Rowing Beyond: Investigating Steering Methods for Rowing-based Locomotion in Virtual Environments

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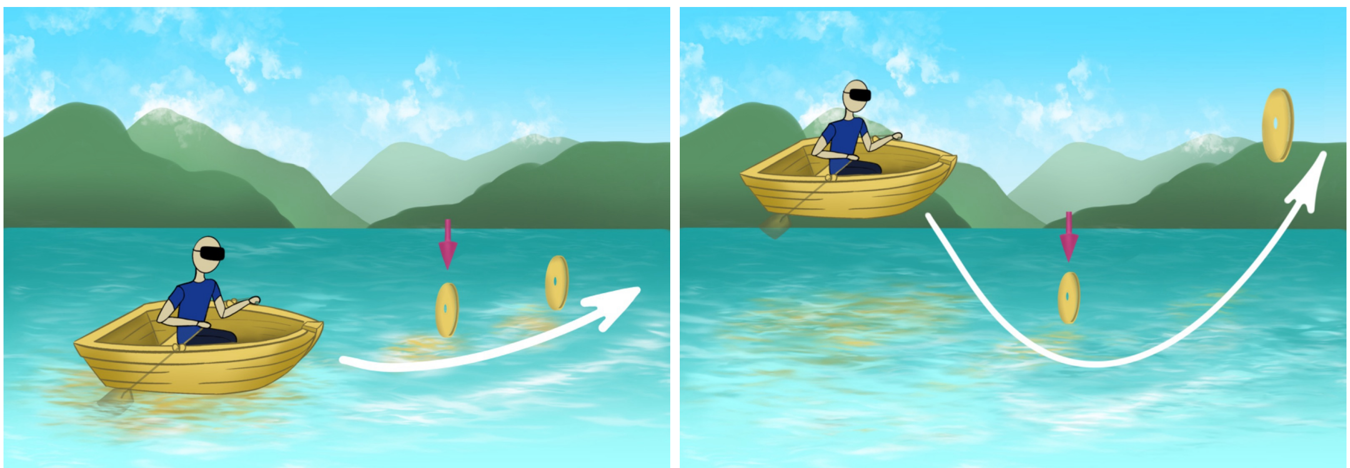

Figure 1: Two possibilities for using steering methods for rowing-based locomotion: a user is moving left and right on a 2D plane (left) and a user is moving left, right, up, and down in a 3D space (right).

ABSTRACT

Rowing has great potential in Virtual Reality (VR) exergames as it requires physical effort and uses physical motion to map the locomotion in a virtual space. However, rowing in VR is currently restricted to locomotion along one axis, leaving 2D and 3D locomotion out of the scope. To facilitate rowing-based locomotion, we implemented three steering techniques based on head, hands, and feet movements for 2D and 3D VR environments. To investigate these methods, we conducted a controlled experiment (N = 24) to assess the user performance, experience and VR sickness. We found that head steering leads to fast and precise steering in 2D and 3D, and hand steering is the most realistic. Feet steering had the largest performance difference between 2D and 3D but comparable precision to hands in 2D. Lastly, head steering is the least mentally demanding, and all methods had comparable VR sickness.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **User studies**; **Empirical studies in HCI**.

KEYWORDS

virtual reality, rowing, exergame, locomotion, steering

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1 INTRODUCTION

Rowing is a form of physical exercise with great potential in Virtual Reality (VR) exergames since it requires physical effort and uses physical motion to map the locomotion in virtual environments [11, 58, 75]. While previous works on rowing in VR have explored one-dimensional locomotion [3, 66, 76, 77, 88], i.e., forward/backward, rowing-based locomotion in 2D and 3D spaces remains underexplored in virtual environments. Given that virtual environments are infinite and have no restriction of natural laws, on a horizontal 2D plane, users can navigate a virtual sea. At the same time, in a 3D space, the rowing experience can be transformed into a flying vehicle or a submarine to steer beyond the surface and gravity. As Ivan Sutherland famously stated: "There is no reason why the objects displayed by a computer have to follow the ordinary rules of physical reality" [81]. However, steering while rowing has no obvious mapping for 2D and 3D spaces, and the rowing activity places physical constraints on bodily movements, e.g., the hands should always hold a handlebar, and feet should be placed at specific locations. Therefore, the question is how rowing-based steering can facilitate locomotion in 2D and 3D space and how efficient they will be. Answering both questions will show the most efficient way to fully explore 2D and 3D virtual environments and facilitate users' exertion.

In this work, we aim to advance rowing-based locomotion on 2D planes and 3D spaces in virtual environments by employing steering methods. For this, we implemented three steering methods based on head, hands, and feet interaction (Figure 1). We designed the methods based on (1) the physical affordances of a rowing machine and (2) implications from previous VR locomotion research. Head steering facilitates locomotion in the direction of head orientation, hand steering utilizes the rotations of a handlebar, and feet steering employs pressure distribution of toes and big toe joints on feet placeholders. To investigate the differences between the rowing-based steering methods in the 2D and 3D VR space, we conducted a controlled laboratory experiment (N = 24) to assess the performance, experience, and VR sickness they induced. We found that head steering leads to fast and precise steering in 2D and 3D, and participants found it the least mentally demanding. However, participants found hand-based steering to be the most realistic method and preferred it as much as the head method. The feet-based method had the largest performance difference between 2D and 3D conditions, with feet in 2D comparable to hands. Participants perceived head steering as the least mentally demanding. Lastly, there was no difference in VR sickness between the methods; however, 3D locomotion induced more VR sickness than 2D.

Our main research contributions include:

- Three steering methods for rowing-based locomotion in 2D and 3D virtual environments.
- An empirical evaluation of the three steering methods, focused on differences in performance, experience and VR sickness.

2 RELATED WORK

In this section, we provide an overview of existing VR steering techniques for 2D and 3D locomotion. This establishes a basis for our implementation of steering for the rowing machine. We also contextualize our work within the larger body of research on fitness equipment exergames and rowing machines for VR.

2.1 Steering in Virtual Environments

Locomotion in virtual environments broadly consists of three elements: (1) input condition (when and how input is triggered), (2) velocity, and (3) direction [12]. For rowing machines, input is naturally applied when a rower pulls, and velocity is derived from the speed of the flywheel. However, how to map movement directions is unclear. Steering addresses direction for locomotion by allowing the user to *continuously* specify the direction of travel while remaining seated [53, 59]. The problem with steering in VR is that the user is relatively stationary. This means that fewer somatosensory and vestibular cues are available to indicate self-motion [59], which can increase susceptibility for VR sickness [16, 31, 34, 73, 84, 99]. Since a rowing machine facilitates self-motion cues in the forward direction, the impact of steering on VR sickness could potentially be minimized. Several steering techniques have been proposed through the years [53], mainly for ground-based 2D locomotion [46]. We categorized these techniques based on which body part controls input and created five groups based on previous literature: *head*, *torso*, *hands*, *legs*, and *feet*. Considering the constraints of the rowing machine, two techniques are unfeasible: torso and legs. In "torso-directed" steering, the user would set the travel direction based on the torso's orientation [70, 100]. On a rowing machine, however, the user's orientation is fixed, and rotating one's back while pulling the handlebar can lead to back injuries [3]. Leg motion for steering has, for example, been implemented for flying [6, 98] and scuba diving [38] in VR but is also unfeasible as the user's feet cannot be reoriented while rowing. Therefore, the following subsection details the body-centered steering techniques (head, hands, feet) for 2D and 3D locomotion.

2.1.1 Head-based steering. Head-based steering is one of VR's most frequently used steering techniques [53]. The technique allows the user to provide input with 6DOF through the HMD's orientation and position in 3D space [70], which can be translated into both velocity and direction. An advantage of head-based steering in VR is that it does not require additional input devices and only uses input from the HMD. However, since the gaze and travel directions are coupled, users can feel constrained, and it can be hard to navigate around obstacles [29, 70]. Head-based steering techniques have been frequently used as direction input for "walk-in-place" locomotion [56, 74, 83, 87]. However, these techniques assume the users can freely rotate 360 degrees, which is not true in a seated rowing context. This limitation can be solved by setting direction relative to the virtual forward vector instead of the user's physical orientation [70]. For ground-based locomotion, studies indicate an advantage of head-based over hand-based steering for VR sickness [13, 42], comfort [13, 80], orientation [13], and sense of control [13]. However, Cardoso et al. [15] found no difference in VR sickness and comfort. Head-based steering has also been used efficiently for 3D locomotion, for example, in flying experiences [47, 60, 78]; however, few studies have compared body-based steering methods for 3D locomotion. Quia et al. [67] compared head-based steering against and combined with joystick and eye-tracking. They found that combining head-based for horizontal with mouse-based for vertical performed the best. Input modalities are most suitable for a given dimension. On the other hand, Medeiros introduced a "magic carpet" [60] locomotion technique and compared three steering methods using head, hand (pointing), and an "elevator" method. The elevator method controls the horizontal dimension through the head angle and the vertical dimension through buttons. They found the elevator method to have the worst performance. It remains unclear how combinations of input modalities might be more or less suitable.

2.1.2 Hand-based steering. Due to their anatomical structure, human hands are exceptionally suited for tasks requiring fine dexterity, manipulation, and sensory feedback [86], such as steering in VR. Many hand-based steering techniques involve spatial tracking in which the user holds a device and points towards the desired direction [53, 70]. The pointing technique has previously been used for 3D steering scenarios, for example, to teleport continuously [20, 54], to drag oneself through the air ("point and tug") [20], or to control a flying carpet [60]. A problem with hand-based steering is that it occupies the user's hand, which ideally could be used to perform other actions. Both hands hold the handlebar on the rowing machine anyway, but pointing to a direction is unfeasible while performing continuous rowing motions. Other hand-based techniques involve both arms to create motion and set direction, for example, through swimming gestures [38] or arm-flapping [78], which would also not be feasible with a rowing machine. Hands are used in steering for various vehicle simulations in which input is derived through a physical wheel [33, 35, 71] or handlebar [10, 14, 57]. An alternative for rowing is to use some form of "wheel" to mimic car or bike steering, i.e., rotating a steering wheel to change direction. This method is easy to use but usually less precise than a real steering wheel, and arm fatigue can also be a problem [70]. However, VR users tend to adapt their steering behavior to latency (i.e., the difference between input and visual change) [68], and for emulating the rowing experience, this might be a manageable problem. Arm fatigue is also reduced as the user's legs function as a counter force to keep the handlebar strained [25]. Three studies have found performance advantages with hand-based over head-based for speed, precision [12, 18] and error-rate [13]. However, other studies found no performance differences [29, 42, 80], as well as and no mental load difference [15, 42]. Regarding general preference, two studies indicate users prefer hand-based steering over head [29, 80].

2.1.3 Feet-based steering. While the hands for interaction might be less prominent than the feet for interaction, there are many scenarios whereby feet-based input could be suitable. An advantage of feet-based steering is that it frees up the head and hands for other tasks. Feet-based interaction is, for example, well-researched for machinery operations [89]. They have also been used in various vehicle contexts, for example, as pedals [89], and can be used to control the altitude direction of airplanes [89] or the rudder of canoes [94]. Using feet as an input mechanism allows for the exploitation of various features such as kicking gestures to trigger events [39, 48, 51, 51], or relative feet positions [79, 92] to indicate direction and length of locomotion. However, these features are unsuitable for a rowing machine, which requires the user's feet always to be positioned on the footrests to counteract the pull force. Feet input has also been used for locomotion speed, combined with head-based and hand-based steering for direction [23, 27]. In our case, a rowing machine already provides speed input through the flywheel, and feet input is better used for direction. To provide fine-grained feet-based steering, toes can be used as an input modality, which could be especially suitable since the user is sitting down and not required to hold their balance [63]. Feet-based locomotion has, to our knowledge, not been compared with other body-based steering techniques; however, it has been found to result in comparable VR sickness but less ease of use compared to joystick [26].

2.2 Virtual Reality Exergames & Rowing

While many application scenarios could exist for rowing-based locomotion, we believe VR exergames are a primary candidate. In this subsection, we contextualize our research within the broader field of HCI research on exergames, particularly those based on fitness equipment and rowing machines.

2.2.1 Exergames. Exergames (games involving physical activity) [65] can increase players' motivation to exercise. In particular, the use of VR for exergames can increase players motivation through immersive and engaging experiences [11, 19, 58, 82, 95, 96]. The problem is that exergames can be initially motivating, but players lose interest over time, leading to abandonment of exercise routines [5, 7, 64, 69]. HCI researchers have studied various solutions to increase player motivation, such as socialization functionalities through multiplayer competition, collaboration and communication [22, 40], dynamic adjustment of challenge level [4, 52, 61, 65], and avatar customization [9]. These solutions typically enhance motivational qualities through *extrinsic* and *social* game design elements [85]. *Intrinsic* motivational game design elements instead engage the player's immersion and curiosity [50, 85]. Introducing steering in exergames would allow players to travel anywhere in virtual environments, providing more possibilities for curiosity-driven game designs (e.g., freely exploring new landscapes) and a sense of autonomy [72]. The steering also adds interactions dependent on physical input (i.e., rowing) and the player's maneuvering skills, which could foster motivation through mastery of the game [72]. However, the controls should not be cumbersome since that can decrease immersion [21]. In this study, we investigate appropriate steering methods, which serve as a starting point for further exploration of rowing-based locomotion for exergames.

2.2.2 Equipment for Exergames. Several research projects have explored treadmills and stationary bicycles with locomotion abilities for VR exergames [10, 14, 45, 49, 57, 97]. These have mapped virtual terrain to treadmill elevation level [45], anxiety reduction [97], heart rate input [49], and bicycle wheel speed [10, 14] for forward locomotion. These exergames only allow locomotion along one dimension, i.e., forward and backward. The exception is a study by McDade et al. [57] with a 2D indoor bike. They found that yaw rotation in the virtual environment produces over-steering and disorientation. Instead, the handlebar's yaw rotation was mapped to lateral steering between left and right, i.e., not curved but horizontal translations perpendicular to the forward direction. This allows repositioning on a predefined track but not full 2D or 3D travel. Among commercial VR exergames, HoloFit [43] supports locomotion with treadmills, indoor bicycles, and rowing machines. However, steering is unavailable, and locomotion is one-directional forward movement along predefined tracks. VZFit [90] supports lateral steering for indoor bicycles similar to McDade et al. [57]. Still, instead of rotating the handlebar, the steering is done either through head-based roll-rotation or head-based horizontal translation of the headset, i.e., leaning. While lateral steering allows players to position themselves from left to right continuously, forward locomotion is still constrained by a predefined travel path, which prohibits unrestricted exploration of 2D and 3D virtual worlds.

2.2.3 VR Rowing Machines. A handful of projects have explored the use of VR for rowing machines. The application scenarios have been either exergames or rowing technique feedback training. The studies of [3, 88] focused on providing a fun experience and visual feedback for proper rowing technique. VR4VRT [88] also supports the rowing technique through motion trackers on the rowers' hands and the seat to estimate the rower's limb posture. Arndt et al. [3] compared a VR rowing exercise to a non-VR equivalent and found that the user's rhythm and breath improved the most in VR. Neither of these projects explored steering possibilities, presumably since the rowing technique was the primary goal. In a rowing exergame by [77], the user had to collect points and avoid being eaten by a crocodile by rowing faster. An HTC Vive tracker was attached to the machine's handlebar to measure speed. A perhaps less stressful approach has been using beautiful virtual environments while rowing, as in the commercial application HoloFit [43]. Parton and Neumann [66] explored social aspects of a rowing exergame and found that a virtual rowing competitor in VR can increase motivation for heavy exertion while rowing. A key difference between the rowing technique and exergame implementations is the locomotion direction. Rowing is typically performed backward, but the rowing exergames support forward locomotion instead for entertainment purposes [88]. While the rowing exergames focus on motivational aspects, steering has not been explored, which limits potential game design scenarios. Our work expands upon previous exergame implementations by adding steering for 2D and 3D locomotion, thus supporting more than forward/backward and lateral movement in the virtual environment.

3 DESIGN CONSIDERATIONS FOR ROWING-BASED LOCOMOTION

In this section, we introduce design considerations for rowing-based locomotion. These considerations are based on the physical constraints imposed by rowing machines and our aim to facilitate good performance for rowing in an exergame context.

3.1 Metaphor considerations

The locomotion generated by the rowing machine could be mapped to any metaphor in the virtual environment. We opted for a rowing boat metaphor as rowing machines have been substituted for real rowing since their invention [30]. We generally aimed for a realistic "feel" in which users' naive sense of physics helps them understand the interactions [37], e.g., pulling harder increases steering rotation force. However, we also went beyond realism for better ergonomics and efficient locomotion [1]. The virtual locomotion speed was increased compared to a realistic rowing boat since we believe this facilitated a more engaging experience, an important motivational aspect of frequent exergame usage [36, 57, 62]. We also assumed moving forward instead of backward (real rowing is performed backward) would be more engaging and ergonomic in most games. Lastly, 3D "flying" locomotion for boats is unrealistic. Still, we believed it would be easier for users to have the same metaphor and controls in both 2D and 3D instead of introducing a new metaphor, e.g., airplane, helicopter.

3.2 Locomotion considerations

3.2.1 When to provide steering power. According to Bowman, when and how input is triggered is one of three important characteristics of any locomotion technique, together with velocity and direction selection [12]. Although steering power could technically be available as soon as the user provides input, this would feel unrealistic for the user if a rowing motion is not co-occurring. Rowing differs from other vehicle steering methods because it requires the oars in the water. In other words, even if the virtual boat moves forward and the oars are up, steering is impossible. While there are no oars on a rowing machine, we decided to provide steering power when the users were pulling the handlebar towards themselves as it mimics the feeling of putting the oars in the water and pulling.

3.2.2 How to control steering power. Various possibilities exist for controlling the applied amount of turning force [24]. Other locomotion methods have increased the force based on the input frequency per time unit, e.g., increasing input events during a second increases the amount of force. This works if a user repeats an input action frequently, such as "hammering" a button, which allows a user to easily prevent further input by not acting [12]. In contrast, continuous input directly sets the turn force value from the input source. We decided to provide continuous input so the user could more smoothly set the value, thereby avoiding distracting maneuvers. This means that unintended inputs could be a problem, making the steering feel "wobbly". However, we avoided this by setting continuous input values only during pulling. We amplified the steering input with a power function [24] with pulling speed as an input, causing faster, heavier pulls to increase the turning force exponentially more than slower pulls.

3.2.3 How to move in 3D space. We considered two forms of forces for movement through vertical space: *combined* and *separate*. A combined force would only apply speed power on the forward vector of the virtual rowing boat. This implies that the angle of the virtual boat must be pitched for locomotion to occur. This creates a mismatch between the user's physical and visual orientations in VR, which increases the risk of VR sickness [31]. Roll and yaw maneuvers must also be implemented for a combined force, increasing steering complexity. Instead, we decided on a separate force approach in which up- and downward input creates vertical locomotion directly perpendicular to the forward vector. To avoid an elevator-like experience, we multiplied the vertical force with the handlebar pull force. Thus, to move vertically, forward speed is needed. We did not include gravity to allow users to rest at higher altitudes. To provide a fluent experience, we ensured that 2D and 3D steering actions could be performed simultaneously, e.g., moving down and left simultaneously.

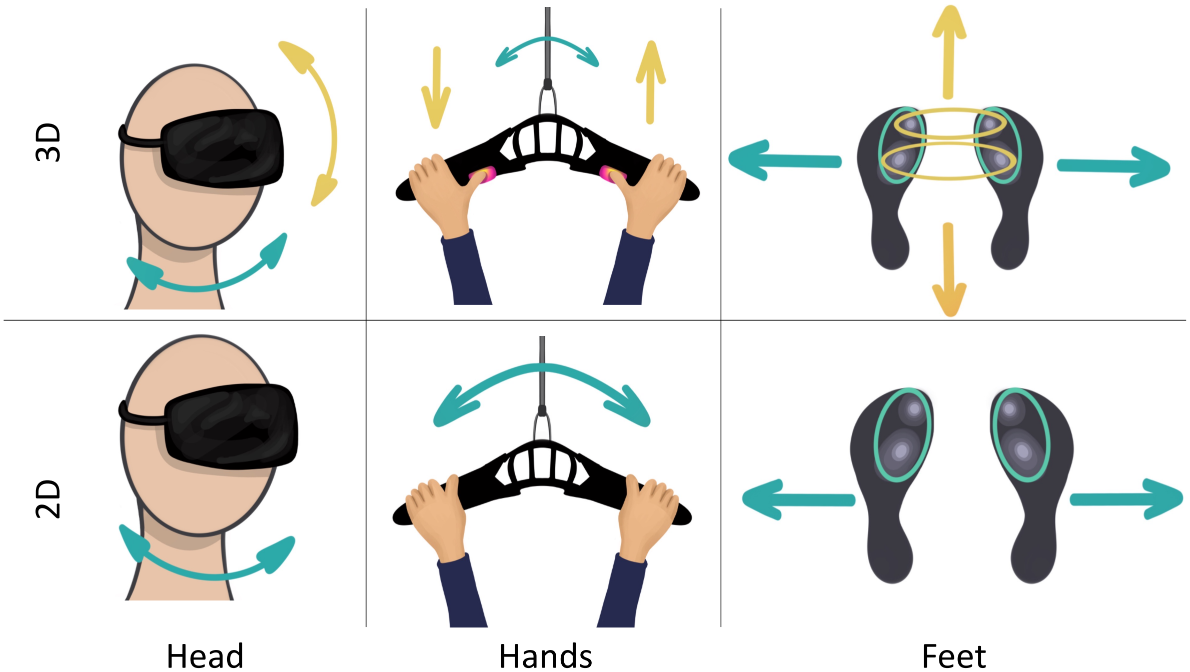

Figure 2: Overview of three steering methods for 2D (lower row) and 3D (upper row) using head, hands, and feet. The head steering facilitates locomotion in the direction of head orientation, hand steering utilizes the rotations of a handlebar, and feet steering employs pressure distribution of toes and big toe joints on feet placeholders.

3.3 Body-specific considerations

We implemented three steering methods based on head, hands, and feet input (Figure 2) since steering techniques are commonly categorized based on which body part controls input [17, 53, 59, 70]. The most frequently techniques employ input from *head*, *torso* and *hands* [53], with *legs* [6, 98], and *feet* [63, 89, 92] gaining research interest in recent years. A rowing machine restricts users from rotating their torso and repositioning their legs, so we did not implement steering alternatives based on these inputs. Thus, the three steering methods we implemented represent the remaining body-specific techniques.

3.3.1 Head. For head-based steering, we employed pitch and yaw orientation. We did not consider the headset position as an input because the rowers' motion on the machine would make it unfeasible. Thus, we mapped the left-right steering to the user's yaw orientation, i.e., rotating around the upward axis, and vertical steering to the user's pitch orientation, i.e., looking up and down. An advantage of this method is that it does not require other devices than the VR headset, thus lowering the usage barrier [70].

3.3.2 Hands. Hand-based steering is restricted by the user's occupation of the hands holding the handlebar. Instead, the handlebar can provide input through 3DoF orientation as with head-based steering [70]. In practice, however, only the handlebar roll and yaw orientations are feasible to use, as the chain attached to the handlebar restricts rotation along the pitch axis. Both roll and yaw are intuitive candidates for left-right steering, resembling the steering of a car or bike. While using yaw would cause the users to pull with either the left or right arm mainly, the roll axis affords both arms to be equally involved. This is important for a regular rowing motion, which prevents injuries [88]. Therefore, we used the roll axis of the handlebar for 2D steering. Since the pitch axis is unavailable for 3D steering, other input sources than handlebar orientation had to be used. As the user's fingers are available, buttons can be attached to the handlebar. We decided to add one button for each thumb, right for up and left for down. The logic behind this mapping is based on possible user familiarity with scooters and mopeds, in which acceleration is typically on the right side. This meant fixed discrete input each frame a button was pushed down. The hands method is arguably most akin to steering a vehicle, e.g., bicycle [55, 57], car [70], or scooter, and could therefore feel familiar to users.

3.3.3 Feet. The user's feet need to be strapped on the rowing machine footstances (figure 3) to provide resistance force while pulling, and could therefore not be lifted. This prevents direction from being set by foot orientation or relative foot position [92]. However, the resistance force could be achieved if the heels remained on the footstances. By loosening the straps a little, the user can elevate one foot a bit, thereby easily controlling the pressure on each foot stance. We used this difference in foot pressure between footstances as input for the left or right directions. For 3D steering, the same method can be applied, but the difference must be measured between the front and back of the feet. Since heels must always apply pressure on the foot stance, we used the difference between the big

Figure 3: We investigated three steering methods for rowing-based locomotion: (a) head-based steering indicates the direction of movement according to the head's orientation, (b) hands-based steering employs handlebar rotation on a 2D plane and buttons under thumbs to go up and down, and (c) feet-based steering is based on the pressure distribution between left and right feet for steering on a 2D plane and between toes and toes joints for steering in a 3D space.

toes and the big toe joints for up and down input. Pressing with the joints increases the upward force, while pressing with the big toes increases the downward force. An inverse mapping could also be feasible. The logic for this mapping was that pressing on one's toes makes one fall forward, i.e., pitching down, and pressing on the joints of one's feet would make one fall backward, i.e., pitching up. With feet-based steering, hands can be free to perform other actions (e.g., using thumbs for input in some games). The user's head is also decoupled from the travel direction, allowing the user to view the environment more easily while moving.

4 EVALUATION

In the experiment, we investigated the influence of three rowing-based steering methods on user performance, Virtual Reality Sickness, and user experience in VR environments. Therefore, for this experiment, we had the following research questions: How do (RQ1) user performance, (RQ2) VR sickness, and (RQ3) user experience differ between the steering methods in 2D and 3D?

4.1 Participants

We recruited 24 participants (identified as 10 F, 14 M) aged between 21 and 44 years old ($M = 30.2, SD = 5.7$) using our university's online marketing channels. Their previous experience in VR ranged between little (5), moderate (11), and extensive (8) experience. Seventeen participants had little to no experience with rowing machines, while 7 had moderate experience. No exclusion criteria was applied. Each participant received cinema vouchers worth 30€.

4.2 Study design

The study was designed to be within-participant with two independent variables: (1) steering method and (2) type of space. Within the scope of this paper, we consider three types of steering methods based on the previous work and design considerations imposed by a rowing setup described in the above section: (1) head- (2) hands-, (3) and feet-based steering (Figure 3). While hands-based steering is a conventional method for many VR simulators, e.g., rotation of a steering wheel while driving and a handlebar while cycling, we included two promising methods based on the previous research for steering and vehicle control using head rotation [56, 74, 83, 87] and feet [79, 89, 92]. With these three methods, we aimed not only to explore existing rowing-based steering methods in virtual environments but also to assess levels of control with different parts of the body: (1) head – HMD, (2) hands – handlebar, and (3) feet – toe- and joint-based input. As for the type of space, we explore steering in (1) 2D and (2) 3D space. Rowing in VR was previously explored for training purposes and focused on movement along one axis, i.e., only straight ahead. Combining all three levels of *steering methods* and two levels of *type of space* resulted in six experimental conditions. The order of the conditions was counterbalanced using a balanced Latin square.

4.3 Task

Participants had to collect fifteen coins by maneuvering a virtual boat as quickly as possible. The virtual environment with coins was designed with minimal distractions, featuring only a flat blue ocean to minimize the impact of VR sickness [2] and mountains in the distance to facilitate height perception. To aid participants in the trajectory estimation, two coins were always spawned. The first coin was the current target indicated by an oscillating arrow above. If a participant missed the target coin, the arrow changed to the subsequent coin, and a new subsequent coin was spawned. Six tracks were created with fixed coin positions (3 for 2D and 3 for 3D), forming curved and straight trajectories. Each track consisted of (5) left, (5) right and (5) forward directions to the subsequent coin. The angle to the left and right subsequent coins was set to 50 degrees. For the 3D tracks, (6) up and (6) down directions were added and spread equally over the left, right, and forward directions. All tracks were above the ground. Collecting the first coin started the timer but was not counted among the 15 coins. Both collected and missed coins were accompanied by audio cues for non-visual feedback.

4.4 Apparatus

We conducted the experiment in the developed VR rowing simulator, which consisted of the rowing machine [1]). The flywheel of the rowing machine was fitted with a Garmin Speed Sensor 2, which transmits real-time speed via ANT+ and Bluetooth to the simulation (Figure 4). The continuous value from the speed sensor was applied to the virtual boat's forward direction as a force. Steering actions were reflected in the simulation shown in the VR head-mounted

[1] https://www.sportig.no/pub_docs/files/dokument_sportig/Epsilon-RX90-Manual-EN.pdf

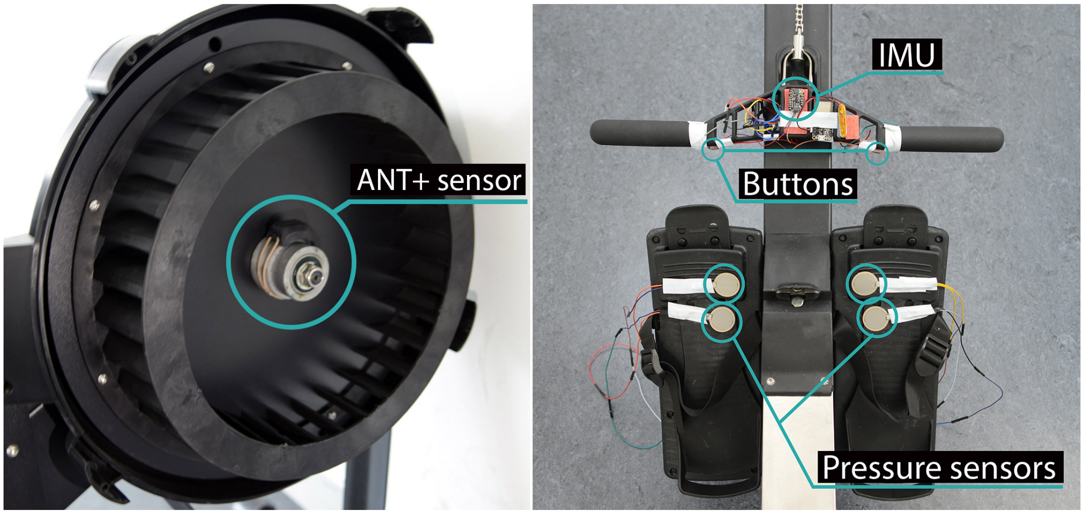

Figure 4: ANT+ sensor attached to the flywheel for speed input (left) and steering sensors for hands (inertial measurement unit, buttons) and feet method (pressure sensors) (right).

display. Steering input was applied as a torque rotation force on the virtual boat's yaw axis. To avoid inconveniences caused by wires, we used the wireless headset Oculus Quest 2. The VR environment was implemented using Unity SDK (2021.1.3) with OculusVR assets and consisted of an ocean with islands. For the *hands-based* method, we placed an Inertial measurement unit on the handlebar of the rowing machine to continuously measure the roll-axis rotation angle of the handlebar left and right. Given that turning a handlebar upwards and downwards is difficult and unnatural, as discussed above in the considerations section, we added two buttons (discrete input)on both sides of the handlebar. Moreover, for steering in 3D space, we aimed to facilitate simultaneous upward-downward and side-wise movement. Pressing the button on the right enables upward movement and the one on the left downwards. The *head-based* method was implemented using the continuous orientation of the Oculus Quest 2 headset (angle tracking error <0.001° [32]) to capture the head's yaw rotation. Finally, four pressure sensors (continuous input) on the two footstances enabled the *feet-based* method. Two sensors were placed under the big toes (toe sensors) and two – under the joints connecting the big toes to the foot (joint sensors). Simultaneous pressure on toe sensors facilitates going downwards, and simultaneous pressure on toe joints – upwards. A pressure on a right toe and/or joint sensor enables turning right, and a pressure on a left toe and/or joint sensor – turning left.

4.5 Measurements

To answer the research questions, we measured the following dependent variables:

- **Task Completion Time (in sec)**: we measured the amount of time it takes to finish a track with each locomotion method (RQ1).
- **Traveled distance (in m)**: for each condition, we measured the traveled distance from the start until the end of the track (RQ1).
- **Rowing speed (in m/sec)**: based on the task completion time and traveled distance, for each condition, we also measured the average rowing speed (RQ1).
- **Coin offset (in m)**: for missed coins, we measured the distance to it (RQ1).
- **Coin collection rate (%)**: for each method, we measured the rate of missed coins along the track (RQ1).
- **Virtual Reality Sickness**: after each experimental condition, participants filled in the questions from the Simulation Sickness Questionnaire (SSQ) to assess their motion sickness. To calculate the SSQ score [41], we used the formula from Bimberg et al. [8]. We calculated scores both with and without the sweating sub-component as sweating commonly occurs in exergames [19] (RQ2).
- **Perceived workload:** for each condition, we asked participants to specify the perceived workload using the NASA Task Load Index, which covers the workload in terms of mental demand, physical demand, temporal demand, overall performance, effort, and frustration level [28] (RQ3).
- **Enjoyment, Ease and Frequency of Use, Intuitiveness, Orientation, Fatigue, and Exertion**: after each condition, participants were asked to assess ease and frequency of use, intuitivity, orientation, exertion, and fatigue of the method using a 5-point Likert scale (1 – the lowest score, 5 – the highest score) (RQ3).

For qualitative feedback, after all conditions, participants expressed their method preferences for 2D and 3D, and ranked them based on perceived realism, VR sickness, and exertion.

4.6 Procedure

After obtaining informed consent, we collected participants' demographic data. Afterward, we provided a brief overview of the procedures, which included explanations of locomotion, steering methods, and the task. We started the experiment when participants

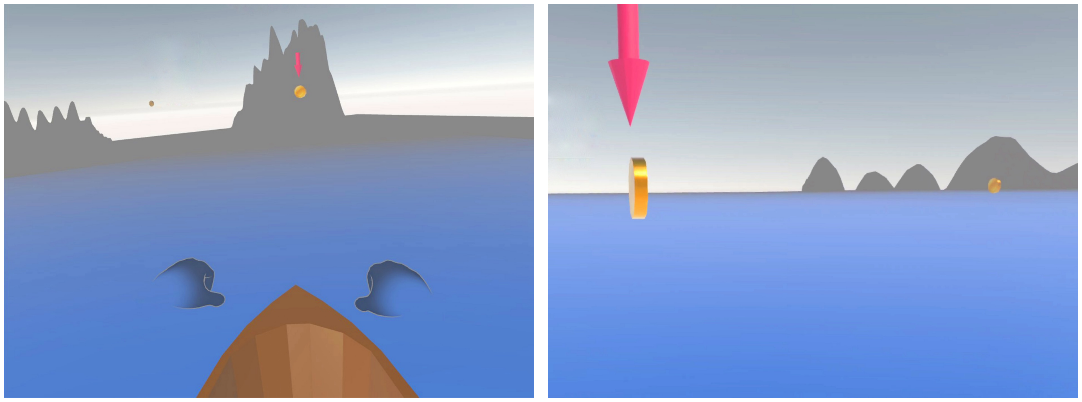

Figure 5: First person perspective of rowing in VR (left) and coins placed in the virtual space (right). The target coin is visualized with an arrow above, and the next coin is seen in the distance.

felt comfortable. Before each condition started, participants were allowed to familiarize themselves with the steering method. Participants were transported to the beginning of the trail when they felt comfortable with it, where the coins started to spawn. Participants' task was to finish the trail as fast and as accurately as possible. At the end of each trial, participants heard an audio cue as an indication to take off the headset and fill out a questionnaire regarding the steering method. At the end of the study, the participants filled in questionnaires about their preferences for the different steering methods. They were also given the option to comment on their preferences. The entire study lasted approximately 75 minutes.

4.7 Data analysis

Given the non-parametric nature of the collected data, we applied the aligned rank transform for non-parametric factorial analyses [93]. For pairwise comparisons, we used a Bonferroni p-value correction.

5 RESULTS

We found that head steering leads to fast and precise steering in 2D and 3D, and hand-based steering is the most realistic. The feet-based method had precision similar to the hand-based method for 2D steering, while for 3D, the feet-based method led to the slowest performance. Participants perceived head steering as the least mentally demanding. Lastly, there was no significant difference in VR sickness between the methods, but participants experienced higher levels of VR sickness in 3D. We outline these results in detail in the following.

5.1 RQ1: How does user performance differ between the steering method in 2D and 3D?

5.1.1 Task Completion Time. Participants were faster with collecting coins and finishing the track using the head ($Md = 167\ sec, IQR = 73$) than the hand ($Md = 200\ sec, IQR = 80$) and feet methods ($Md = 249\ sec, IQR = 86$). As for the type of space, participants were faster in 2D ($Md = 180\ sec, IQR = 80$) than in 3D ($Md = 222\ sec, IQR = 105$). Both of these findings were supported by the statistically significant main effects for the steering method ($F(2, 46) = 59, p < 0.001, \eta^2 = 0.72$) and the type of space ($F(1, 23) = 34, p < 0.001, \eta^2 = 0.59$). The post-hoc analysis has shown statistically significant differences between all pairs ($p < 0.001$) for both independent variables (Figure 6 left). Finally, our statistical analysis revealed a statistically significant interaction effect for steering method*space ($F(2, 46) = 12.3, p < 0.001, \eta^2 = 0.35$). The post-hoc analysis has shown that the head method in 3D takes longer than in 2D ($p = 0.02$), and the feet in 2D take longer than the hands ($p = 0.007$) and head ($p = 0.0015$) in 2D. The remaining pairwise comparisons were statistically insignificant ($p > 0.05$).

5.1.2 Traveled distance. We found that participants covered shorter distances using the head ($Md = 3644\ m, IQR = 154$) than the hand ($Md = 3824\ m, IQR = 334$) and feet methods ($Md = 4053\ m, IQR = 790$). As for the type of space, participants covered shorter distances in 2D ($Md = 3729\ m, IQR = 385$) than in 3D ($Md = 3809\ m, IQR = 410$). Both of these findings were supported by the statistically significant main effects for the steering method ($F(2, 46) = 40, p < 0.001, \eta^2 = 0.63$) and the type of space ($F(1, 23) = 10.6, p = 0.003, \eta^2 = 0.32$). The post-hoc analysis has shown statistically significant differences between all pairs ($p < 0.05$) for both independent variables (Figure 6 center). Finally, our statistical analysis revealed a statistically significant interaction effect for steering method*space ($F(2, 46) = 5, p = 0.01, \eta^2 = 0.18$). The post-hoc analysis has shown that participants covered longer distances with the feet in 2D than with hands ($p = 0.003$) and head ($p < 0.001$) in 2D. Moreover, they covered longer distances with feet in 2D than head in 3D ($p = 0.03$) and hands in 3D than head in 2D ($p = 0.019$). The remaining pairwise comparisons were statistically insignificant ($p > 0.05$).

5.1.3 Rowing speed. We discovered that participants' rowing speed was higher using the head ($Md = 21.1\ m/sec, IQR = 9$) and the hand ($M = 20.2\ m/sec, IQR = 9$) than feet methods ($Md = 17.1\ m/sec, IQR = 7.2$). As for the type of space, participants were rowing faster in 2D ($Md = 21.6\ m/sec, IQR = 10$) than in 3D ($Md = 18.1\ m/sec, IQR = 7.3$). Both of these findings were supported by the statistically significant main effects for the steering method ($F(2, 46) = 16.3, p < 0.001, \eta^2 = 0.41$) and the type of space ($F(1, 23) = 29, p < 0.001, \eta^2 = 0.56$). The post-hoc analysis for the steering method has shown statistically significant differences between feet and head ($p < 0.001$),

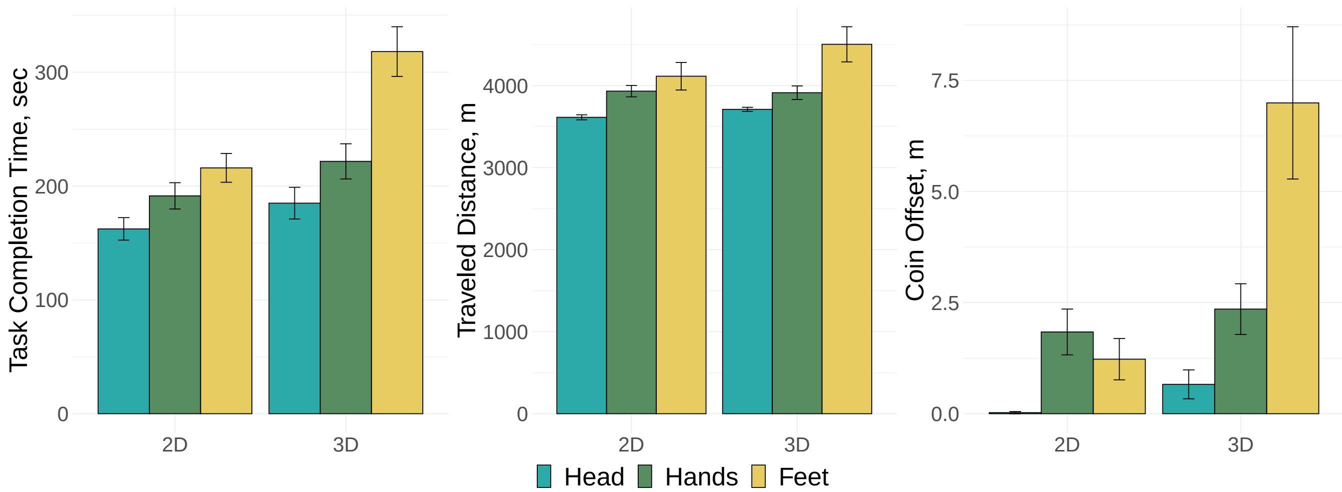

Figure 6: Overview of results averaged over steering methods: means and standard errors for task completion time (left), traveled distance (center), and coin collection offset (right).

and feet and hand ($p < 0.001$), but not between head and hand ($p = 0.76$). The post-hoc analysis for the type of space has shown statistically significant differences between 2D and 3D ($p < 0.001$). However, our statistical analysis did not reveal a statistically significant interaction effect for steering method*space ($F(2,46) = 2.2, p = 0.12, \eta^2 = 0.08$).

5.1.4 Coin offset. We found that the coin offset was smaller when steering with head ($Md = 0.24\ m, IQR = 1.17$) than with hand ($Md = 2.08\ m, IQR = 5.85$) and feet ($Md = 3.76\ m, IQR = 9.7$). As for the type of space, participants experienced smaller coin offsets in 2D ($Md = 0.88\ m, IQR = 3.9$) than in 3D ($Md = 3.16\ m, IQR = 8.38$). Both of these findings were supported by the statistically significant main effects for the steering method ($F(2,46) = 34.8, p < 0.001, \eta^2 = 0.6$) and the type of space ($F(1,23) = 361, p < 0.001, \eta^2 = 0.94$). The post-hoc analysis has shown statistically significant differences between all pairs ($p < 0.05$) for both independent variables (Figure 6 right). Finally, our statistical analysis revealed a statistically significant interaction effect for steering method*space ($F(2,46) = 80.3, p < 0.001, \eta^2 = 0.77$). The post-hoc analysis has shown statistically significant differences between all pairs ($p < 0.05$) (Figure 6 right illustrates all differences).

5.1.5 Coin collection rate. We found that the coin collection rate was higher when steering with head ($Md = 100\%, IQR = 8.3$) than with hand ($Md = 78\%, IQR = 21$) and feet ($Md = 63\%, IQR = 40$). As for the type of space, participants' coin collection rate was higher in 2D ($Md = 93\%, IQR = 15$) than in 3D ($Md = 76\%, IQR = 35$). Both of these findings were supported by the statistically significant main effects for the steering method ($F(2,46) = 85.7, p < 0.001, \eta^2 = 0.79$) and the type of space ($F(1,23) = 150, p < 0.001, \eta^2 = 0.87$). The post-hoc analysis has shown statistically significant differences between all pairs ($p < 0.001$) for both independent variables (Figure 7 left). Finally, our statistical analysis revealed a statistically significant interaction effect for steering method*space ($F(2,46) = 30.8, p < 0.001, \eta^2 = 0.57$). The post-hoc analysis has shown statistically significant differences between all pairs ($p < 0.05$), except for the pairs: feet in 2D and hand in 3D ($p = 0.74$), feet in 2D and head in 3D ($p = 0.77$), hand and head in 2D ($p = 0.68$), hand in 2D and feet in 3D ($p = 0.93$), head in 2D and feet in 3D ($p = 0.98$), and hand and head in 3D ($p = 0.99$).

5.2 RQ2: How does VR sickness differ between the steering method in 2D and 3D?

We found that participants experienced comparable motion sickness using head- ($Md = 13.09, IQR = 26$), hand- ($Md = 17.5, IQR = 18$), and feet-based steering ($Md = 21.4, IQR = 26$). This finding was supported by the statistically non-significant main effect for the steering method ($F(2,46) = 2.6, p = 0.08, \eta^2 = 0.1$) However, participants' VR Sickness was higher in 3D ($Md = 16.83, IQR = 26$) than in 2D ($Md = 11.2, IQR = 18$). This finding was supported by the statistically significant effect for space ($F(1,23) = 13, p < 0.001, \eta^2 = 0.24$). The post-hoc analysis has shown statistically significant differences between 2D and 3D ($p < 0.001$) for the type of space (Figure 7 center). Finally, we did not observe a statistically significant interaction effect for steering method * space ($F(4,212) = 0.47, p = 0.65, \eta^2 = 0.3$).

We also considered SSQ scores without sweating and found that participants experienced comparable motion sickness using head- ($Md = 11.22, IQR = 26$), hand- ($Md = 7.48, IQR = 17.7$), and feet-based steering ($Md = 11.2, IQR = 26$). This finding was supported by the statistically non-significant main effect for the steering method ($F(2,46) = 2.03, p = 0.14, \eta^2 = 0.08$). However, participants' VR Sickness was higher in 3D ($Md = 11.22, IQR = 22$) than in 2D ($Md = 7.48, IQR = 18.7$), supported by the statistically significant effect for space ($F(1,23) = 13.3, p < 0.001, \eta^2 = 0.23$). The post-hoc analysis has shown statistically significant differences between 2D and 3D ($p < 0.001$) for the type of space. Finally, we did not observe a statistically significant interaction effect for steering method * space ($F(4,212) = 0.33, p = 0.71, \eta^2 = 0.016$).

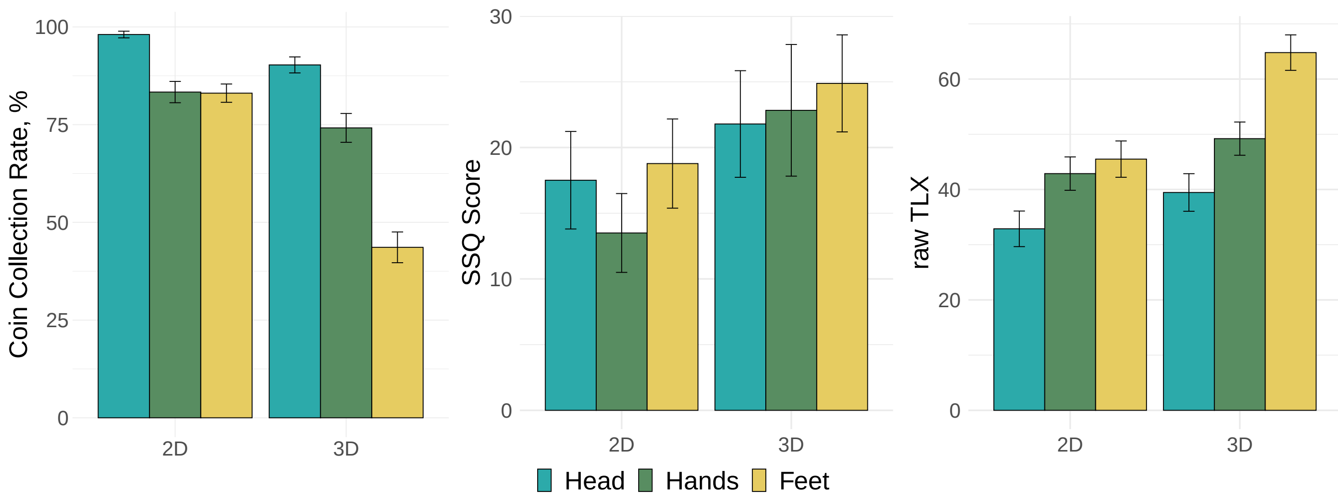

Figure 7: Overview of results averaged over steering methods: means and standard errors for coin collection success rate, VR sickness (SSQ Score), and Task Load (NASA-TLX).

5.3 RQ3: How does user experience differ between the steering methods in 2D and 3D?

5.3.1 Perceived workload. We discovered that participants found it more mentally demanding to steer with feet ($Md = 55, IQR = 26.7$), followed by hands ($Md = 46, IQR = 17$) and head ($Md = 37.5, IQR = 28.5$). As for the type of space, participants found it more mentally demanding to move in 3D ($Md = 52, IQR = 25$) than in 2D ($Md = 43, IQR = 24$). Both of these findings were supported by the statistically significant main effects for the steering method ($F(2, 46) = 23.8, p < 0.001, \eta^2 = 0.51$) and the type of space ($F(1, 23) = 23.1, p < 0.001, \eta^2 = 0.5$). The post-hoc analysis has shown statistically significant differences between all pairs ($p < 0.001$) for both independent variables (Figure 7 right). Finally, our statistical analysis revealed a statistically significant interaction effect for steering method*space ($F(2, 46) = 5.6, p = 0.006, \eta^2 = 0.19$). However, none of the pairwise comparisons were statistically significant ($p > 0.05$) due to the p-value correction.

5.3.2 Enjoyment. Participants enjoyed steering with head ($Md = 4, IQR = 1$) and hands ($Md = 4, IQR = 1$) more than with feet ($Md = 4, IQR = 0$). As for the type of space, participants enjoyed steering in 2D ($Md = 4, IQR = 1$) more than in 3D ($Md = 4, IQR = 1$). Both of these findings were supported by the statistically significant main effects for the steering method ($F(2, 46) = 9.8, p < 0.001, \eta^2 = 0.3$) and the type of space ($F(1, 23) = 13.8, p < 0.001, \eta^2 = 0.39$). The post-hoc analysis has shown statistically significant differences between all pairs ($p < 0.001$) for both independent variables, except for head and hands steering ($p = 0.19$) (Figure 8). Finally, we did not observe a statistically significant interaction effect for steering method * space ($F(4, 46) = 2.3, p = 0.11, \eta^2 = 0.09$).

5.3.3 Ease of Use. Participants found steering with head ($Md = 5, IQR = 1$) easier to use than with hands ($Md = 4, IQR = 1$) and feet ($Md = 3, IQR = 1$). As for the type of space, participants found steering in 2D ($Md = 4, IQR = 2$) easier than in 3D ($Md = 4, IQR = 2$). Both of these findings were supported by the statistically significant main effects for the steering method ($F(2, 46) = 57.4, p < 0.001, \eta^2 = 0.71$) and the type of space ($F(1, 23) = 22.8, p < 0.001, \eta^2 = 0.51$). The post-hoc analysis has shown statistically significant differences between all pairs ($p < 0.001$) for both independent variables (Figure 8). Finally, we observed a statistically significant interaction effect for steering method * space ($F(4, 46) = 5.2, p = 0.009, \eta^2 = 0.18$). However, none of the pairwise comparisons were statistically significant ($p > 0.05$) due to the p-value correction.

5.3.4 Frequency of Use. Participants would use steering with head ($Md = 4.5, IQR = 2$) and hands ($Md = 4, IQR = 2$) more frequently for gaming than with feet ($Md = 3, IQR = 2$). As for the type of space, participants would use steering in 2D ($Md = 4, IQR = 2$) more frequently than in 3D ($Md = 3, IQR = 3$). Both of these findings were supported by the statistically significant main effects for the steering method ($F(2, 46) = 14.6, p < 0.001, \eta^2 = 0.39$) and the type of space ($F(1, 23) = 9.05, p = 0.006, \eta^2 = 0.29$). The post-hoc analysis has shown statistically significant differences between all pairs for the steering ($p < 0.001$), except for head and hands ($p = 0.11$), and the type of space ($p = 0.03$) (Figure 8). Finally, we observed a statistically significant interaction effect for steering method * space ($F(4, 46) = 3.4, p = 0.042, \eta^2 = 0.12$). However, none of the pairwise comparisons were statistically significant ($p > 0.05$) due to the p-value correction.

5.3.5 Intuitiveness. Participants found steering with head ($Md = 5, IQR = 1$) the most intuitive, followed by hands ($Md = 4, IQR = 1$) and feet ($Md = 3, IQR = 2$). As for the type of space, participants found steering in 2D ($Md = 5, IQR = 1$) more intuitive than in 3D ($Md = 4, IQR = 1$). Both of these findings were supported by the statistically significant main effects for the steering method ($F(2, 46) = 3.44, p < 0.001, \eta^2 = 0.6$) and the type of space ($F(1, 23) = 5.39, p < 0.001, \eta^2 = 0.7$). The post-hoc analysis has shown statistically significant differences between all pairs for the steering ($p < 0.01$) and for the type of space ($p < 0.01$) (Figure 8).

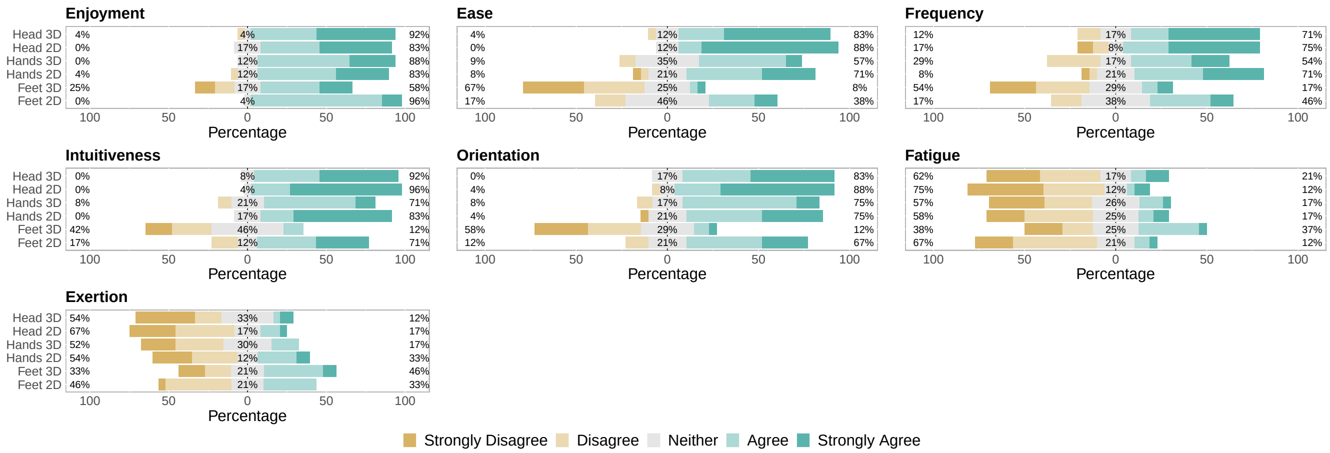

Figure 8: Overview of Likert data for each question: enjoyment, ease of use, preference for using the methods frequently, intuitiveness of methods, assistance by orientation in space, subjective assessment of fatigue and exertion.

Finally, we observed a statistically significant interaction effect for steering method * space ($F(4, 46) = 13.3, p < 0.001, \eta^2 = 0.3$). Steering with feet in 3D was less intuitive than with feet in 2D ($p = 0.01$), feet in 2D were less intuitive than head in 2D ($p = 0.002$), head in 2D was more intuitive than hand in 2D ($p = 0.048$), head in 2D was more intuitive than head in 3D ($p = 0.002$). The remaining pairwise comparisons were statistically not significant ($p > 0.05$).

5.3.6 Orientation. Participants found it easier to orient in space when steering with head ($Md = 5, IQR = 1$), followed by hands ($Md = 4, IQR = 1$) and feet ($Md = 3, IQR = 2$). As for the type of space, participants found it easier to orient in space when steering in 2D ($Md = 4, IQR = 1$) than in 3D ($Md = 4, IQR = 1$). Both of these findings were supported by the statistically significant main effects for the steering method ($F(2, 46) = 33.4, p < 0.001, \eta^2 = 0.59$) and the type of space ($F(1, 23) = 19, p < 0.001, \eta^2 = 0.46$). The post-hoc analysis has shown statistically significant differences between all pairs for both independent variables ($p < 0.01$) (Figure 8). Finally, we observed a statistically significant interaction effect for steering method * space ($F(4, 46) = 14.2, p < 0.001, \eta^2 = 0.38$). Steering with feet in 3D led to lower orientation than with head ($p = 0.005$) and hand in 3D ($p = 0.009$) and feet in 2D ($p = 0.002$). Moreover, steering with feet in 2D led to lower orientation than with head in 2D ($p = 0.03$). The remaining pairwise comparisons were statistically not significant ($p > 0.05$).

5.3.7 Fatigue. Participants found it more tiresome to steer with feet ($Md = 2, IQR = 1.25$) than with head ($Md = 2, IQR = 2$) and hands ($Md = 2, IQR = 1$). This finding was supported by the statistically significant main effect for the steering method ($F(2, 46) = 3.73, p = 0.03, \eta^2 = 0.14$). The post-hoc analysis has shown statistically significant differences only between feet and head steering ($p < 0.05$) (Figure 8). As for the type of space, participants steering in 2D ($Md = 2, IQR = 2$) and 3D ($Md = 2, IQR = 3$) comparably fatiguing. This finding was supported by a non-statistically significant main effect for the type of space ($F(1, 23) = 2.6, p = 0.11, \eta^2 = 0.1$). Finally, we observed a statistically significant interaction effect for steering method * space ($F(4, 46) = 5.8, p = 0.005, \eta^2 = 0.2$). However, none of the pairwise comparisons were statistically significant ($p > 0.05$) due to the p-value correction.

5.3.8 Exertion. Participants found that they exerted more when steering with feet ($Md = 3, IQR = 2$) than with head ($Md = 2, IQR = 2$) or hands ($Md = 2, IQR = 2$). As for the type of space, participants steering in 2D ($Md = 2, IQR = 2$) and 3D ($Md = 3, IQR = 3$) led to comparable exertion. Both of these findings were supported by the statistically significant main effects for the steering method ($F(2, 46) = 8.49, p < 0.001, \eta^2 = 0.27$) and a non-statistically significant main effect for the type of space ($F(1, 23) = 0.32, p = 0.57, \eta^2 = 0.01$). The post-hoc analysis has shown statistically significant differences between feet and head ($p < 0.001$) and feet and hand ($p = 0.03$) steering, but not between hand and head ($p = 0.34$) (Figure 8). Finally, we did not observe a statistically significant interaction effect for steering method * space ($F(4, 46) = 0.51, p = 0.6, \eta^2 = 0.02$).

5.4 Preferences and Feedback

The results suggest that the participants preferred hands- and head-based steering. For 2D, 13 participants ranked head as the preferred and nine preferred hands, while only 2 preferred the feet method. For 3D, hands were the most preferred method (N = 12), followed by head (N = 10) and feet (N = 2).

5.4.1 Realism. The general preference for hands could partly stem from the perceived realism as a majority of participants found the hands method to be the most realistic (N = 17), followed by feet (N = 4) and head (N = 3). Most participants said hands were the most realistic method since it felt intuitive and akin to using oars to steer a rowing boat. For feet, they mentioned that some real boats and kayaks are steered with the feet. The participant who ranked the head method as the most realistic said it was because it was the easiest, and they did not have to think too much.

5.4.2 VR Sickness. The hands method was rated the most comfortable method for motion sickness (N = 13), followed by feet (N = 6) and head (N = 5). A self-motion miss-match with the head-based steering method contributed to it: *"With hand-relative steering you keep looking straight ahead, whereas with head-relative you're for a short while moving in a different direction than the one you're facing toward"* [P12, M, 34 years old]. However, many participants commented that motion sickness was not an issue for any method.

5.4.3 Exertion. Most participants found the feet method to be the most exhausting (N = 10), followed by head (N = 8) and hands (N = 6). Comments indicate that head-based exertion stems more from faster rowing, while feet-based exertion stems more from mental load. For example: *"It was easier to go where I wanted [with head] so I could focus more on going faster"*[P3, M, 30 years old]. Comments on the hand method were mixed, with some pointing out it was easy and allowed for more physical exertion, and others pointed out the added mental demand similar to the feet method.

5.4.4 General Feedback. For the head method, three participants said flying in a straight line in 3D was more difficult than the other methods. For the Hands method, one participant suggested using a throttle instead of buttons for 3D locomotion. For the Feet method, one of the participants who preferred feet liked the separation of concerns: *"I think the fact that I could split tasks between my hands and feet made it feel more realistic. I did not have to think about rotating the handle or pressing a button because that task was handled by a different body part, making it easier to navigate. "*[P6, F, 34 years old]. Moreover, two participants commented that they expected the 3D mapping for feet to be the opposite, i.e., pressing toes goes up instead of down, and 6 participants said they sometimes missed or accidentally pressed the feet sensors. Lastly, five participants would like to see a combination of methods: hands and feet (N = 2) and hands for 2D with head for 3D (N = 3).

6 DISCUSSION AND FUTURE WORK

We found that head-based steering generally outperforms hands and feet for maneuvering a rowing machine in 2D and 3D environments. Moreover, steering with hands is comparable to steering with feet in 2D but more efficient than in 3D. The head method received the highest subjective ratings; however, hands were regarded as the most realistic method and were preferred by roughly the same number of participants as the head method. Motion sickness was generally low for all methods but slightly higher in 3D than in 2D. We discuss these results in detail in the following subsections.

6.1 Don't believe me, just watch

Our results suggest that the established head-based VR locomotion method [53] is well suited for maneuvering a virtual boat while rowing. Steering horizontally and vertically by rotating the head in the desired direction was deemed the easiest and most intuitive method. This is evident by faster completion time, better accuracy, more collected coins, and shorter travel distances. These results could be explained through a lower task load, as participants did not have to concentrate on hand or feet coordination. Participants might implicitly look at the desired target in a coin collection task, and steering can feel almost automatic, i.e., natural. The maneuverability advantage of head over the hand method has not been found in other contexts [12, 13, 18, 29, 42, 80]. However, these studies have compared with hand-pointed steering, which indicates a general maneuverability advantage of hand-pointing over hand-rotations for steering precision.

While maneuverability is one aspect, the purpose of an exergame is also to facilitate physical exercise. Even if longer distances were covered with the feet method, participants traveled at higher velocities with the head and hands methods. This suggests these methods are more suitable for facilitating endurance and cardiovascular fitness. However, the feet method was perceived as more fatiguing, which could partly be explained by increased mental demand. Moreover, traveling at a lower speed could be tiresome for the muscles, as they must work harder to overcome the pull resistance on each stroke [91]. These findings also apply to 2D over 3D space, as rowing in 2D allowed for higher velocity.

Although the head-based method is easy, intuitive, and enables fast travel, it can cause a "lock-in" experience [70], i.e., the user may feel restrained from looking around. Our data does not suggest this phenomenon was a problem since the turning force leading to steering was only applied when a user pulled the handlebar. Thus, users could freely look around between strokes without impacting travel direction. One of the first taxonomies of VR locomotion [12] named input conditions (when and how to start and stop a travel motion) as one of three considerations for any given locomotion technique. This aspect might have been overshadowed over time by focusing on velocity or direction selection methods. The ability to toggle head-based steering, i.e., the input condition, could be advantageous in other head-based steering scenarios, e.g., walk-in-place [29, 87], and should be explored in-depth in further studies.

6.2 Head for precision, hands for realism, and feet for fun?

Even if head-based steering had the best performance in both 2D and 3D, roughly the same number of participants preferred it to the hand-based method. This raises the point that choosing the rowing-based steering method depends on the purpose. While head-based steering might bring precision, hand-based steering brings realism. Tilting hands while rowing is akin to paddling with an oar, making the experience more realistic, *despite the reverse travel direction compared to real rowing*. Despite maneuverability deficits, the relative preference for hand-based methods also aligns with previous findings [29, 80], suggesting a general preference bias for hands in interaction. Using hands in 2D had similar scores as the head-based methods for enjoyment, frequency of use, and intuitiveness. However, hands in 3D with the added button-based input received lower scores, raising the question: *"How can we utilize hand-based steering in 3D?"*. As the yaw axis for handlebar rotation is unavailable, some form of input other than rotation is needed. Discrete button input might not provide as fine-grained control as continuous input [60]. On the other hand, the user's pulling speed adjusts the applied vertical force and thus provides another source of continuous input control. It could also be the positions of the buttons were not intuitive enough. Some form of a thumb throttle, used with one hand, might be a more suitable affordance for up and down direction and provide continuous controls.

The feet-based steering had the most prominent performance difference between 2D and 3D locomotion. In 2D, steering with feet is comparable to hand-based steering performance, and its subjective scores lie closer to the other methods than its 3D alternative. In other words, steering left and right works well, but up and down is too complicated. The first potential explanation for the complexity is that mapping toes for down and toe joints for up might be counter-intuitive. Like mappings for scrolling on handheld devices and aiming direction with joysticks, some users prefer the settings to be inverted, as the qualitative feedback shows. Secondly, the shape of people's feet varies, impacting the comfort of pressure distribution. Although we adjusted the sensor positions for each participant, individual differences in dexterity vary more for feet than hands [44], requiring further considerations in future work. Lastly, participants might accidentally rotate their feet slightly, causing them not to press the sensor fully. Future iterations can improve the feet-steering design by adding haptic feedback on the sensors and enlarging their size. However, some participants found the feet steering method to be the most realistic since it reminded them of steering kayaks with pedals, and another participant liked the separation of concerns afforded by feet steering (i.e., hands focus on velocity, feet focus on direction). Combining the advantages of the methods is another possibility to explore in future studies, for example, using the handlebar rotation for 2D and the feet or head input for 3D, thus separating concerns for 2D and 3D direction. Separation of modalities by dimension has, for example, been found to improve performance in 3D for head and mouse input [67]. On the other hand, head and hand separation for 3D lowered performance [60]. Future studies should investigate appropriate modalities combinations in 2D and 3D locomotion scenarios.

We observed no significant differences in the SSQ ratings in individual methods for VR sickness, but participants rated the hand-based steering as the most comfortable regarding VR sickness. Although controller-based VR games are typically rated high on SSQ ratings (M = 32.5, 95% CI 28.2 - 36.8) [73], rowing-based locomotion for all methods scored relatively low (M = 23, SD = 20 for 3D and M = 16, SD = 16 for 2D). In controller-based games, the user remains in one position. At the same time, the virtual environment updates the representation of user surroundings, and this mismatch has been shown to increase motion sickness [31, 73, 84]. These results suggest that *motion cues* provided by rowing could mitigate experienced VR sickness. However, a rowing machine does not provide motion cues for vertical locomotion, which likely caused participants to experience more VR sickness in 3D than in 2D. Additionally, sweating is a sub-component of the SSQ, which impacts scores through physical exertion. By comparing the ratio of non-sweat SSQ to SSQ, the SSQ scores are lowered by: head (25%), hands (30%), and feet (24%) for 2D, and head (21%), hands (20%), feet (20%) for 3D. In other words, accounting for sweating, the actual VR sickness was lower. Still, more so in 2D than in 3D. The low SSQ score demonstrates rowing machines' viability as VR locomotion controllers. However, future studies could look into how longer-duration usage impacts VR sickness and compare it with non-rowing alternatives.

6.3 Practical implications & Suggestions

The results of this study provide guidelines for researchers and practitioners interested in using rowing as a form of locomotion in VR. First, implementing exergames in which maneuverability at high speeds is important would benefit from using head-based steering. This is advantageous since it does not require external hardware except the speed tracker mounted on the fly-wheel. Second, feet-based steering has a steeper learning curve and can be suitable for slower exergames, emphasizing muscle endurance instead. Some users may even prefer a more difficult method for the challenge of mastery. Third, hand-based steering can facilitate a similar speed as the head while heightening perceived realism. While we used a virtual rowing boat metaphor, our travel direction was forward instead of backward to facilitate entertaining exergame applications. Future studies can explore steering methods to support rowing as a sport, including impact on rowing technique [3, 88], and other metaphors than boats. Tennet et al. [84], for example, introduced the concept of *"abstract machines"*, in which the physical sensation can be mapped to different visual inputs, generating entirely different experiences from physically existing machines. For example, a virtual horseback riding experience is one example in which the hand and feet method are combined to control the reins and stirrups of a horseback rider. One could also imagine a manual helicopter that the user propels upwards by rowing. 3D locomotion affords going below the ground, for example, by steering a virtual submarine. Game designers can create exergame experiences for the gym where users can race for high scores or explore vast virtual worlds. Multiplayer functionality could enhance the experience [40] as each player could visit their local gym and row together, for example, on the same virtual boat.

7 LIMITATIONS

Our study design involved a coin collection task suitable for evaluating speed and precision. This study does not cover other tasks, e.g., search or free-exploration scenarios. These tasks could be explored in future work. Our choice of metaphor was a "magic" boat that propels in the forward (opposite of typical real rowing boats) and vertical direction; the results reflect this context. The 3D environment used in the study did not feature obstacles, and we used simple graphics for minimal distractions. Higher visual fidelity (e.g., color grading, shadows) could aid depth and height perception and impact the perceived level of motion sickness. Participants spent around 30 minutes each in VR. A longer duration could impact proficiency with a steering method and motion sickness. The use of visual feedback, such as a Head-Up Display, to indicate steering power and direction was not included in this study. We did not measure participants' energy expenditure or the effects of exercising. Our sample of participants was between ages 21 and 44, and other age groups might yield different results. The participants also varied in familiarity with VR and rowing machines. We did not observe a pattern in the data suggesting that the level of familiarity impacted the results; however, larger samples for each familiarity category are needed to verify our observation. Many of these limitations can provide constraints for designing future studies.

8 CONCLUSION

In this paper, we investigated locomotion in VR through a rowing machine that can travel in both 2D and 3D virtual environments. We explored three steering rowing-based methods based on established interaction techniques using head-, hands- and feet-based interaction. We conducted a controlled lab experiment with a 2D and 3D coin collection task to assess user performance, experience, and VR sickness. We found that head steering leads to fast and precise steering in 2D and 3D and is the least mentally demanding. However, participants found hand-based steering to be the most realistic method and preferred it as much as the head method. Lastly, feet-based steering in 3D is tricky and can lead to poor performance, but it works well in 2D. All methods led to comparable and low levels of VR sickness.

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