particularly evident in specialized applications like design software or gaming. This study explores the effectiveness of interaction techniques and 3D content rendering on trackpads, focusing on primary tasks performed on laptops running Windows and Linux operating systems. This is primarily due to these devices' lower cost than OSX laptops, which are relatively expensive. The research compares the work results regarding performance and effectiveness in navigating 3D environments. Developers used three game engines to develop applications in similar environments with different navigation methods: mouse and keyboard control, WASD keyboard control [5][6], trackpad and keyboard control, and touchpad control only. Usability data was collected using the System Usability Scale (SUS) [7][8] and satisfaction scores from a sample of 90 participants. The study's results will show each control method's advantages and disadvantages, providing guidelines for developing more intuitive and easy-to-use trackpad navigation systems. This research will guide intuitive trackpad-based navigation systems in 3D action-adventure games. The applications focus on in-world exploration and interaction, where players use the trackpad for camera control and movement, like using a mouse in traditional PC games. While users navigate primarily with the trackpad, they will still use the keyboard to jump, attack, and interact with objects. By analyzing the effectiveness of different trackpad navigation methods, this research aims to inform the design of future games that prioritize trackpad-based input.:

RQ1: Can 3D navigation using a trackpad alone be as effective as using a mouse and keyboard and a trackpad with a keyboard?

RQ2: Can the evaluation of trackpad usability be used as a guideline for navigation system design?

## 2. Related Work

This research develops a program to record user log files through the Unity game engine.

### 2.1 Game Engine

The game engine is a primary tool for creating interactive game media. Users can start developing games or interactive media quickly, saving time and allowing for

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rapid game content and systems development without writing all the code from scratch [9]. This rapid development is possible because the engine includes many components that work together, which users do not need to set up initially. These include physics, graphics processing, and memory management systems, allowing game developers to focus on game design and content without worrying about technical details. Currently, game engines support multiple platforms. This research uses the Unity game engine as the primary game engine for development with the C# programming language. It collects navigation and control data through log files recorded at 30 frames per second (FPS) for analysis of usability evaluation of 3D navigation.

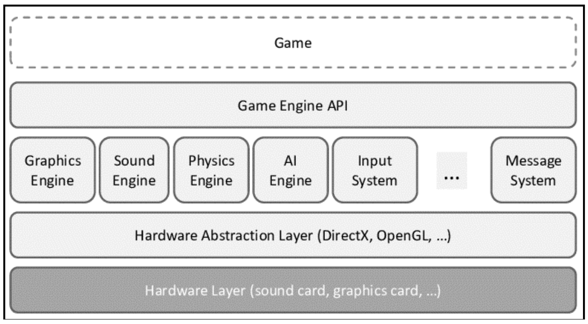


*Figure 1. The architecture of Game Engine [10].*

## 2.2 System Usability Scale (SUS)

The primary data analysis in this research utilized a usability evaluation of the 3D navigation system. Usability is defined in the ISO 9241 standard as the effectiveness, efficiency, and satisfaction of targeted users in achieving specified tasks in a particular environment. Quesenbery (2004) [11] further defines usability through the 5Es principles:

**Effective:** The system must enable users to complete tasks accurately and successfully.

**Efficient:** The system must allow users to complete tasks quickly and with minimal effort.

**Engaging:** The system must be enjoyable and motivating to use.

**Error tolerance:** The system must be forgiving of user errors and provide clear feedback.

**Easy to learn:** The system must be easy to understand and use, even for first-time users.

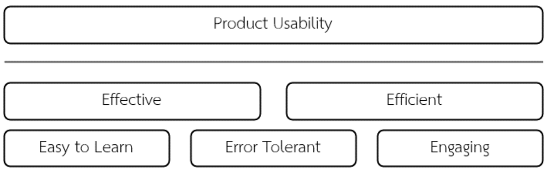


*Figure 2. 5Es usability model.*

## 2.3 Usability Evaluation of 3D Navigation Systems

Usability evaluation is a systematic method for determining whether a product or service aligns with its target users' usability needs and expectations. Within 3D navigation, these evaluations often emphasize technical components, such as data visualization quality (Bleisch, 2012). Various research efforts have explored the usability of navigation systems to enhance their effectiveness. For instance, Delikostidis et al. (2013) [13] highlighted that the presence and visibility of landmarks significantly improve navigation usability.

Similarly, Liao et al. (2017) [14] conducted a comparative study between 2D and 3D maps, analyzing their effectiveness for navigation tasks. Furthermore, Aditya (2010) proposed a comprehensive five-factor model, known as the 5Es, which serves as a framework for assessing the usability of map interfaces [15]. To further develop the findings of these foundational studies, the current research adopts a similar evaluation framework to understand better user preferences and requirements for 3D map-based navigation systems.

## 2.4 Characteristics, Advantages, and Limitations of Input Devices in 3D Navigation

Input devices such as trackpads, mice, and keyboards are critical in user interaction within 3D environments. Each device offers unique characteristics that influence usability, performance, and user experience, particularly in tasks involving navigation and interaction in virtual spaces.

The trackpad, widely recognized for its compact design and integration into laptops, is a direct, absolute input device with two degrees of freedom (DoF). Its portability and convenience are prioritized by users who value mobility. Trackpads eliminate the need for external accessories, making them ideal for mobile setups. However, accuracy is generally reduced compared to a mouse, and reaction times are slower, leading to decreased movement efficiency. These limitations can increase cognitive load, particularly during complex tasks that demand precision or rapid input.

In contrast, the mouse is an indirect, relative input device that provides precise control with two DoFs, making it a preferred choice for tasks requiring detailed navigation or fine control. Typically used alongside a keyboard, the mouse offers faster reaction times and greater accuracy than a trackpad, enhancing its usability in 2D and 3D environments. Nevertheless, the mouse's reliance on a flat surface and its role as an external accessory limit its portability, which can be inconvenient for some users.

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On the other hand, the keyboard serves primarily as a tool for inputting commands or controlling navigation through predefined key mappings. It does not offer direct control over orientation but is reliable for executing discrete commands. Layouts like WASD are commonly used for movement in gaming and virtual spaces, providing a standardized approach for directional inputs. However, the keyboard's inability to handle rotational or orientation control necessitates using complementary devices such as a mouse or trackpad to enable complete navigation functionality.

The usability and efficiency of input devices in 3D navigation depend on their ability to balance movement and orientation control. While the mouse offers superior precision, the trackpad’s convenience and integration make it a viable alternative in scenarios where portability is prioritized. While robust for movement input, keyboards require complementary devices for effective orientation control.

Previous studies have explored the usability of various input devices, highlighting their respective strengths and limitations in different contexts. For instance, Watral et al. (2023) compared the performance of mice and trackpads in a web-based application for assessing visuomotor adaptation. While motor learning outcomes were similar for both devices, reaction times were significantly faster for mouse users, emphasizing the trackpad's relatively higher cognitive demands and reduced movement efficiency. These results underline the importance of considering cognitive load and precision when evaluating input devices for 3D navigation tasks [16].

Similarly, Kar et al. (2015) conducted a comparative analysis of input devices, including mice and trackpads, focusing on their impact on posture, performance, and user comfort. The study found that mice consistently outperformed trackpads in precision-based tasks, which aligns with the findings of Watral et al. However, trackpads demonstrated ergonomic advantages in certain scenarios, suggesting that their usability may depend on the specific context and user requirements. Together, these studies provide a foundation for understanding how input device characteristics influence user performance and inform the selection of appropriate tools for 3D navigation. The research by Watral et al. (2023) aligns with the provided summary. It focuses on comparing mouse and trackpad performance in an online application designed to assess visuomotor adaptation. The study concluded that while both devices resulted in similar motor learning outcomes, mouse users demonstrated faster reaction times than trackpad users. The findings suggest that operating a trackpad may impose greater cognitive demands and result in less efficient movement control.

# 3. Methodology

## 3.1 Current navigation techniques

Researchers broadly classify navigation techniques in 3D environments into Discrete and Continuous navigation. [17]

Discrete navigation explicitly defines the user's orientation or position without any intermediate transition. In a 3D environment, a predefined "area" in the form of cells or a "grid" restricts the user. The user can move from one point to another by instantly changing position from one cell to another.

Continuous navigation, on the other hand, rotates and moves the user gradually over time. Users can move freely in the virtual world without being restricted by cells or grids. Users can move through simulated walking, running, jumping, or flying to any point in the 3D environment at any time during the game.

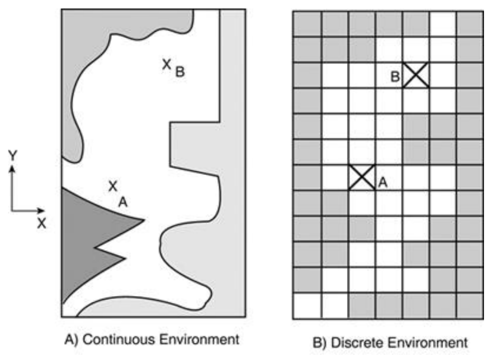


*Figure 3. Discrete and Continuous navigation techniques.*

Navigation can be divided into two components: Travel and Orientation. Travel allows users to explore their surroundings, while Orientation allows them to change their viewpoint within the environment. Each navigation technique is typically tied to a specific input method. Combined with task design for users, data on time and usage can be collected and analyzed to assess the efficiency, effectiveness, and usability of navigation techniques through statistical analysis of data collected from user groups or experimental samples. [18]

## 3.2 Interface Navigation

The three navigation interfaces presented in this study were limited to using only three input devices: a trackpad, a mouse, and a keyboard. The first method paired mouse control with the keyboard through the keyboard. The second method paired trackpad control with the keyboard. Both methods used the WASD keyboard layout for travel input and the mouse for orientation input in the first method and the trackpad in the second method.

The third method used the trackpad as the primary input device but changed the orientation input method to tapping and holding the trackpad with one finger and used the travel input method by tapping the trackpad with two fingers and moving in the Y-axis on the trackpad by moving from the bottom to the top for forward movement and from the top to the bottom for backward movement.

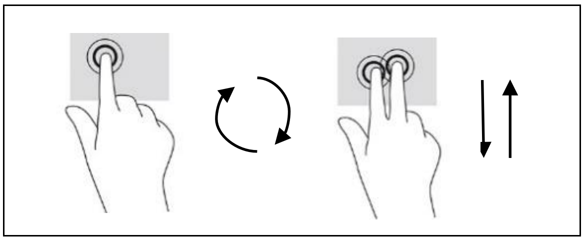

*Figure 4. The third method is used via trackpad.*

**User Interface 1: Mouse and Keyboard**
This navigation system employs a traditional setup using a mouse and keyboard. The user controls movement with the keyboard's WASD keys—W for forward, S for backward, and A/D for sidestepping left and right. The mouse controls orientation, allowing users to adjust their view by moving the mouse to rotate in the desired direction.

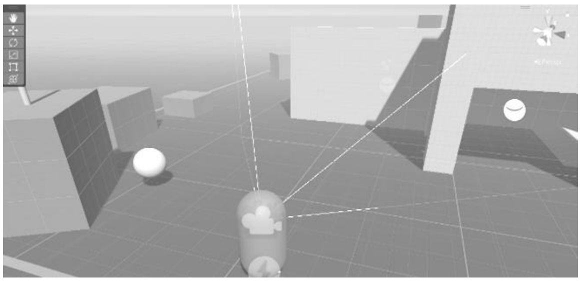

*Figure 5. Design a consistent user interface in Unity where elements can be controlled through different movement mechanisms.*

**User Interface 2: Trackpad and Keyboard**
This navigation system combines a keyboard and trackpad for user input. The keyboard's WASD keys are utilized for movement in the virtual environment, while the trackpad facilitates directional adjustments. Users can swipe or tap the trackpad with a single finger along the x-axis (left and right) to simulate rotation towards a desired direction, providing an intuitive way to control navigation.

**User Interface 3: Control using Trackpad**
In this interface, the trackpad is the sole input device for navigation. Directional control differs from the second interface, requiring two fingers instead of one to input travel commands. Users can simultaneously tap and move their fingers on the trackpad to adjust direction and simulate movement, offering a more dynamic and tactile navigation experience.

## 3.3 Designing an environment and tasks

In this study, we designed a 3D environment using the Unity 3D game engine. The environment consisted of a rectangular room with a clearly defined path for the user to follow around the map. The user's task was to navigate to four Points of Interest (POIs) located in each corner of the scene within a specified time limit.

## 3.4 Experiment Participants and Conditions

This experiment involved 90 participants, consisting of students and members of the public. The participants were divided into three subgroups of 90 people each, according to the following conditions:

Group α: Used interface 1 Mouse and Keyboard
Group β: Used interface 2 Trackpad and Keyboard
Group γ: Used interface 3 Control using Trackpad

## 3.5 Operation and Procedure

For each group of participants (α, β, γ), an instructor will guide them through completing the assigned tasks in each trial. The tasks require participants to navigate the 3D environment and visit all designated Points of Interest (POIs). Each participant will receive a one-minute introduction to the system before the experiment.

This introduction will cover the controls for navigation and the locations of the POIs, which will be displayed on a map along with the corresponding navigation routes. Following the instructor's demonstration, participants will proceed to begin their trials.

Suppose a participant fails to complete the task within the allotted time of one minute. In that case, the researchers will mark the trial as unsuccessful and allow the participant to repeat the task.

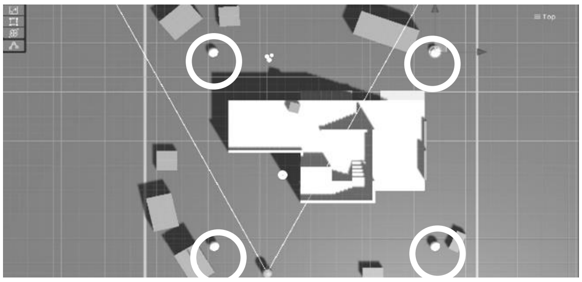

*Figure 6. Top view of a simulated environment designed in Unity, including the positions of four POIs. The user's task is to travel to all four locations that appear on the square area of the scene.*

After the repeated trials, researchers will interview to collect information on the factors contributing to the task failure. This information will support the research topic. After the users or the sample group have completed the experiment, there will be a usability evaluation form for the developed program, the System Usability Scale

(SUS), to collect data on whether the overall score is more than 68 points.

### 3.6 Data Definition

This research primarily collects time-based data in seconds to evaluate the effectiveness of navigation techniques. However, the program also collects other control input data that affect user actions, such as decision-making, accuracy, and task correctness. Researchers analyze the collected data together with time. The definitions of each measurement data are as follows:

**Total Time:** The experiment's timer starts when the user presses any button to begin the task and stops when the user visits all POIs in the program. Visiting all POIs and stopping the timer signifies task completion for the user or the sample group.

**Navigation Time:** This navigation tool records the time spent exploring a simulated environment. It captures data every time a navigation-related key is pressed, including WASD keyboard movement and camera rotation. The recorded time data and user location data at POIs are used to verify whether users or participants are completing the target or task correctly.

**Camera Translation:** In a 3D environment, a character created in a first-person view has a camera that serves as the user's viewpoint, like their regular sight. In navigation that specifies the movement of this camera, data on the time spent exploring the simulated environment is recorded. This happens every time a button related to movement is pressed in all three groups: α, β, and γ, and there is a change in the movement position values in the program on the x and z axes.

**Camera Rotation:** This data records the time spent rotating the camera view in horizontal and vertical axes. For groups β and γ, the system records the time of a single finger tap on the device. For group α, the system records the time of a mouse button press. Like camera translation, the corresponding button/mouse press increases the time value.

**Camera Total Time:** This metric measures the total duration of camera movements initiated by the user, such as panning and rotating, within a first-person perspective (FPP) environment [19]. It refines previously established metrics, focusing specifically on camera interactions.

**Idle Time:** Idle Time represents the duration a user is not actively interacting with the navigation system. Researchers determine Idle Time by subtracting the total camera usage time from the overall navigation time. This metric quantifies the pauses or inactive periods users take while navigating the environment.

$$Idle_{Time} = Navigation_{Time} - CameraTotal_{Time}$$

## 4. Result

The results of the study are presented in the appropriate sections for each of the measurements defined above. We elaborate more on these results in the discussion section.

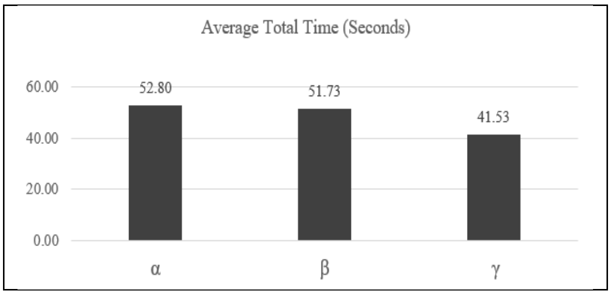


*Figure 7. Average total time of task.*

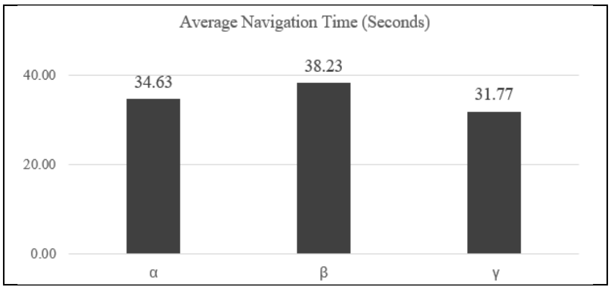


*Figure 9. Average navigation time of task.*

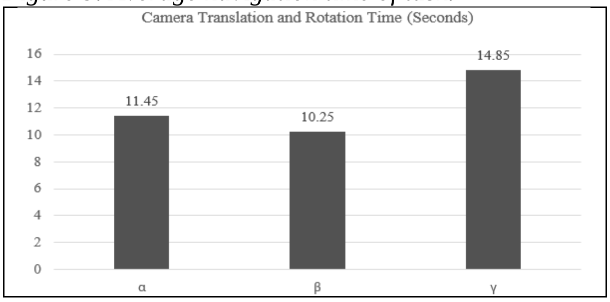


*Figure 10. Average Camera translation time of task*

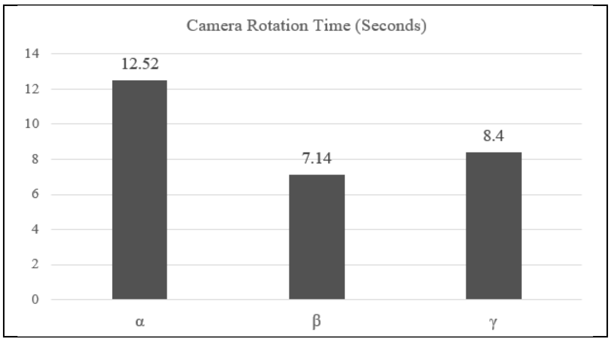


*Figure 11. Average Camera rotation time of task*

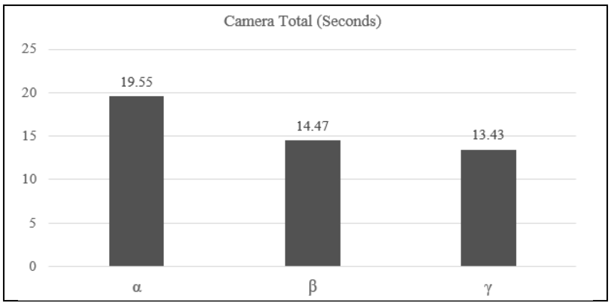


*Figure 12. Average Camera Total time of task.*

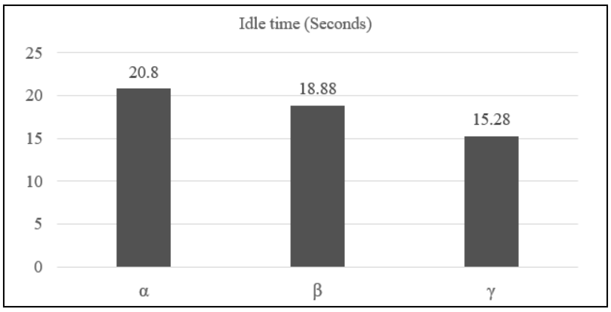


*Figure 13. Average idle time of task.*

The interface γ exhibited the shortest average total time (41.53s, SD = 1.431s), followed by interface β (51.73s, SD = 1.981s) and interface α (52.80s, SD = 1.689s) (see Figure 7). A one-way ANOVA revealed a significant difference in mean total game times across at least one group ($F(2, 87) = 4.52$, $p < 0.01$). Interface γ demonstrated significantly shorter game times compared to interface α (WASD and mouse controls), while interface β (WASD and trackpad) showed no significant difference compared to either. This lack of a significant difference between interface β (WASD and trackpad) and interface γ (trackpad only) indicates that trackpad-only navigation could be as efficient as a combined WASD and trackpad approach.

About average camera translation Interface α average total time was 11.45s (SD 1.185s), interface β average total time was 10.25s (SD 1.083s), and interface γ was 14.85s (SD 2.065s). An ANOVA revealed significant differences in camera translation and rotation (see Figures 10 and 11). The average time for camera translation for γ was significantly different with $F(2, 87) = 4.76$, $p < 0.0114$. The average time spent rotating the camera for Interface α was 12.52s (SD 2.255s), interface β was 7.14s (SD 2.025s), and Interface γ was 8.4s (SD 2.061s), which was also significantly different from $F(2, 87) = 4.12$, $p = 0.02$. Camera rotation times differed significantly between control methods. Interface α (WASD and mouse) was significantly faster than interface γ (trackpad-only). Interface β (WASD and trackpad) did not significantly differ in rotation speed from the other interfaces. This analysis revealed a significant main effect of the control method on the average camera total time: $F(2, 87) = 11.23$, $p = 0.00003$.

Post-hoc comparisons utilizing Tukey's HSD test [20] demonstrated that interface α exhibited significantly longer durations for camera tasks compared to both trackpad-based control methods (β, $p = 0.001$) and Trackpad only (γ, $p = 0.005$). However, the two trackpad-based methods did not significantly differ ($p = 0.999$).

The ANOVA results are significant, revealing a substantial main effect of the control method on navigation times. The findings, with a significant main effect of the control method on navigation times, $F(2, 87) = 10.23$, $p < 0.0001$, are crucial for our understanding. Post-hoc comparisons test further revealed that the interface β took the longest time to navigate, while the interface γ took the shortest time.

The interface α had an average navigation time. The results showed a significant main effect of the control method on idle times, $F(2, 87) = 10.34$, $p = 0.0002$. Researchers observed that interface γ had the lowest average idle time, and interface α had the highest idle time. This indicates that the control method significantly influences idle times, with interface γ being the most efficient and interface α being the least efficient.

Assessing whether this aspect constitutes a disadvantage necessitates considering additional metrics such as task completion time and accuracy. The System Usability Scale (SUS) [21] scores obtained for the three interfaces indicate minor differences in perceived usability. Interface α (WASD and mouse) recorded the highest average SUS score of 70.15, followed by interface γ (trackpad only) at 69.66 and interface β (WASD and trackpad) at 68.94. These findings have practical implications for the design and implementation of control methods in 3D navigation systems.

Although the differences in scores are relatively small, they imply a slight preference for the traditional WASD and mouse setup regarding overall usability in the context of 3D navigation. Importantly, the usability scores for all interfaces fall within the acceptable range, providing reassurance that users did not perceive any interfaces as unusable.

## 5. Conclusion and Future Work

The findings of this research demonstrate that interface γ, which relies solely on trackpad controls, exceeded expectations (RQ1). Although the traditional combination of WASD keys and a mouse (interface α) showed a slight advantage in overall navigation time, the trackpad-only interface proved to be a surprisingly strong contender. It stood out regarding navigation performance and minimizing idle time, showcasing an efficient and well-structured control approach. While interface γ required slightly more time for camera translation, its performance in other areas reinforces the trackpad's potential as a capable and user-friendly tool. These results suggest that trackpad-based controls can challenge traditional human-computer interaction (HCI) and virtual reality (VR) standards.

Moreover, the System Usability Scale (SUS) scores revealed minimal differences in perceived usability across the interfaces (RQ2). Interface α achieved the highest average score of 70.15, but all interfaces (α, β: 68.94, and γ: 69.66) remained within the acceptable range for usability. This indicates that all control schemes can provide a user-friendly experience for 3D navigation and instill confidence in users regarding their choices. This study introduces alternative control methods for navigating 3D virtual environments, with the trackpad-only approach demonstrating competitive performance against traditional methods. Despite a slight increase in camera translation time, the trackpad-only interface excelled in navigation efficiency. It reduced idle time, confirming its potential as a practical and effective choice for virtual space navigation.

Beyond exploring 3D navigation, this research allows further improvements in trackpad usability across various contexts. The results highlight the strengths and limitations of trackpad navigation, particularly in terms of accuracy, comfort, and cognitive load. These insights can inform the development of interfaces that cater to a broader range of users.

Finally, this study provides valuable guidance for game designers and software developers seeking to create products that maximize the functionality of trackpads. The findings offer practical insights into designing navigation systems that balance usability and responsiveness to real-world user needs. This research encourages the development of accessible and practical products that enhance navigation and interaction in virtual environments while delivering more user-friendly solutions.

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