The RayHand Navigation: A Virtual Navigation Method with Relative Position between Hand and Gaze-Ray

Sei Kang
Chonnam National University, Gwangju, Korea, Republic of
200793@jnu.ac.kr

Jaejoon Jeong
Chonnam National University, Gwangju, Korea, Republic of
182709@jnu.ac.kr

Gun A. Lee
University of South Australia, Adelaide, SA, Australia
gun.lee@unisa.edu.au

Soo-Hyung Kim
Chonnam National University, Gwangju, Korea, Republic of
shkim@jnu.ac.kr

Hyung-Jeong Yang
Chonnam National University, Gwangju, Korea, Republic of
hjyang@jnu.ac.kr

Seungwon Kim*
Chonnam National University, Gwangju, Korea, Republic of
seungwon.kim@jnu.ac.kr

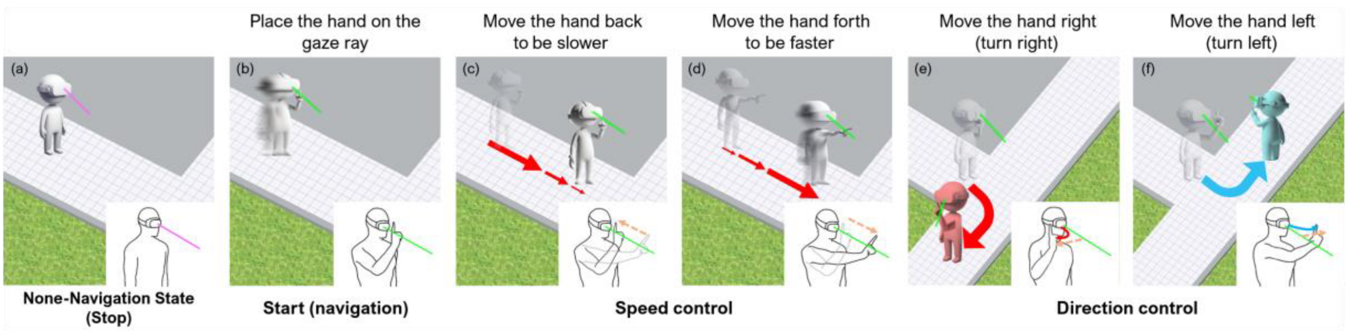

Figure 1: The RayHand navigation technique: A semi-transparent purple gaze ray indicates the initial navigation direction before starting navigation in the none-navigation state (a). A user starts navigation by placing his/her hand on the gaze ray which changes its color to green and starts being controlled by the hand rather than the gaze direction (b). The user controls the navigation speed by moving her hand back and forth (c-d), and changes the navigation direction by moving the hand left or right (e-f).

ABSTRACT

In this paper, we introduce a novel Virtual Reality (VR) navigation method using gaze ray and hand, named RayHand navigation. It supports controlling navigation speed and direction by quickly indicating the initial direction using gaze and then using dexterous hand movement for controlling the speed and direction based on the relative position between the gaze ray and user's hand. We conducted a user study comparing our approach to the head-hand and torso-leaning-based navigation methods, and also evaluated their learning effect. The results showed that the RayHand and head-hand navigations were less physically demanding than the torso-leaning navigation, and the RayHand supported rich navigation experience with high hedonic quality and solved the issue of the user unintentionally stepping out from the designated interaction area. In addition, our approach showed a significant improvement over time with a learning effect.

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CCS CONCEPTS

• **Human-centered computing** → Interaction design; Interaction design process and methods.

KEYWORDS

virtual reality, navigation, gaze-ray

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1 INTRODUCTION

Navigation in Virtual Reality (VR) has been studied for decades [15, 39, 46], and the main two components are controlling the travel speed and direction [38]. Many researchers have proposed novel navigation techniques [4, 11, 14, 33, 35], and their approaches can be categorized into four types: walking [11, 51], steering [33, 35, 60], selection [4, 8, 15], and manipulation based navigations [14, 45, 52]. Among them, steering-based navigation (e.g., as if driving a car with a steering wheel) has two main benefits: 1) providing a rich navigation experience by allowing the user to look around the scene without any omission or distortion in viewpoint changes [4, 39], and 2) efficiently traveling to the destination without requiring a large physical area or a large physical movement [6]. Most steering-based navigation methods, however, exploit single input modality such as gaze, hand, or torso [5, 7, 33, 57], hence being limited to the weakness of the input modality. The gaze navigation has the Midas touch issue [30] (e.g., simply looking at an object causes unintentional movement). The hand navigation typically requires additional device for speed control [53] and sometimes conflicts with hand object manipulation. The torso navigation has issues of requiring additional tracker for tracking torso, and causing physical stress on the body due to the leaning pose [33, 60].

As a solution to overcome these issues, we introduce a new navigation technique which combines gaze and hand interactions. With our new navigation technique, a user can initiate navigation by placing her hand on the gaze ray which decides the initial navigation direction (see Figures 1a and 1b). Then the user can control the navigation speed either slower or faster by moving the hand back or forth (see Figures 1c and 1d), and turn left or right by moving the hand left or right relative to the ray which is no longer updated by the gaze direction (see Figures 1e and 1f). This resolves the Midas touch issue because the gaze input does not control the direction and speed after initiating navigation. However, it still takes the benefit of quick gaze based indication of the initial navigation direction. Moreover, no additional input device is required by leveraging the hand motion to control the navigation speed and direction. To evaluate the new navigation technique, we conducted a user study comparing it to two other conditions: the most well-known torso-leaning navigation [60] and another promising head-hand position-based navigation [38]. In addition to comparing the three navigations, we investigated the learning effect of each navigation technique by conducting two rounds of the experiment and comparing their results.

This study has two major novelties. First, to the best of our knowledge, this is the first study introducing the design of a navigation technique which combines the gaze ray and hand interactions. Second, this is the first user study that empirically evaluates not only the proposed new method but also the head-hand position-based navigation proposed by Mine [38] by comparing against each other and the torso-leaning navigation [60].

2 RELATED WORK

Navigation (a.k.a. travel) is a task of moving the user's viewpoint from the current location to a new target location or rotating to the desired direction in a virtual environment (VE) [34].

2.1 Elements of Navigation

Navigation basically includes two types of movements: rotation (or turn) and translation [6], and each of them has speed and direction [38]. The direction of the rotation is either clockwise or anticlockwise around each axis in the 3-dimensional (3D) environment, and there are three types: pitch, roll, and yaw. The direction of the translation is the moving direction of the positional change, and it is also performed in any given dimension in the VE. To simulate the real-world navigation, the translation is mostly performed on a 2-dimensional (2D) floor in many previous studies [18, 33], so it typically includes moving forward/backward and left/right but not flying up or down. Similarly, the rotation in navigation usually involves rotation around the up vector, which is turning left or right, in many previous studies [1, 13, 20, 28].

The navigation speed implies how fast the rotation or translation is performed within a given amount of time, [5]. When controlling the rotation speed, researchers have been cautious of simulator sickness because fast rotation causes significant simulator sickness [13, 20]. According to Hu et al. [28], the rotation speed should be less than 60deg/s. There are mainly three types of translation speed control: constant [39], user selection [26, 60], and environment adaptive [42]. For example, Müller et al. [39] implemented a constant speed navigation for 'undo' locomotion. Zielasko et al. [60] and Hombeck et al. [26] allowed a user to control the translation speed by leaning the body and using voice input. Piumsomboon et al. [42] implemented the adaptive speed control according to the size of the user's avatar or the height of the user's viewpoint.

2.2 Navigation Techniques

Synchronizing real walking to VR navigation is the most natural and intuitive navigation but it is subject to a critical constraint of limited physical space [15, 51]. To overcome this, researchers investigated various types of interaction for navigation, such as walking, steering, selection, manipulation-based navigation, and automated navigation [37]. Automated navigation is a simple animation showing the view change or avatar movement without any user interaction, so it is less realistic and the user may sometimes feel like an observer.

Walking-based navigation uses a physical walking motion such as swinging arms [11] and/or moving legs [51]. It could be achieved with a special device like a treadmill [18] or with a dedicated body tracking system to identify the walking motion [43, 51]. Typical examples are the 'walking-in-place' [51] and the 'redirected walking' techniques [46] that enable infinite walking in a constrained physical environment. These walking-based navigation techniques are natural and intuitive as they adopt a walking motion. However, they require a high level of physical movement and advanced motion tracking solutions, and some approaches (e.g., 'redirected working') still need a decent amount of physical space. In addition, a user can have simulator sickness if the scene is not properly updated according to user's body movement [34].

Selection-based navigation allows users to choose the destination, and then their viewpoint either moves along a path or gets translated directly to the destination [15]. The latter method is typically referred to as 'teleportation', and instantly moving to the destination has the benefit of reducing motion sickness but also has risks of missing environmental details and causing spatial disorientation. To address this issue, Bozgeyikli et al. [8] introduced a method which allows a user to decide the orientation at the destination before teleportation. Bhandari et al. [4] introduced the "Dash" teleportation technique which does not instantly translate the viewpoint but animates a smooth translation to the destination.

This approach, however, still has the weakness of losing control of navigation during the dashing animation.

Manipulation-based navigation allows a user to manipulate camera to control the viewpoint. Cho et al. [14] and Raees et al. [45] implemented virtual-camera manipulation to control the user's navigation by rotating a sphere and using a finger control, respectively. Stoakley et al. [52] introduced the world-in-miniature interface that allowed a user to manipulate her replica in a miniature of the virtual scene and synchronized the replica manipulation with the navigation in the full-scale virtual scene. These manipulation-based navigations could be effective in controlling the viewpoint but it reduces the realism and sometimes makes discord between navigation and manipulation interactions.

Steering-based navigation provides spatial awareness and enhances immersion due to their continuous viewpoint movement [6]. It is also intuitive to control the direction and speed as this technique is also used in the real world, such as driving a car [9, 34]. Apart from using a special device (e.g., a driving wheel), researchers mainly used three body parts for steering navigation: gaze [16, 33], hand [35, 53], and torso [60]

From the review, we found that most navigation techniques are designed for two main purposes: 1) quickly arriving at the destination, and 2) providing a rich experience with continuous view change based on user's control of speed and direction. The selection and manipulation-based navigations focused more on quick arrival rather than providing a rich experience. The walking-based navigation would be the best for a rich navigation experience but requires a high level of physical movement. The steering-based navigation is well-balanced between the two purposes of quick arrival and rich experience.

2.3 Steering-Based Navigation and Issues

In this section, we review gaze, hand, and torso steering-based techniques that are rigorously studied [7, 33, 54]. When navigating in the real world, people tend to gaze in the direction they intend to move [21, 25, 29], hence navigating in the direction where the user is looking at in VR is natural, intuitive, easy to understand, and ideal for novice users [16, 34]. The gaze, however, can only indicate the direction element of navigation, so it requires additional methods to control the speed to work as a navigation method. Gaze based navigation also has the Midas Touch issue [30] which causes unintentional navigation while simply looking-around the scene. Hence, many researchers introduced additional input methods for controlling the speed while the gaze decides the navigation direction, in order to solve the Midas Touch issue and allow users to look around when not moving. Pressing a button is a simple way to control the speed but the speed is predetermined and discrete [16, 44, 53]. To support speed control in a continuous range, researchers developed leaning torso [59] or swinging arm [23] methods (i.e., leaning angle or arm-swinging speed decides the navigation speed). These approaches still have a weakness of a user not being able to simultaneously navigate and look-around, but has to stop the navigation to look-around.

As an alternative, researchers exploited hand or torso for steering navigation, and this allowed the user to freely look around while navigating [7, 55, 58]. Bowman [5] and Downey et al. [17] implemented hand steering navigation which allows the users to decide the navigation direction with a pointing hand but only at a constant speed. Mine [38] suggested the 'crosshairs navigation' which utilized the direction from user's head to a fingertip for translation. This solution, however, was only proposed and has not been formally evaluated with a user study. It can also suffer from accidentally triggering navigation while manipulating an object with user's hand. Zhang et al. [58] designed bimanual hand gestures to set navigation speed with the left hand and direction with the right hand, but it supported only three discrete speed levels: zero, walking, and running. Many researchers [33, 35, 53] explored pointing based steering with a hand-held controller because of the better tracking accuracy compared to tracking bare hand movements, and also the availability of a joystick and buttons on the controller for controlling speed. Holding a controller and using buttons and joysticks on it [34, 53, 60], however, may reduce the naturalness of navigation.

Torso steering navigation technique uses the torso-facing direction for navigation, hence it has the benefit of decoupling looking-around and navigation activities like the hand-steering method [54]. The torso steering navigation frees up user's hands by controlling the speed based on the leaning angle of the torso [22, 59, 60]. Nevertheless, it requires an additional tracker to track the torso, and the leaning pose causes physical demand on the body, especially when a user is standing.

2.4 Combining Gaze and Hand Interaction

Recently, several researchers combined the gaze and hand inputs for selection and manipulation, and their strategy is to use gaze for fast object identification and hands for precise operation [40, 41]. Bao et al. [3] adopted hand forward and backward movement to control the object depth on a gaze ray. Lystbæk et al. [36] introduced a selection technique which confirms selection of the gazed object when a fingertip moves into the gaze ray. Ryu et al. [47] introduced a distance object selection and manipulation technique in a dense area with many objects. In his technique, a user gaze decides a distant hand-operation area where the precise hand interaction is performed. These approaches were mainly for object selection and manipulation, hence may not be directly applicable for designing a navigation technique. Nevertheless, we took the lessons from these prior works to develop the two design principles for navigation: 1) employ precise hand movement as in Ryu's object-hand operation [47], and 2) use relative position between the hand and gaze ray as in the Bao's depth control [3]. Additionally, we defined two more principles in designing steering navigation based on reviewing previous navigation studies: 3) decouple looking-around and navigation activities and support both simultaneously, and 4) support full control of the speed and direction in continuous ranges for rich navigation experience.

With these principles, we designed a novel navigation technique named RayHand explained in the next section in detail, and conducted a user evaluation with a simple yet fundamental research question: '*Does the proposed navigation method which combines gaze and hand interactions serve a better navigation experience compared to other techniques?*'.

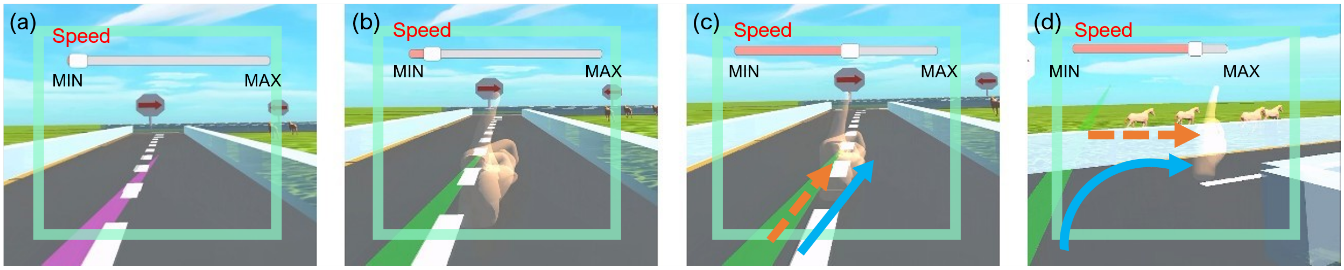

Figure 2: The user's views of the RayHand navigation interactions: The green-bounding box represents the hand tracking area and the speed bar shows the current navigation speed. A user looks at the road and the user's gaze direction is represented with a purple gaze ray (a), when a hand is placed on the ray, the navigation starts and the ray changes its color to green (b), moving the hand forward increases the navigation speed (c), moving hand left or right makes the view turn left or right (d).

3 RAYHAND NAVIGATION

With the design principles described in the previous section, we designed a navigation technique that combines gaze ray and hand interactions. The width of the gaze ray was 0.03m and the hand model was from the Vive Hand Tracking SDK 1.0.0 [19] (see Figure 2). Both were semi-transparent to mitigate the effect of occlusion. A green bounding box (0.8m × 0.8m) is placed at the center of the view, 0.82m away from the user's head to encourage the user to place and perform the hand movement inside of this tracking area. We refer to our proposed technique as the RayHand navigation.

3.1 Navigation Start and Stop

Before starting navigation, a user can freely look around and the system keeps displaying and updating a purple gaze-ray according to user's gaze direction (see Figures 1a and 2a). This purple gaze-ray allows the user to decide the initial direction of the navigation before starting. Navigation starts when the user places a hand on the gaze-ray for more than 0.3 second (see Figures 1b and 2b), and this 0.3 second threshold helps the user avoid an unintended start. Our initial design was placing an index fingertip on the ray, but it was found difficult as the ray kept moving quickly. When the navigation starts, the ray color is changed from purple to green as a visual feedback (see Figure 2b), and the hand takes the control of turning the ray left or right which indicates the navigation direction while keeping its origin at the head position (more details about the hand control is described in section 3.2; since the gaze loses the control of the gaze ray, we use the word 'ray' instead of 'gaze-ray' afterward). This switching of input method used for the ray control is for decoupling the navigation and looking-around activities by assigning navigation interaction to the hand control and looking-around activity to the head and gaze movement. The fist gesture or simply holding-down the hand (so the system would lose the tracked hand) stops the navigation, then the gaze ray turns back into purple and is updated by the user's eyes indicating the gaze direction.

3.2 Speed and Direction

After the navigation is initiated, a user can control the navigation direction and speed by hand. The translation speed is determined by the distance between the hand and head (where the ray starts). The minimum speed is set to the average human walking speed, 1.44m/s [48]. To decide the maximum translation speed, we conducted a pilot study with five participants wearing a VR head-mounted display (HMD), HTC Vive Pro Eye [56]. In the pilot study, the participants continuously increased navigation speed from 1.44m/s to 8m/s (which is the maximum speed without simulator sickness in Schäfer's study [49]) by stretching arm interaction while placing their hands on the gaze ray. Through the pilot study, we found the participants chose a maximum speed of 6m/s (maxspeed in the formula below). We mapped the maximum distance (MaxDistance) between the hand and head when stretching the arm completely, to the maximum speed. Additionally, we asked the participants to place their hands to identify their preferred minimum speed, and the average distance between the placed hand and head (MinDistance) was about 30% of the maximum distance. To calculate the speed with the current distance (CurrentDistance) between the hand and head positions, the following formula was formulated:

$$d = \frac{(CurrentDistance - MinDistance)}{(MaxDistance - MinDistance)} \tag{1}$$

$$speed = maxspeed \times d + minspeed \times (1 - d) \tag{2}$$

With the formula, a user can control the translation speed by moving the hand forward or backward for faster or slower translation, respectively (see Figures 1c, 1d, and 2c). The calculated translation speed is visually presented on a slider bar, located 5m away and 0.2m above the user's head with a width of 2.5m and a height of 0.2m (see Figure 2).

During the navigation, the hand's relative position to the ray decides the rotation of navigation direction (without requiring real-world body rotation; see Figures 1e, 1f, and 2d). The rotation speed is adjusted based on the orthogonal distance between the ray and the hand. We set a 0.05m threshold to prevent unintentional rotation, so there is no rotation if the hand is placed within 0.05m from the ray. The navigation direction turns left or right if the hand is placed away from the ray more than 0.05m (see Figure 2d). We also adopt a similar formula used in calculating the translation speed to calculate the rotation speed. We set the maximum and minimum rotation speeds based on the results from the pilot study. The most preferred minimum and maximum rotation speeds were 0.5rad/s (minspeed in the formula above) and 1rad/s (maxspeed), respectively. The minimum rotation speed is applied when placing the hand 0.05m away (MinDistance) from the ray and the maximum speed is applied when the hand reaches the left or right edge of the green bounding box (MaxDistance).

When the user turns their body in the real world it may also move their hand left or right of the ray, hence causing rotation. Additionally, the ray also turns at the same degree of rotation to indicate the updated navigation direction. Since the hand interaction controls the rotation and translation during the navigation, the user can look around freely with her head and eye movement independent from the hand navigation control.

4 USER STUDY

To evaluate our RayHand navigation in terms of how it affects the navigation experience, we conducted a user study comparing it to two other navigation methods: head-hand and torso-leaning navigations. The main difference among the three conditions is the input modality. Our RayHand navigation exploits the gaze and hand input modalities while the head-hand and torso-leaning navigations use only one modality for each: the hand and torso, respectively. We note that the head-hand navigation was from Mine's design [38] and the torso-leaning navigation was from a recent study by Zielasko et al. [60]. The study used a within-subject and repeated measures design where each participant tried three conditions in the first round, and repeated them again in the second round. These two rounds of comparisons were to investigate the three navigation techniques in two levels of familiarity with them and assess the learning effect of using them. We analyzed the results of the first and second rounds individually by comparing three conditions from each round, and together by comparing the results of each condition from the first and second rounds.

4.1 Conditions

The head-hand navigation was chosen as a condition for comparison because the comparison between the RayHand and head-hand navigations would show the effect of combining gaze and hand interaction against using only the hand. The torso-leaning navigation was chosen because the torso-based navigation is the most popular technique that supports both speed and direction controls without any additional input device [33, 60]. Additionally, the hand and torso-based navigation are popular comparison conditions in several previous studies of steering navigation [9, 10, 16, 33, 53, 54, 59, 60]. The gaze steering navigation, however, has a significant issue with coupling the navigation and looking-around activities (Midas touch issue [30]), so we did not include it as an experimental condition.

A user can control both direction and speed in all three conditions, and they all support decoupling between the looking-around and navigation activities. They were all set with the same range of translation speeds, had the same visual components (speed slider bar, green bounding box, and hand model), and the rendering frame rate was at 60 fps.

4.1.1 Head-Hand Navigation. The head-hand navigation exploits the relative position between the head and hand for controlling the translation direction and speed, while turning user's physical body controls the rotation. Navigation is initiated when raising a hand into the tracking area and keeping it inside for more than the threshold of 0.3 second. The head-hand navigation uses the distance between the hand and head to control the translation speed (see left of Figure 3), and it is the same way as how the RayHand determines the translation speed by the formula in section 3.2 (i.e., the head-hand navigation uses the same values for the MaxDistance, MinDistance, maxspeed, and minspeed). The difference between the RayHand and head-hand conditions is in interactions for controlling the rotation and translation direction. The head-hand navigation directly maps the head-to-hand direction to the translation direction and the user needs to turn their physical body to rotate their viewing direction. Hence, unlike the RayHand navigation where the rotation changes translation direction as rotated, the head-hand navigation supports performing the rotation and changing translation direction independently from each other (e.g., rotating right by turning body right while translating to the left by pointing left with hand). We note that a user can also synchronize them even if both can be performed independently. For example, holding a hand in front of the head while rotating the body synchronizes the translation direction and the rotation. Either making a fist gesture or simply holding the hand down stops the head-hand navigation as in the RayHand navigation.

4.1.2 Torso-leaning Navigation. The torso-leaning navigation exploits the torso-leaning angle to control the speed and the horizontal facing direction for controlling the translation direction (see the right of Figure 3). The leaning angle is measured as an angle between the two lines defined as: 1) a line between the head and torso positions when standing straight up, and 2) another line between the current head and torso positions when leaning forward. We measured the maximum torso leaning angle for each user by asking to lean forward as much as possible while being able to comfortably look around the VE. The average angle taken over a minute is used as the maximum leaning angle (MaxDegree in the formula below) and it is mapped to the maximum speed, 6m/s. The minimum leaning angle (MinDegree) is set to 30% of the maximum leaning angle, and this is mapped to the minimum speed, 1.44m/s. Torso-leaning navigation is initiated when leaning more than or equal to the minimum leaning angle for more than the threshold of 0.3 second, and the navigation speed with the current leaning angle (CurrentDegree) is calculated by the following formula, similar to the one for the RayHand and head-hand navigations:

$$d = \frac{(CurrentDegree - MinDegree)}{(\max Degree - MinDegree)} \tag{3}$$

$$speed = maxspeed \times d + minspeed \times (1 - d) \tag{4}$$

The translation direction is decided by the torso tracker's forward facing direction. Like the head-hand navigation, the body orientation is directly mapped to the navigation direction. Returning to a straight standing pose with an angle less than the minimum leaning degree stops the torso-leaning navigation.

4.2 Apparatus

We used HTC Vive Pro HMD which has an integrated Tobii Eye tracker. The headset has a resolution of 1440×1600 pixels per eye (2880×1600 pixels combined), a 90 Hz refresh rate, and a 110∘ field of view (FoV). The HMD was connected to a PC with a 3.8GHz AMD Ryzen 7 5800X 8-Core, 32GB of RAM, and an NVIDIA GeForce RTX 3060 graphics card. We developed the VE with Unity game engine

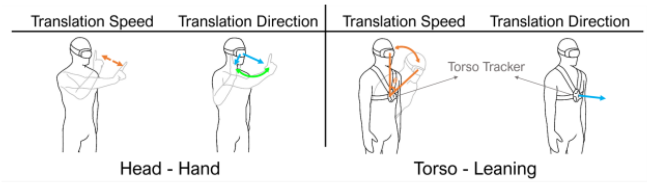

Figure 3: The interaction for controlling speed (represented by orange arrows in the left picture of each navigation) and translation direction (represented by blue arrows in the right picture of each navigation) for head-hand and torso-leaning navigation techniques. The green curve represents the hand movement for changing translation direction with the head-hand navigation.

2020.3.37f1. We imported Vive Hand Tracking SDK 1.0.0 to track hands and participants wore Vive tracker 3.0 on their chest for the torso-leaning navigation.

4.3 Tasks

The task was navigating to the destination as quickly as possible without bumping into the virtual walls while counting the number of target objects (i.e., horses [12]). We prepared one map for training and six experimental maps (see left of Figure 4) for two rounds of a user study with three conditions. Participants navigated the first three experimental maps in the first round of the experiment, and another three maps in the second round. The training map included eight turns from the departure to the destination, and the road was 10m wide with a total length of 180m. The road in each experimental map was 200 meters with a five-meter width and required six (three left and three right) 90-degree turns. There was a semi-transparent wall at each side of the road, directional signs, and horses (see right of Figure 4). For effective navigation, 5m × 5m signs indicating the turning direction were placed at every turning point. There were semi-transparent walls with a height of 0.5m at the left and right edges of the road. The system prevented the user from navigating over the wall.

Being able to easily look around during navigation is important for providing a rich navigation experience [60], so we asked the participants to count horses on the field over the wall while navigating. The number of horses was randomly assigned in a range from 16 to 22, and to maintain consistency among participants, the total number of horses in one round of a user study was 60. The horses were 2.9m in width and 2.3m in height and randomly placed within a 20m × 10m area on either side of the field every 40m (40m, 80m, 120m, and 160m away from the starting point). The horses were positioned to be more than 3.3m away from each other to ensure they did not obscure each other. After completing the navigation with a map and a given condition, participants responded to a question asking how many horses they found during the navigation.

4.4 Procedure & Data Collection

On arrival, participants were informed about the study in written and verbal explanation and filled out a consent form and a demographic questionnaire asking about their gender, age, hand dominance, and VR experience. They were then instructed on the

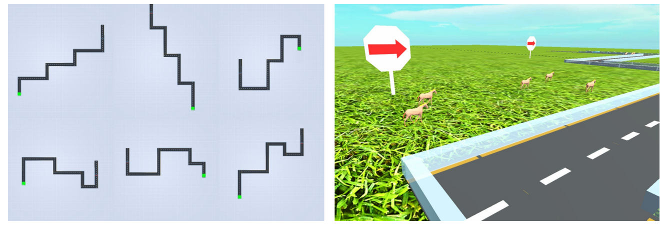

Figure 4: The virtual environment includes a road for navigation, semi-transparent walls on each side of the road, directional signs at each corner, and horses on the field outside the road (right). The six experimental maps (left) show the road path with black lines and the green point is the start position of the navigation.

usage of the devices and technology, and wore a torso tracker strap and an HMD while standing in a designated area (1m×1m, see left of Figure 5). After calibrating the eye tracker, the maximum leaning angle and outstretched hand length were measured.

Once everything was ready, the training phase began. Participants practiced until they were familiar with the given condition in the training map. This training was for participants to be familiar not only with the conditions but also with the task and devices in use. After training, the experimenter prepared the experimental trial with the given condition by showing the map for the next navigation to the participant, reminding of the horse counting task, and asking the participant to stand in the middle of the designated area and be ready to perform the task. The experimental trial started when participants crossed the start line in the VE and the system recorded their activity till crossing the finish line. The recorded data were total navigation time and distance from start to finish, average speed, the sum of head rotation and position change, the number of times bumping into the wall, and incorrect horse counting. After completing the navigation with the given condition, participants answered five questionnaires: Subjective mental effort questionnaire (SMEQ) [61], NASA Task Load Index (NASA-TLX) [24], System Usability Scale (SUS) [2, 31], Simulator Sickness Questionnaire (SSQ) [32], and short version of User Experience Questionnaire (UEQ-S measuring practicality and hedonic quality) [50]. Participants performed this training and experimental trial for each condition, and the order of the conditions was counterbalanced using a balanced Latin square design. After finishing all three conditions, participants ranked their preference (from 1 to 3 for the best to the worst conditions) and ended the first round of the user study.

After taking a sufficient break, the second round was conducted in the same manner as the first round, but without the training phase. This second round was mainly for investigating the learning effect of the three techniques by comparing the data from the first and the second rounds. Additionally, at the end of the second round, an interview was conducted to ask what they liked and disliked in speed and direction controls, the benefits and weaknesses of the three techniques, and suggestions for improving the RayHand navigation. Overall, the experiment took about 50 ∼ 60 minutes per participant (excluding the break time between the first and second rounds in the experiment), and they received a gift certificate with a value of about ten dollars as a reward. All participants performed

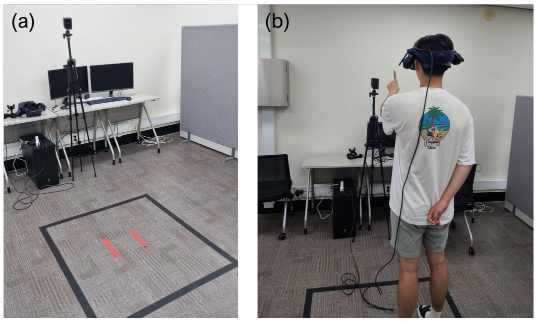

Figure 5: Designated area (1m by 1m) for participants to perform navigation task under each condition (left). A participant is performing the navigation task while standing in this area (right).

the experiment while standing (see right of Figure 5), and they were allowed to take sufficient breaks or withdraw from the experiment.

4.5 Participants

We recruited 27 participants (17 female and 10 male) aged between 20 to 28 (M = 22.96, SD = 2.344). Participants were recruited voluntarily from the local universities. Most of them had little experience in using VR. Nine participants reported that they experienced VR less than once a month, fifteen reported rarely, and three were once a week. Five participants were left-handed, and the others were right-handed. In the user study, they were told to use any convenient hand.

5 RESULTS

We present results of the user study with objective and subjective measures, and user interviews. According to the Shapiro-Wilk test, our objective measures (total navigation time and distance, average speed, sum of head rotation and its position change, the number of times bumping into the wall, and incorrect horse counting) were not normally distributed for each condition in the first and second rounds of experiment. The subjective questionnaire data for SUS, SMEQ, NASA-TLX, UEQ-S, SSQ, and user preference are in ordinal scales. We thus ran the Friedman test (α = .05) to compare the rating scales among the three conditions, and for those showing a significant difference, we ran post hoc tests for pairwise comparison using the Wilcoxon Signed-Rank Test with Bonferroni correction applied (α = .05/3 = .0167). We also compared data of each condition between the first and second rounds to assess the learning effect using the Wilcoxon Signed-Rank Test (α = .05). We report the results of comparison among the three conditions in the first and second rounds together.

In this section, we use the abbreviations: RH, HH, and TL for the RayHand, head-hand, and torso-leaning conditions, and 1R and 2R for the first and second rounds of the experiment respectively. The main results are summarized below:

- The three navigations have 'okay' or higher levels in Bangor's adjective scale of usability [2].
- The RH and HH navigations were perceived as being better than the TL condition in terms of usability, task load, mental effort, simulator sickness, and user experience measurements because of the leaning forward for accelerating speed being uncomfortable.
- The RH condition required less amount of body movement than the HH and TL navigations, and it helped participants stay inside of the designated interaction area (1m × 1m) while the HH and TL navigations had a significant issue of participants accidentally leaving the area.
- The RH navigation supported higher hedonic quality compared to the HH and TL navigations.
- The HH navigation helped participants perform effective control of the translation direction which resulted in a shortened navigation distance.
- The RH navigation had a significant learning effect between the first and second rounds with participants showing significant improvements.

5.1 Subjective Measures

Results from subjective measures are summarized in Figure 6. The Friedman test among the three conditions showed significant differences in all subjective measures for both rounds of the experiment (all p-values are less than .05). When comparing the first and second rounds of the experiment (see Table 1), significant learning effects were observed for all measures with the RH condition except the usability (SUS). There is no learning effect between the two rounds with the HH and TL conditions in all measures. We summarize the results of the learning effect in Table 1.

5.1.1 Usability (SUS). In both first and second rounds, the TL condition was less usable for navigation compared to the HH and RH conditions (TL-HH in 1R: Z =-4.160, p<.001; TL-HH in 2R: Z =-4.365, p<.001; TL-RH in 1R: Z =-2.453, p =.014; TL-RH in 2R: Z=-2.524, p =.012), but there was no significant difference between the HH and RH conditions (1R: Z=-1.311, p=.190; 2R: HH-RH: Z=-0.509, p=.611).

According to Bangor's adjective scale of usability [2], the HH and RH conditions were in the range of 'Good' in both the first and second rounds (HH in 1R: M=78.89, SD = 18.61; RH in 1R: M = 73.43, SD = 21.72; HH in 2R: M = 78.70, SD = 15.12; RH in 2R: M = 76.94, SD = 17.98), and the TL condition was in the range of 'Okay' (1R: M = 60.09, SD = 21.91; 2R: M = 60.93, SD = 21.28).

5.1.2 Task Load (NASA-TLX). In both rounds, participants felt they experienced less task load to complete the task with the HH and RH conditions compared to the TL condition (TL-HH in 1R: Z = -3.847, p < .001; TL-HH in 2R: Z = -3.501, p < .001; TL-RH in 1R: Z = -2.959, p = .003; TL-RH in 2R: Z = -3.941, p < .001), but no significant difference was found between the HH and RH conditions for the level of task load (1R: Z = -0.565, p = .572; 2R: Z = -2.019, p = .043).

5.1.3 Mental Effort (SMEQ). Using the HH condition required significantly less mental effort to navigate compared to using the TL condition in both rounds (1R: Z = -3.005, p = .003; 2R: Z = -3.586, p < .001). The RH condition was also superior compared to the TL condition but only in the second round (1R: Z = -2.365, p = .018 – not significant but marginal; 2R: Z = -3.987, p < .001). There was no significant difference between the HH and RH conditions in the

Table 1: Learning effect of subjective data: usability (SUS), task load (NASA-TLX), mental effort (SMEQ), simulator sickness (SSQ), pragmatic, hedonic, and overall experience qualities (UEQ-S).

Measurement	Wilcoxon signed-rank test (Learning effect 1R VS. 2R)					
	RH		HH		TL	
	Z	p	Z	p	Z	p
Usability (SUS)	-1.563	.118	-1.048	.295	-0.140	.889
Task Load (NASA-TLX)	**-2.526**	**.012**	-0.288	.773	-0.991	.321
Mental Effort (SMEQ)	**-2.175**	**.030**	-0.505	.614	-1.823	.068
Simulator Sickness (SSQ)	**-2.352**	**.019**	-1.761	.078	-0.595	.552
Pragmatic Quality	**-2.185**	**.029**	-0.260	.795	-0.703	.482
Hedonic Quality	**-2.171**	**.030**	-0.425	.671	-0.015	.988
User Experience (UEQ-S)	**-3.014**	**.003**	-0.627	.531	-0.257	.797
Preference	**-2.121**	**.034**	-0.905	.366	-1.0	.317

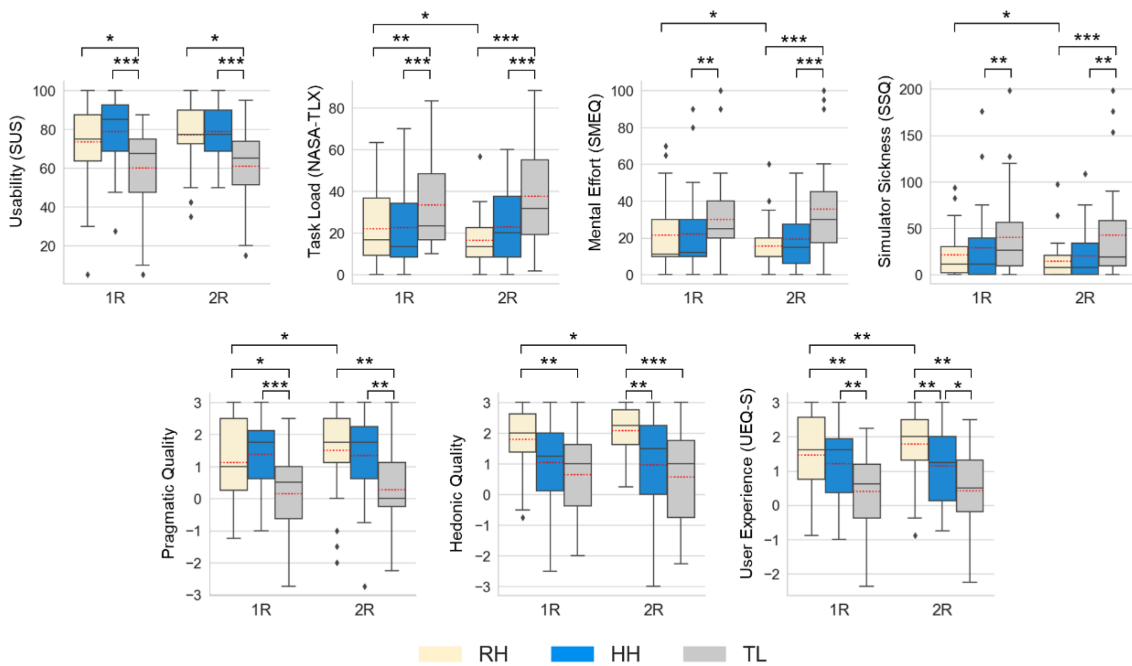

Figure 6: Results of subjective measures: usability (SUS), task load (NASA-TLX), mental effort (SMEQ), simulator sickness (SSQ), pragmatic, hedonic, and overall experience qualities (UEQ-S). RH: RayHand, HH: Head-Hand, TL: Torso-Leaning, 1R: first round, 2R: second round, red-line: mean, diamond: outliers, * = p < .0167, ** = p < .005, and *** = p < .001 for Wilcoxon signed rank test - Alpha level has been adjusted with Bonferroni correction; learning effect: * = p < .05, ** = p < .01, and *** = p < .001 for Wilcoxon signed rank test.

first (Z = -0.260, p = .795) and the second (Z = -1.187, p = .235) rounds.

5.1.4 Simulator Sickness (SSQ). Participants felt significantly more simulator sickness when using the TL condition in comparison to when using the HH and RH conditions for the second round (TL-HH: Z = -3.145, p = .002; TL-RH: Z = -3.644, p < .001). A significant difference was also revealed in the first round between the TL and HH conditions (Z= -2.927, p = .003) but not between the TL and RH conditions (Z = -2.300, p = .021 – not significant but marginal). They did not feel a significant difference between the HH and RH conditions in both rounds (1R: Z = -0.650, p = .516; 2R: Z = -1.211, p = .226).

5.1.5 User Experience (UEQ). The UEQ questionnaire measures the level of pragmatic and hedonic qualities together with the overall user experience. For pragmatic quality, the TL condition was rated lower compared to the HH and RH conditions in both rounds (TL-HH in 1R: Z = -4.054, p < .001; TL-HH in 2R: Z = -3.165, p = .002; TL-RH in 1R: Z = -2.407, p = .016; TL-RH in 2R: Z = -2.897, p =

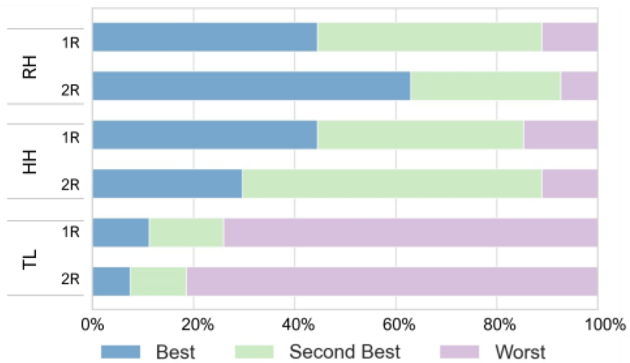

Figure 7: Results of user preference (RH: RayHand, HH: Head-Hand, TL: Torso-Leaning).

.004), and the rating results for the HH and RH conditions did not show significant difference in both rounds (1R: Z = -1.097, p = .273; 2R: Z = -0.874, p = .382).

Additionally, they felt a higher level of hedonic quality when using the RH condition in comparison to when using the TL conditions in both rounds (1R: Z=-2.963, p=.003; 2R: Z=-3.838, p<.001). They also felt a higher level of hedonic quality when using the RH condition compared to when using the HH condition in the second round (Z=-3.262, p=.001), but not in the first round (Z =-2.276, p=.023 – not significant but marginal). There was no significant difference in the level of hedonic quality between the TL and HH conditions in both rounds (1R: Z=-1.554, p=.120; 2R: Z=-1.447, p=.140).

By aggregating the ratings for the pragmatic and hedonic qualities, overall user experience quality was measured. In both rounds, the participants felt higher experience quality with the HH and RH conditions over the TL condition (TL-HH in 1R: Z = -3.378, p = .001; TL-HH in 2R: Z = -2.705, p = .007; TL-RH in 1R: Z = -2.961, p = .003; TL-RH in 2R: Z = -3.462, p =.001). Since the experience quality with the RH condition was significantly improved in the second round, the participants felt significantly better experience quality with the RH condition compared to the HH condition (Z = -3.046, p =.002) in the second round although it was not in the first round (Z = -0.794, p =.427).

5.1.6 *Preference.* At the end of each round, the participants ranked the conditions according to their preference (see Figure 7). In the first round, 24 participants were equally split between the RH and HH conditions in selecting the best while the other three chose the TL condition. 20 participants chose the TL condition as the worst, and 3 and 4 chose the RH and HH conditions as the worst respectively. In the second round, 17, 8, and 2 participants most preferred the RH, HH, and TL conditions, respectively, and 2, 3, and 22 participants least preferred the RH, HH, and TL, respectively. In pairwise comparisons, the TL condition was significantly less preferred than the RH (1R: Z = -3.304, p = .001; 2R: Z = -3.727, p < .001) and HH (1R: Z = -3.025, p = .002; 2R: Z = -3.497, p < .001) conditions in both rounds, but no significant difference was found between the RH and HH conditions (1R: Z = -0.156, p = .876; 2R: Z = -1.684, p = .092).

5.2 Objective Measures

Results from objective measures are summarized in Figure 8. A Friedman test with the three conditions showed a significant difference in total distance, head rotation, and head position change in both rounds, and the number of times bumping on the wall only in the second round (all p-values are less than .001; see Table 2). Unlike these results, there was no significant effect in total navigation time, speed, and incorrect horse counting for both rounds in a Friedman test. One important result is that participants had only a few numbers of 'incorrect horse counting' while performing navigation with all three conditions, which indicates that all three conditions support decoupling of looking-around and navigation activities. In the rest of this section, we report the results of measurements that showed significant effect among three conditions by the Friedman Test while Table 2 summarizes all results.

5.2.1 *Total Navigation Distance.* The geometric distance from the start to the finish line was fixed at 200m, but the navigating distance was different according to participants' navigation skills, such as cornering and diagonal navigation rather than orthogonal navigation. Interestingly, participants navigated shorter distance with the HH condition compared to the TL (1R: Z =-2.517, p = .01; 2R: Z =-3.844, p < .001) and RH (1R: Z =-3.844, p < .001; 2R: Z =-4.493, p < .001) conditions in both rounds. These results indicate that the translation direction control using the head-to-hand direction (implemented in the HH) is the best for performing skillful navigation while the body-turning (in the TL condition) and hand-ray (in the RH condition) interactions support moderate affordability. They also navigated shorter distances with the TL condition compared to the RH condition in the first round (Z =-2.859, p = .004) but not in the second round (Z =-1.273, p = .203). No significant difference was found between the two rounds in all three conditions (RH: Z =-1.874, p = .061; HH: Z =-0.769, p = .442; TL: Z =-1.033, p = .302).

5.2.2 *Bumping on the Wall.* To measure the quality of navigation, we counted the number of times bumping on the wall during the navigation. The number of times bumping showed a significant difference among the three conditions with the Friedman test in the second round (x^2 =36.247, p <.001), but not in the first round (x^2 =2.891, p =.236). In pairwise comparisons in the second round, participants bumped more on the wall in the TL condition compared to the HH (Z =-3.833, p < .001) and RH (Z =-2.509, p = .012) conditions, and no significant difference between the HH and RH conditions (Z = -0.982, p = .326) was found. Comparing the two rounds, we found that participants bumped less in the second round compared to the first round with the HH condition (Z =-2.462, p = .014), but no significant difference was found with the TL (Z =-1.553, p = .121) and RH (Z =-0.462, p = .644) conditions.

5.2.3 *Head Movement.* The head movement includes head rotation and position change. Body-turning interaction triggered the rotation in the TL and HH conditions but hand movement did it in the RH condition. Hence, the RH condition had significantly less head rotation compared to the other two conditions in both rounds (TL-RH in 1R: Z = -3.82, p < .001; TL-RH in 2R: Z = -3.219, p = .001; HH-RH in 1R: Z = -3.099, p = .002; HH-RH in 2R: Z = -2.547, p = .011). Additionally, since the TL condition used leaning the body for moving forward and the leaning motion caused small

Table 2: Results of Friedman tests and learning effect of objective measures: total navigation time, total navigation distance, speed, the number of bumping on the wall, incorrect horse counting, head rotation and head position change.

Measurement	Round	Friedman test (RH vs. HH vs. TL) x^2 (2) (p)	Mean and standard deviation: M (SD)			Wilcoxon signed-rank test (Learning effect 1R VS. 2R): Z (p)		
			RH	HH	TL	RH	HH	TL
Total Navigation Time	1R	0.667 (.717)	58.67 (17.60)	55.62 (14.26)	54.52 (16.97)	**-3.051 (.002)**	**-2.451 (.014)**	-1.706 (0.088)
	2R	0.519 (.772)	50.24 (10.45)	48.64 (8.20)	50.23 (11.76)			
Total Navigation Distance	1R	**17.852 (< .001)**	191.06 (8.03)	182.26 (4.73)	185.25 (4.22)	-1.874 (.061)	-0.769 (.442)	-1.033 (.302)
	2R	**24.889 (< .001)**	189.07 (5.76)	180.93 (2.15)	187.36 (7.53)			
Speed	1R	2.0 (.369)	3.72 (0.91)	3.66 (0.76)	3.92 (0.81)	**-3.147 (.002)**	**-2.811 (.005)**	-1.418 (.156)
	2R	0.963 (.618)	4.11 (0.84)	4.11 (0.69)	4.10 (0.78)			
Bumping on the Wall	1R	2.891 (.236)	2.11 (1.71)	2.37 (1.92)	3.11 (2.31)	-0.462 (.644)	**-2.462 (.014)**	-1.553 (.121)
	2R	**36.247 (< .001)**	1.88 (2.06)	1.44 (1.71)	3.74 (2.44)			
Incorrect Horse Counting	1R	0.096 (.953)	1.19 (1.52)	1.33 (1.86)	1.37 (1.64)	**-2.676 (.007)**	**-2.097 (.036)**	**-2.328 (.020)**
	2R	2.652 (.266)	0.19 (0.56)	0.41 (0.8)	0.41 (0.89)			
Head Rotation	1R	**24.0 (< .001)**	686.57 (385.43)	941.29 (381.31)	1370.79 (616.76)	-0.577 (.564)	-0.649 (.517)	-1.369 (.171)
	2R	**20.222 (< .001)**	715.54 (429.77)	869.72 (265.19)	1219.17 (432.28)			
Head Position Change	1R	**40.222 (< .001)**	2.52 (1.09)	3.15 (1.11)	7.80 (2.85)	-0.889 (.374)	-0.529 (.597)	-1.177 (.239)
	2R	**36.963 (< .001)**	2.37 (1.25)	2.97 (0.89)	7.33 (2.54)			

but frequent head rotation, the participants made more of it with the TL condition compared to the HH condition in both first (Z = -3.147, p = .002) and second (Z = -3.700, p < .001) rounds. There was no significant difference in the amount of head rotation between the two rounds for each condition (TL: Z =-1.369, p = .171; HH: Z =-0.649, p = .517; RH: Z =-0.577, p = .564)

The leaning motion in the TL condition caused significantly more head position change compared to the RH and HH conditions in both rounds (TL-HH in 1R: Z = -4.493, p < .001; TL-HH in 2R: Z = -4.541, p < .001; TL-RH in 1R: Z = -4.541, p < .001; TL-RH in 2R: Z = -4.469, p < .001). The comparison between the RH and HH conditions did not show significant differences in both rounds (1R: Z = -2.114, p = .034; 2R: Z = -2.282, p = .022). No significant difference was found between the two rounds with each condition (TL: Z =-1.177, p = .239; HH: Z =-0.529, p = .597; RH: Z =-0.889, p = .374).

5.3 Participant Feedback

We collected user feedback answering the question of what they liked or disliked regarding the direction and speed controls, and the pros and cons of each condition. In speed control, the majority of the participants (21 out of 27) preferred the hand-based interaction implemented in the HH and RH conditions, against the torso leaning interaction in the TL condition. Participant 1 (P1 afterward), P14, and P19 commented that "*adjusting speed with moving hand is intuitive*". Another two participants (P22 and P25) reported the easy operation and learning of the hand speed control ("*it was easy*" and "*it was easy to learn*"). Six participants (P3, P4, P13, P21, P24, and P26) criticized using the leaning motion for speed control in the TL condition ("*Leaning forward is uncomfortable, causes high physical fatigue*", "*When Leaning body, my face looks down and I felt difficult to lift my head for looking forward*"). P7 and P8 were worried about leaning forward ("*During the navigation, I suddenly felt that I was not at a proper (physical) position and started worrying about bumping into any object by leaning head*").

Regarding direction control, their opinions were divided. About half (14 out of 27) of the participants stated positive answers for the RH hand control (rotate according to the relative hand position against the ray) while the rest favored physically turning their bodies (implemented in the HH and TL conditions). P2, P6, and P14 liked little body movement with the RH hand control ("*I can control the direction even with a little amount of hand movement.*"). Four other participants (P19, P25, P26, and P21) gave similar comments but in the aspect of turning body for direction control being physically demanding in the TL and HH conditions ("*Moving body required more physical demand*"). The wired HMD was also a factor bothering participants when turning their bodies (P7, P18, and P27 – "*Turning body was restricted by wires such as HMD cable*"). P20 and P24 were unsatisfied with the familiar but uninteresting turning interaction ("*Turning my body for rotation is stale*"). Additionally, P25 and P26 stated the benefit of visualizing navigation direction with the ray ("*Thanks to the ray, I was less confused about the forward*

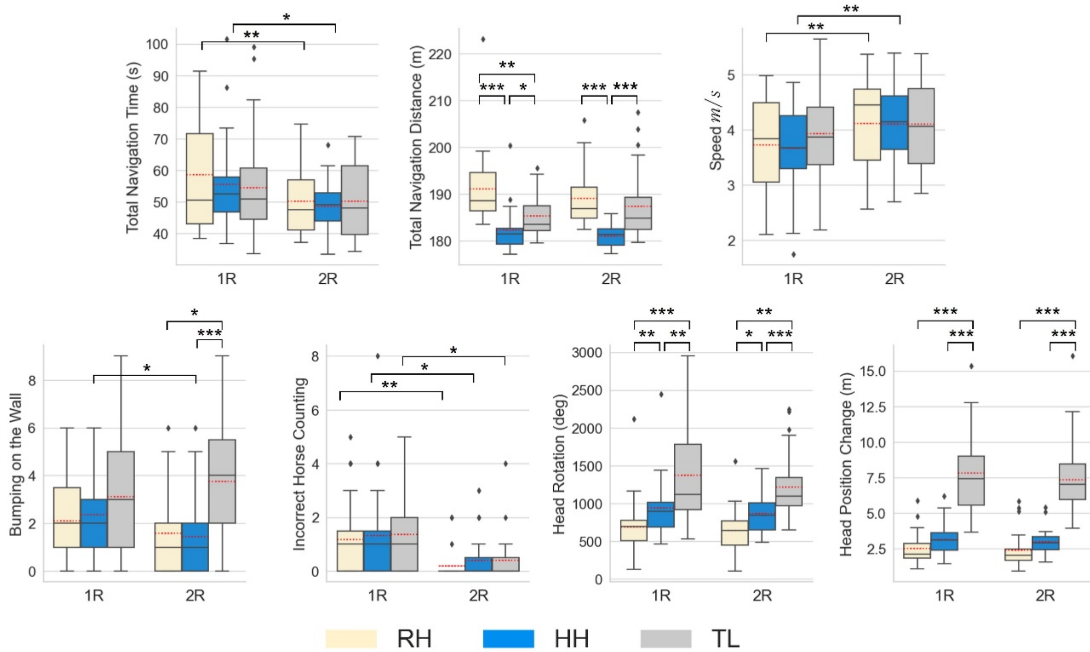

Figure 8: Results of objective measures: total navigation time, total navigation distance, speed, the number of bumping on the wall, incorrect horse counting, sum of head rotation and position change. RH: RayHand, HH: Head-Hand, TL: Torso-Leaning, 1R: first round, 2R: second round, red-line: mean, diamond: outliers, $^{*} = p < .0167$, $^{**} = p < .005$, and $^{***} = p < .001$ for Wilcoxon signed rank test - Alpha level has been adjusted with Bonferroni correction; learning effect: $^{*} = p < .05$, $^{**} = p < .01$, and $^{***} = p < .001$ for Wilcoxon signed rank test.

direction to go"). An interesting comment from P1 and P10 was a reduction of simulator sickness with the RH condition ("*I felt less simulator sickness with the hand turning method compared to the body turning method because I did not need balancing myself caused by body movement*"). The participants who preferred the body-turning method took the level of intuitiveness into account. Six participants commented they liked the body turning method because of the intuitiveness (P3, P4, P13, P16, P22, and P23 - "*I liked body rotation. It was comfortable and intuitive*"). P8, P9, P11, and P12 commented on the difficulty level of the hand direction control ("*It was difficult to have precise control with the RH condition*").

In addition, P10, P20, and P24 commented on the learning effect on the RH condition ("*It's hard at first, but once adapted, it's the most comfortable method*"), and P2, P6, P14, and P25 compared the RH condition to driving ("*It felt like driving because I can leave my body as it is and using only-hand input to rotate, which was fun*"). Moreover, five of them (P5, P14, P20, P24, and P26) commended the design of the RH condition ("*It was creative and cutting-edge*"). One interesting comment for the TL condition by P18 was that "*It was like flying when opening my arms to left and right sides while leaning down my torso*". P11, P12, and P17 stated that "*Leaning torso forward feels more dynamic (like skiing)*".

We collected design suggestions for the three conditions. P9 suggested visualizing the threshold of five centimeters in the RH condition to easily recognize whether the user activates the turning interaction or not. P10 and P20 suggested visualizing the translating direction for the HH and TL conditions like the ray in the RH conditions.

5.4 Observation

During the user experiment, we found several interesting observations. With the RH condition, eight participants rotated their bodies for rotating viewpoint and changing translation direction. This interaction was possible because body rotation caused moving hands left or right which activated the rotation in the desired left or right direction. This rotation, however, was not the same amount of rotation that they did in the real world, but the participants hardly felt the difference (between how much they rotated their body and how much rotation is performed by the hand and ray relative position). Additionally, nine participants with the HH condition fixed their arms and hands on the body and kept rotating their bodies to decide translation direction, not only at the corners but also at the straight navigation course. These two misapplications of the RH and HH conditions mostly occurred in the early stage of the user experiment, and were hardly found in the second round of the experiment.

Participants kept using the same hand for navigation rather than switching between two hands. Additionally, controlling direction by hands in the RH and HH conditions caused a mild unintentional change of the speed (because the RH and HH conditions calculated the speed based on the distance between the head and hand), but participants did not significantly take it into account.

One significant issue in turning body for rotation with the TL and HH conditions was that participants kept accidentally moving out from the designated area (1m × 1m), and it was more serious with the TL condition. The experimenter sometimes had to intervene to keep them in the safe area, but we reported that this intervention happened only from the back of the participants in a manner not to disturb body rotation and hand interaction.

6 DISCUSSION AND LIMITATIONS

6.1 Navigation Experience

From the user study, three key findings emerged: 1) all three navigations supported positive user experience at a moderate level or above, 2) the RH and HH navigations served better user experience compared to the TL navigation, and 3) the RH and HH navigations had their own benefits compared to each other. Therefore, our answer to the research question '*Does the proposed navigation method which combines gaze and hand interactions serve a better navigation experience compared to other techniques?*' is 'Yes' with an excuse of the RayHand navigation not being perfect. The positive user experience for the three navigations was verified by the 'okay' or higher level of usability while having similar results in the navigation speed, completion time, and incorrect horse counting. We attribute these results to the user having full control of the speed and direction in continuous ranges while decoupling the looking-around and navigation activities.

6.1.1 *Issue of Torso Leaning Navigation.*

Even though the TL navigation supported 'okay' level of usability, it had a significant issue of physically demanding workload while making the leaning forward pose and served a worse user experience compared to the RH and HH navigations. This physical demand influenced participants' ratings that measured usability, task load, pragmatic quality, and hedonic quality, and resulted in significantly lower levels of those measures compared to the RH and HH navigations. Additionally, the leaning pose also influenced the navigation performance: more bumping on the wall, more head movement, and causing simulator sickness. Stronger simulator sickness might lead to feeling more demanding mental effort [27] to perform the navigation with the TL condition.

Interestingly, the issue of TL navigation was less obvious in the objective measures compared to the subjective measures. This might be because participants endured the inconvenience of the leaning body pose with the TL navigation achieving similar results in the objective measures such as total navigation time and average speed compared to the two other navigation techniques.

6.1.2 *Benefit of Head-Hand Navigation.*

The HH navigation supported effective control of the translation direction which helped participants shorten the navigation distance. This might be made with the easy and quick hand interaction to change the translation direction. We note that changing the translation direction in the HH navigation method could be exceedingly fast by quick left and right hand swing interaction.

6.1.3 *Benefit of RayHand Navigation.*

A benefit of the RH navigation was the low amount of required body movement. Because of using relative hand position against the ray for both translation and rotation, the participants did not need to perform any big body movement nor had to move any steps, but simply looking around and moving their hands was enough. According to our observation, not having any stepping movement is crucial to keep the user inside the small designated area, like in our study (1m × 1m area). This benefit could increase the practicality of the RH navigation because most rooms do not have large empty spaces. Another strong point of the RH navigation was the high hedonic quality compared to the HH navigation. The gaze-ray is not a real-world component and using it in the interaction might influence hedonic quality. In addition, the RH navigation employed the relative position that is not common in the real world while pointing hand to the destination and leaning body forward for walking or running is common. Turning body for rotation in HH and TL navigations is natural but stale.

6.2 Learning Effect with the RayHand Navigation

The RH navigation showed a significant learning effect while the TL and HH navigations did not. Participants initially felt unfamiliar with hand control using the relative position between the hand and the ray. Nevertheless, participants learned very quickly and once they got used to it, they felt convenient with the low amount of required physical demand. This fast learning was possible because of the simple and intuitive mapping of the hand movements to turning direction and controlling the speed.

6.3 Extensibility & Application

Our RH navigation supports both looking around and navigation activities to be performed individually and simultaneously. In addition, our RH navigation has the potential to be extended by supporting other interactions. First, since the RH navigation includes the function of calculating the distance to the ray-collided object, adaptive speed control according to the distance can be easily added. If the ray collides with an object (i.e., a wall) which is far away, our RH could automatically increase the speed to reach the far destination quickly. If the collided object is close enough within an arm-reachable area (or within a certain distance), the RH navigation can slow down or even stop for other interactions such as grabbing (selection) or manipulating the object. Additionally, since the RH navigation employs one-hand navigation, a user can perform other interactions using the other hand (e.g., shooting a gun or picking an item with one hand while navigating with the other hand). Besides, it could also support 3D navigation by taking the hand vertical movement for flying up or down together with the current horizontal navigation, and a user can perform the RH navigation while sitting or standing.

6.4 Limitations

In our study, we compared the RH navigation to the typical hand and torso steering navigations: the HH and TL conditions in our study. Walking-in-place technique [51], however, could be another interesting condition to compare as it supports direction and speed controls by body turning and stepping speed, respectively, while decoupling the looking around and navigation interaction. In future work, we will compare a walking-in-place technique to our RH condition.

A limitation of the RH navigation is the visualization of the gaze ray and minimum speed point. Since the gaze ray starts from the middle point between two eyes, it could bother the user's view. To mitigate the effect of the issue, the ray is only visible when navigating, to allow a user to have a clear sight when not navigating. We also note that we mitigated the issue by making the gaze ray semi-transparent. Additionally, there is no visual indication representing the minimum distance from the head to the hand to trigger the navigation at minimum speed. A simple pointer or a small sphere at the point representing the minimum distance from the head could be added as a visual indication.

There are also other limitations in our study design. For example, our navigation map included only 90-degree rotations rather than a variety of rotation angles and all participants were in their twenties. In future work, more complex secondary task such as avoiding bullets or bombs could be applied in the user study instead of the simple and easy horse counting task.

7 CONCLUSION AND FUTURE WORK

In this paper, we introduce a novel VR navigation technique, named RayHand navigation which combines gaze and hand interactions. It supports both speed and direction controls by the relative position between the hand and the gaze ray while decoupling looking-around and navigation activities. We evaluated our approach by comparing it to the head-hand and torso-leaning navigations and additionally investigated the learning effect of each navigation. The results showed that the RayHand and head-hand navigations were better than the torso-leaning navigation in terms of usability, task load, and quality of navigation experience because of the physical demand for a leaning pose in the torso-leaning navigation. The RayHand navigation supported rich navigation experience with a high level of hedonic quality even when a small interaction area was given. The head-hand navigation had the benefit of performing skillful navigation which took shorter distance with a given road by taking advantage of easy control of the translation direction. Additionally, there was a significant learning effect on the use of the RayHand navigation in task load, mental effort, simulator sickness, and user experience.

For future work, we plan to extend our RayHand technique for better supporting object selection and manipulation by implementing adaptive speed control according to the distance to the object (i.e., if the ray-collided object is far away, the navigation speed is increased to reach the object faster, while if it is nearby, no translation is made but perform object selection and manipulation). Additionally, we also plan to explore how our RayHand technique works for 3D navigation by taking vertical hand movement for flying up or down in addition to the current horizontal navigation.

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