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ViewShift:
Comparing Interactive and Adaptive Rotation Gains for Amplified Head Rotation in Seated VR

Arash Goodarzi

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Abstract

In seated virtual reality (VR), where large physical turns are limited, altering the mapping between physical and virtual movements can amplify head rotation, enabling efficient view control with reduced physical effort. This thesis introduces two amplified head rotation (AHR) techniques for seated VR: the user-empowered Interactive, which affords user-timed switching between high and low gain, and Adaptive, which adjusts gain automatically based on head-motion kinematics. We evaluated both techniques in a mixed-methods study ($n = 31$), compared with a Static constant-gain baseline across a head-pointing task and a 180° rotation task. Both Interactive and Adaptive improved head-pointing performance relative to Static, while increasing physical head movement; cybersickness remained low and virtual–physical heading offsets were generally modest. Qualitatively, participants valued Interactive for the agency and control it afforded. Notably, this control enabled an emergent behavior in which users intentionally reoriented the virtual view via asymmetric rotational gains—a user-initiated redirection strategy we term ViewShift. *Adaptive reduced cognitive load but could occasionally misalign with user intent. Together, the findings suggest potential for giving users control over rotational gains and highlight visible, user-centered AHR as an interaction technique for seated VR.*

Keywords: Virtual Reality, Head-Mounted Display, Seated VR, Amplified Head Rotation, Rotation Gains, Control–Display Gain, Adaptive Gain, Gain Switching, ViewShift, Virtual–Physical Heading Offset, Redirected Walking, Perceptual Manipulations, Cybersickness

1 Introduction

Virtual reality (VR) is used in diverse modes of interaction, including standing and walking. Yet a substantial portion of everyday use takes place while seated, such as on a couch or at a desk. In clinical and care settings, moreover, seated VR is common and, in some cases, it is the only feasible mode due to safety and mobility constraints (Lundström and Fernaeus, 2019; Lundström et al., 2021). Seated use is therefore not a niche case, but rather a primary and widely adopted mode of VR interaction.

In *seated VR*, users remain seated without room-scale locomotion. View control is primarily through head yaw and modest torso rotation, which limits the extent to which they can physically turn. These constraints make it difficult to explore a full 360° scene and maintain spatial awareness. To address such limitations, a range of techniques has been used that alter the mapping between physical movements and resulting virtual movements, enabling more efficient interaction when space or movement is limited. These mappings enable power-user capabilities, such as redirected walking (Razzaque et al., 2001) to explore large virtual spaces in small rooms, or amplified movements to cover more distance with less physical effort (Abtahi et al., 2019). This includes amplified head rotation (AHR) (Langbehn et al., 2019; Sargunam et al., 2017; Wang et al., 2022), which increases the rotational gain (i.e., the ratio of how much the virtual rotation is scaled relative to the physical rotation) so that a smaller physical turn results in a larger virtual rotation, enabling a 360° virtual head turn when physical head movement is limited.

Prior research has investigated the acceptability and perceptual detection thresholds of various gain ranges, along with static and dynamic techniques for adjusting rotational gain in AHR. Wang et al. (2022) examined detection thresholds for gain ranges in seated AHR, finding that values between 0.89 and 1.28 typically fall below the threshold of perceptibility, leaving the amplification unnoticed. They further reported that gains well above this perceptibility threshold—up to nearly 2.5—can still be acceptable to users.

Several studies have proposed dynamic rotational gain. Sargunam et al. (2017) employed a dynamic gain that gradually increased as users rotated to explore the virtual environment. Zhang et al. (2021) suggested a velocity-based technique that determines gain from head-rotation speed. Langbehn et al. (2019) introduced a dynamic rotation-gains technique that specifies gain based on target proximity to optimize for speed and precision. In such techniques, higher gain helps users reach the target quickly and then is reduced near the target to support precise pointing. While effective, this approach relies on target knowledge to decide when to switch between speed and precision. This, in turn, motivates alternative ways to determine the gain mode, such as through explicit user input or head-motion kinematics, even when the target is unknown.

To the best of our knowledge, no prior work has examined such alternatives: (1) user-empowered gain techniques for AHR, allowing users to adjust the rotation gain and control the amplification rate; and (2) an adaptive gain technique that switches gain modes based on head-motion kinematics (velocity and acceleration) without requiring target knowledge.

This work introduces two novel techniques. The first is the user-timed gain *Interactive* technique, which allows users to switch between high- and low-gain modes. It gives users direct control to activate a high-gain mode for rapid traversal of the VR environment and to switch to a low-gain mode when higher precision is needed. The second is the *Adaptive* technique, which automatically switches between high- and low-gain modes based on the user's head rotation velocity and acceleration. The rationale is that, as users approach a target, they naturally slow their head movements, signaling the need for lower gain to support precise pointing. We also identify *ViewShift*, a user-initiated redirected-viewing strategy in which users leverage the techniques' high/low gain switching to apply an asymmetric fast–slow sequence across an out-and-back head turn, thereby reorienting the virtual view toward a desired direction.

The aim of this study was to evaluate the performance and user experience of different AHR techniques in seated VR and to provide qualitative insights into head amplification more broadly. We conducted a mixed-methods study with 31 participants, comprising a quantitative within-subjects experiment comparing three head-rotation gain techniques—Static, Interactive, and Adaptive—and qualitative interviews analyzed through thematic analysis. Measures included objective metrics (completion time, errors, cumulative head movement, and virtual–physical heading offset), subjective ratings (workload, usability, and cybersickness), and interview accounts of users' experiences. This work makes three contributions: (1) two novel AHR techniques, with design rationale and implementation details, including the identification of *ViewShift*, an emergent, user-initiated view-reorientation strategy achieved via gain switching; (2) an empirical comparison with a constant-gain baseline; and (3) a qualitative account of users' experiences of AHR and of the novel techniques.

Research Questions

We evaluate Interactive and Adaptive against a constant-gain baseline through three research questions concerning performance and movement effort, user experience, and virtual–physical heading offsets. Regarding virtual–physical heading offsets, altering rotation gain can introduce a persistent mismatch between a user's physical yaw heading and the virtual view when asymmetric gains are applied to outward and return turns (e.g., under user-timed or kinematics-triggered switching). For example, a low-gain return may not fully cancel a high-gain outward turn, resulting in a net offset that can accumulate over repeated turns. RQ3 examines the magnitude and accumulation of this offset, as well as how participants perceive, manage, and recover from it.

The research questions are as follows:

RQ1 – Performance and movement effort. How do Interactive and Adaptive techniques affect task performance (completion time, errors) and cumulative head rotation, relative to a constant-gain baseline?

RQ2 – User experience. How are the techniques experienced in terms of control and agency, naturalness, acceptance, workload, comfort, and cybersickness?

RQ3 – Heading offset. How large are virtual–physical heading offsets, how do they evolve across tasks, and how are they perceived, managed, and recovered from by users?

2 Related Work

Virtual reality systems are constrained by the limits of the user's physical movements and available space, which can make it difficult to fully explore large or immersive environments. To overcome such limitations, researchers have developed a family of techniques that alter the mapping between physical and virtual motion. Such approaches are often referred to as *redirection techniques* in the context of locomotion (Razzaque et al., 2001; Suma et al., 2012), and have also been described more broadly as *perceptual manipulations* in virtual environments (Tseng et al., 2022), where the system exploits visual dominance to reshape user perception and interaction subtly.

These approaches have been explored across diverse domains of interaction. Redirected walking subtly bends the user's walking path to fit within a limited physical space while maintaining the illusion of straight virtual movement (Razzaque et al., 2001). Translational and speed gains enable users to traverse larger virtual distances with fewer physical steps, achieved through approaches that alter body scale or amplify movement along the walking path (Abtahi et al., 2019). In the haptic domain, haptic retargeting dynamically remaps a single physical prop to multiple virtual objects, enhancing interaction richness without additional hardware (Azmandian et al., 2016; Matthews et al., 2019). Such techniques illustrate how changing the mapping between physical and virtual motion can address practical constraints and extend interaction possibilities.

2.1 Amplified Head Rotation and Redirection for View Control

In seated VR, similar redirection approaches have been applied, where rotation gains scale physical head yaw to produce larger virtual rotations, enabling 360° viewing with reduced physical effort. Early work has explored constant rotation gains (a fixed mapping ratio of virtual to physical rotation) and reported effects on task performance, spatial orientation, and user comfort. Jay and Hubbold (2003) found that AHR with a gain of 2 improved performance in visual search tasks without increasing cybersickness. Notably, several participants described the AHR condition as feeling *normal*, whereas the 1:1 mapping was perceived as *slowed down*. Kopper et al. (2011) examined amplified head rotations across visual scanning and counting tasks under different fields of view. They found that amplification had no significant effect on scanning performance, but did affect counting accuracy, particularly at higher gains. Another study by Ragan et al. (2017) demonstrated the feasibility of using amplified head rotation to view 360° of virtual space, showing that amplification did not affect search performance. Still, higher gains (gain of 4) introduced noticeable cybersickness and negatively impacted spatial orientation.

Additionally, rotation gains can be applied below perceptual thresholds, making them unnoticeable to users. While such imperceptible mappings are often perceived as more natural, they restrict the range of applicable gains and thereby limit the extent to which the physical–virtual mapping can be altered. For example, early redirected walking techniques deliberately stayed within detection thresholds to prevent users from noticing the manipulation (Razzaque et al., 2001). Later work, however, shifted beyond imperceptibility by framing redirected walking as an interaction technique, applying detectable overt gains that were still perceived as acceptable and usable (Rietzler et al., 2018). Similarly, Wang et al. (2022) investigated perceptibility in seated AHR, reporting that gains between 0.89 and 1.28 typically fall below detection thresholds, whereas considerably higher values—up to nearly 2.5—can still be acceptable to users.

Beyond constant amplification, researchers have proposed a range of techniques that adjust rotation gains dynamically, combine amplification with guided redirection, or reorient the scene itself to extend viewing range under seated constraints. Langbehn et al. (2019) introduced a dynamic gain mapping designed to enable a 180° virtual rotation from 90° of physical head turn. The gain increases until half of the target rotation (90° virtual for a 180° target) and then decreases toward the target, enabling rapid movement initially while preserving precision near the end. This technique thus requires knowledge of the target position to determine the gain. In their study, dynamic gains yielded lower cybersickness than static gains and a scrolling technique, and higher usability than both, while performing comparably to the baseline condition. Sargunam et al. (2017) employed a dynamic gain that gradually increased with the user's physical head yaw, implemented as $g(h) = 2 - \cos(h)$, reaching a gain of 2 at 90°. In addition to this amplified condition, they introduced a guided variant that, during virtual travel, rotated the virtual scene to encourage the user's head to return toward a neutral forward orientation (a redirection achieved by counter-rotating the virtual world toward the physical forward axis) so that the same virtual view could be maintained from a more comfortable forward-facing posture. Although participants were able to complete the tasks, the guided rotation induced greater sickness and, for some, was perceived as acting against their will. Zhang et al. (2021) proposed a velocity-based technique that determines the gain from head-rotation speed. Their mapping decreased amplification with increasing velocity, from about 2.95 at low speeds down to 2.22 at high speeds, keeping it within a defined comfort zone. Using this mapping, participants could explore a full 360° scene with only 61°–81° of physical yaw. They report that the technique outperformed constant mappings in search and counting tasks, achieving better performance with less discomfort.

Other works proposed alternatives to gain-based AHR by reorienting the virtual scene when users reached angular thresholds. Norouzi et al. (2019) proposed continuous counter-rotation (shifting the scene opposite to head or eye movements) and discrete reorientation steps once thresholds were exceeded, enabling users to explore a full 360° scene. For seated virtual workspaces, Mcgill et al. (2020) proposed rotating curved multi-display “screens” around the user to improve access to peripheral content. Their techniques included a constant counter-rotational gain of 2, *deadzones* that suppressed counter-rotation within $\pm 12.5°$ around display centers to maintain stability, and sliding transitions at display edges. They further introduced an event-driven *boundary switching* method, where crossing a ± 5% display margin triggered a discrete $\pm 30°$ shift, keeping about 90% of each display stable while still enabling wide reachability.

2.2 Control–Display Gain for Head-Pointing and Selection

We draw on models of aimed movement and prior work on control–display (CD) gain to develop our techniques. Meyer’s optimized initial impulse model, proposed by Meyer et al. (1988), explains human aiming movements as a sequence of submovements: an initial primary submovement intended to bring the effector close to the target, followed, when necessary, by a corrective secondary submovement to refine accuracy. Previous research on pointing and selection tasks has widely adopted a similar approach to the Meyer model, considering selection to consist of two primary phases: an initial rapid, coarse (ballistic) movement toward the target, followed by corrective movements for fine adjustments (Casiez et al., 2008; Deng et al., 2024; Kytö et al., 2018; Wang et al., 2024). In these models, a higher gain is applied during the ballistic phase to facilitate rapid movement, and a lower gain is used for the corrective phase. Gains are typically applied to a 2D/3D cursor or an object to enhance selection and pointing.

Prior work explored various gain mode switching methods. It can be triggered manually (e.g., button presses or gestures) (Kytö et al., 2018; Voelker et al., 2020), or automatically based on target proximity (target assistance) (Deng et al., 2024; Langbehn et al., 2019). Deng et al. (2024) adapted a dual mode gain that switches from ballistic-gain to corrective-gain at the moment the cursor first touches the target boundary. This marks the end of the ballistic phase. They found that increasing the control–display gain reduced movement time during the initial ballistic phase but reduced accuracy in the corrective phase. Moreover, the dual-gain mode outperformed the mono-gain mode by applying a lower gain during the corrective phase.

Automatic gain switching can also be achieved without target knowledge. Wang et al. (2024) introduced HeadShift, which infers movement phases directly from head kinematics (velocity and acceleration) and switches between high- and low-gain modes accordingly: it enters a high-gain (fast) mode when acceleration exceeds a threshold and remains there while speed is high; when both speed and acceleration fall below their thresholds, it returns to the low-gain mode.

3 Method

3.1 Design of Techniques

The aim of designing the techniques is to enable users to rotate their virtual view fully (180°) when physical rotation is limited. The primary objectives are to maximize navigation speed and precision, minimize orientation offsets and negative effects on spatial orientation. Techniques must also avoid increasing cybersickness, which can result from excessive gain or unnatural mappings. These criteria define the core requirements for the techniques.

Design of Interactive Technique

The Interactive technique was designed to allow users direct control over the rotation gain during virtual head movement. Two design variants were pilot-tested:

Low-to-High Switching. The first variant used a default 1:1 mapping ($g_{\text{low}} = 1.0$), with an input (e.g., button press) temporarily enabling a higher gain ($g_{\text{high}} = 2.5$) for faster rotation. Pilot testing indicated that returning to a slower rotation after releasing the button felt unintuitive, resulting in reduced usability.

High-to-Low Switching. The second variant, which was adopted for the study, enabled a high gain ($g_{\text{high}} = 2.5$) by default, with an input switching to a lower gain ($g_{\text{low}} = 1.0$) for tasks requiring greater precision. This configuration allows for fast virtual rotation with less physical effort and provides precise control when needed. With this design, users can efficiently achieve a full $180°$ rotation and switch to a lower gain for improved accuracy during tasks such as pointing and selection.

Variant Used in the Study The implemented variant used the trigger button on the VR controller for gain switching. The default gain was $g_{\text{high}} = 2.5$. Pressing the trigger switched the gain to $g_{\text{low}} = 1.0$. Analog or pressure-sensitive input for varying gain was not used; the gain change was binary, with no gradual or curve-based transition between gain levels.

The gain at any time t, $g(t)$, can be defined as a piecewise constant function based on the input state $s(t)$:

$$g(t) = \begin{cases} g_{\text{high}} = 2.5, & \text{if } s(t) = 0 \\ g_{\text{low}} = 1.0, & \text{if } s(t) = 1 \end{cases} \tag{1}$$

where $s(t) = 0$ indicates the trigger is not pressed, and $s(t) = 1$ indicates the trigger is pressed.

Design of Adaptive Technique

The objective in designing the Adaptive technique is to automatically identify when a user requires rapid movement versus precise movement, without the need for manual switching. The technique dynamically adjusts the gain based on kinematic features of the head movement, applying a higher gain during fast movements to support rapid rotation and a lower gain during precise movements to have higher precision.

Adaptive (Threshold-Based). In designing the Adaptive technique, we adopt an approach similar to HeadShift (Wang et al., 2024), automatically determining high- and low-gain modes based on the velocity and acceleration of head rotation. This kinematic-based detection enables the technique to apply higher gain during rapid head movements for fast rotation and lower gain during slower, more precise rotation to have precision, without requiring manual intervention or target assistance. The motivation for using velocity and acceleration to determine gain modes is that head-movement dynamics can reflect user intent. As users approach a target, they tend to slow down, signaling the need for lower gain to support precise pointing. Conversely, more rapid head rotations typically indicate coarse, ballistic movement, where higher gain is desirable to cover distance efficiently.

High-gain mode is activated when either the angular velocity $v(t)$ or the angular acceleration

$a(t)$ exceeds a threshold. Let v_{thresh} and a_{thresh} denote these velocity and acceleration thresholds, respectively. The gain function is defined as:

$$g(t) = \begin{cases} g_{\text{high}} = 2.5, & \text{if } v(t) \geq v_{\text{thresh}} \text{ or } |a(t)| \geq a_{\text{thresh}} \\ 1.0, & \text{otherwise} \end{cases} \tag{2}$$

Here, g_{high} is applied when the velocity or acceleration threshold is exceeded; in all other cases, the gain function defaults to the low-gain state.

Adaptive (Threshold + Smooth Transfer). We can have a transfer function for gain modulation, which provides a smooth transfer between low- and high-gain modes. Different linear and non-linear functions have been used to achieve such transitions in dynamic gain techniques, including linear and parabolic (non-linear) mappings (Langbehn et al., 2019), as well as cosine-based mappings (Sargunam et al., 2017). For the Adaptive technique, we used a sigmoid function similar to (Nancel et al., 2013; Voelker et al., 2020; Wang et al., 2024) to provide a smooth, non-linear transition between high- and low-gain states:

$$g_{\text{sigmoid}}(x) = \frac{G_{\text{max}} - G_{\text{min}}}{1 + \exp\left(k \cdot (x_{\text{inf}} - x)\right)} + G_{\text{min}} \tag{3}$$

where G_{min} and G_{max} are the minimum and maximum gain values, x_{inf} is the inflection point, and k controls the slope of the transition. The input x can be selected from various kinematic or temporal features of head movement, such as angular velocity (Zhang et al., 2021), angular acceleration, angular distance (Langbehn et al., 2019), or elapsed time since the start of a submovement. As adapted in the HeadShift technique (Wang et al., 2024), a dual-mode approach can be also used, with velocity as input in the low mode and acceleration in the high mode. The choice of input and mode depends on the desired behavior and should be determined empirically. In our study, we used angular velocity as the input for both modes, resulting in a gain function that adapts to how fast the user rotates their head.

With this transfer function, the gain is defined as:

$$g(t) = \begin{cases} g_{\text{sigmoid}}(v(t)), & \text{if } v(t) \geq v_{\text{thresh}} \text{ or } |a(t)| \geq a_{\text{thresh}} \\ 1.0, & \text{otherwise} \end{cases} \tag{4}$$

Here, $g_{\text{sigmoid}}(v(t))$ enables a smooth transfer to the high-gain mode; in all other cases, the gain function defaults to the low-gain state.

Adaptive (Continuous). The goal of the Adaptive technique is to determine whether rapid or precise movement is required from the head's kinematic features. Slower movements signal the need for lower gain to preserve precision, whereas faster rotations indicate ballistic movement and therefore benefit from a higher gain. Based on this rationale, the Adaptive technique can also be implemented without thresholds (as in the first variant) by using a smooth transfer function, such as a sigmoid, that maps velocity directly to gain:

$$g(v) = G_{\text{min}} + (G_{\text{max}} - G_{\text{min}}) \cdot S(v), \quad S(v) = \frac{1}{1 + \exp\big(k(x_{\text{inf}} - v)\big)} \tag{5}$$

Here, x_{inf} is the half-gain (inflection) point and k controls the steepness of the transition. As users slow down to point at a target, velocity v decreases and the gain remains close to G_{min} for precision; when they rotate faster, v increases and the gain rises smoothly toward G_{max}. The trade-off is that, unlike the Adaptive Threshold-Based variant, there is no stable G_{min} plateau: small changes in v lead to small variations in gain even at low speeds. Alternatively, a Hill function may be used instead of the sigmoid.

Variant Used in the Study. For the experiment, we employed the Adaptive Threshold + Smooth Transfer variant, as it provided a reasonable balance between smoothness and stability during preliminary pilot testing. In the implemented variant, fast mode was triggered when the filtered angular velocity exceeded 0.5 rad/s (v_{thresh}) or the absolute filtered angular acceleration exceeded 1 rad/s^2 (a_{thresh}). The sigmoid gain function in fast mode was set with $g_{\text{low}} = 1.0$, $g_{\text{high}} = 2.8$, inflection point $x_{\text{inf}} = 0.5$, and slope $k = 2$. These parameters were selected to ensure that the technique was not too fast, risking overshoot and loss of precision, nor too slow, which would require excessive physical head movement and increase user effort. While increasing the maximum gain or expanding the range of the dynamic function could further reduce required head movement, this would likely result in overshoot, and increase the risk of larger orientation offsets.

To identify optimal parameters for the Adaptive technique, a systematic and iterative tuning process using controlled pointing tasks (e.g., Fitts' Law) would be required. In this work, the parameters were determined through researcher testing and a small pilot study, and should therefore be considered preliminary rather than fully optimized. In addition, a more comprehensive comparative study of all three Adaptive variants would be valuable to better understand their respective trade-offs and suitability for different contexts.

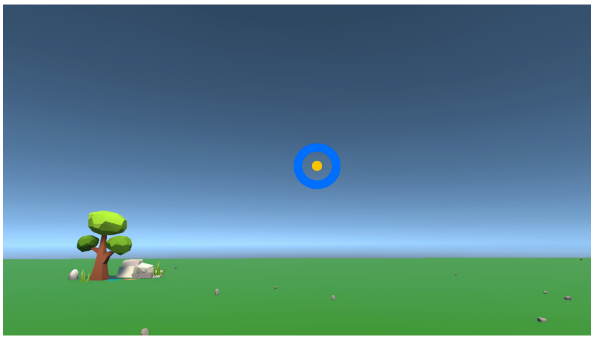
3.2 Evaluation Study

Study Design

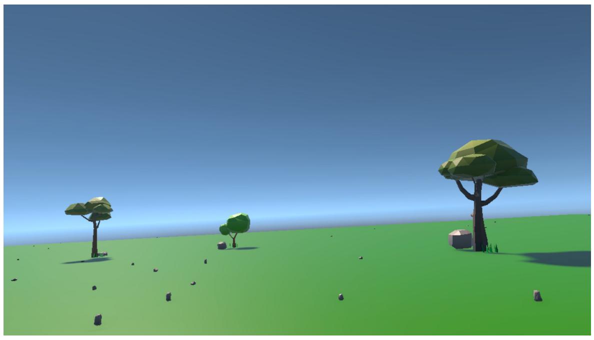
We employed a mixed-methods, within-subjects design to compare three head-rotation gain techniques for seated VR: Static (2.5 gain), Interactive (user-timed switching between high and low gain), and Adaptive (automatic switching based on head-motion kinematics). Each participant completed two tasks (Head-Pointing Task, 180° Rotation Task) under all techniques. Technique order in the main phase was randomized per participant to mitigate learning and fatigue effects. Because Interactive requires users to learn a mode-switching strategy, the training block was conducted with this technique, allowing participants to learn both the tasks and the technique before the main trials.

The primary objective measures were task completion time, error rate, cumulative physical head rotation, and virtual–physical heading offset, sampled at mid- and end-of-task. Heading offset was the absolute angular difference in degrees (°) between a participant's baseline yaw at trial start (recorded by selecting a front-facing target) and their yaw when re-aligning to the same target at mid- and end-task checkpoints.

Subjective measures included NASA-TLX workload ratings, a short usability questionnaire (control, comfort, ease of use, precision, applicability, and naturalness), and the paper-and-pencil version of the CSQ-VR questionnaire for cybersickness (Kourtesis et al., 2023), measured at baseline and before and after each technique block. Qualitative data were



(a) Front view with ground plane, reference tree, and the *front home target*.



(b) Rear view with three reference trees.

Figure 1: Seated VR environment: uniform dark-green ground plane, static low-poly trees, and scattered stones as spatial references.

gathered through short post-block interviews and a final semi-structured interview probing experiences of control, orientation, comfort, and preferences. We analyzed interview data using thematic analysis and integrated the resulting themes with the quantitative findings to enable comparison and triangulation.

Task Design

To evaluate the performance and user experience of AHR techniques in seated VR, we implemented two tasks for both broad rotational exploration and precise head-pointing. Each technique block began with the 180° Rotation Task, followed by the Head-Pointing Task.

Environment. Participants were seated at the center of a large, uniform ground plane rendered in a dark-green tone to simulate natural ground cover. To enrich the scene and provide stable visual references, static low-poly trees (simplified 3D models with a low polygon count) were placed at approximate angular offsets relative to the participant's front: one tree at $-30°$ in front and three trees behind at $-125°$, $-170°$, and $+160°$. In addition, small low-poly stones were scattered across the plane to increase realism without obstructing the tasks (Fig. 1).

Common visual aids and UI. *Cursor*. A red, head-anchored cursor provided continuous aiming feedback; selections were confirmed with the `A` button (Fig. 2). *Guidance arrow*. A floating arrow appeared above the cursor to cue the horizontal direction of the next target (left or right; Fig. 2). *Front realignment*. Whenever a black screen appeared, participants were instructed: *"Please face forward in a comfortable position."* and *"Press any button to start."* On button press, the current physical head orientation was recorded as the neutral "front," re-zeroing the heading offset before the next phase (Fig. 3). *Front home target*. At the beginning of each trial, a bullseye-style target spawned at the current neutral front (large blue outer ring with a filled yellow center; see Fig. 1a). Upon selection, the system recorded the *trial baseline heading* and started the trial. Returning to and selecting the same front target at predefined steps logged mid- and end-of-trial heading offset samples relative to that baseline, providing a consistent anchor for offset measurement across tasks. *Targets*. Task-specific targets comprised *rear large targets* for the 180° Rotation Task and *small pointing targets* for the Head-Pointing Task (see Fig. 4); these are described in detail with each task. *Feedback.* Hovering over a target triggered visual and audio cues, while confirmed selections removed the target from the scene with a confirmation sound.

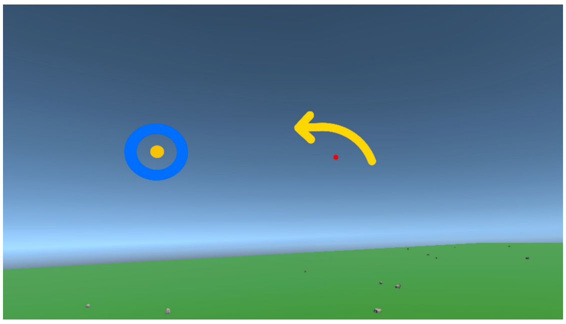


Figure 2: Interaction aid: cursor with guidance arrow, shown toward the front home target.

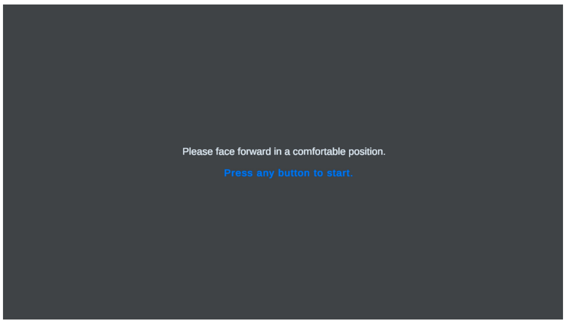


Figure 3: Front realignment screen: shown between phases to re-zero heading.

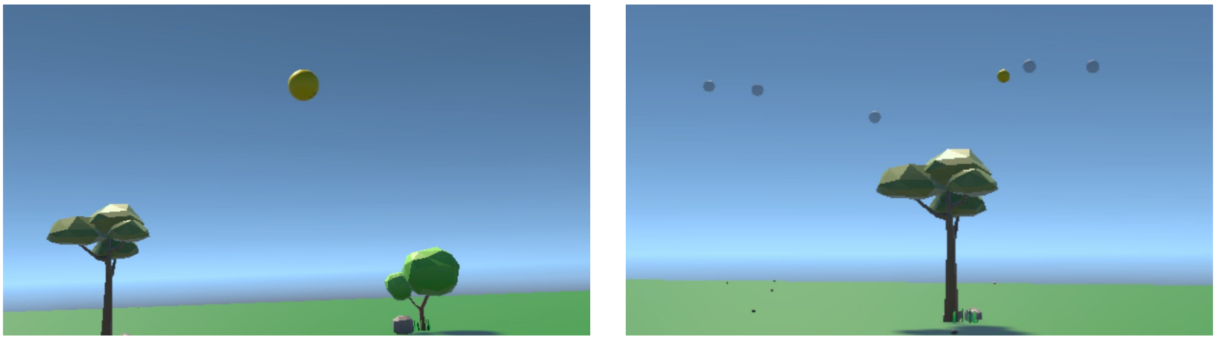
180° Rotation Task. This task involves continuous, large-angle turns. Each trial used a *front home target* (also used for offset sampling) and two *rear large targets*:

- *front home target.* Spawned at the current neutral front; selection logged a baseline heading sample.
- *Rear large targets.* Two targets spawned almost directly behind the participant at angles of $+179°$ and $-179°$ (i.e., 1° to the right/left of the rear pole), at a horizontal distance of 7 m and positioned +2 m above head height. Each *target sphere* had a diameter of 0.35 m (see Fig. 4a).

Sequence. At the start of the 180° Rotation Task, participants were first shown a front-realignment screen ("Please face forward ..."). After confirming, the front home target appeared and served as the baseline offset sample. The task then proceeded as follows: (1) Select the front home target. (2) Follow the arrow and rotate to acquire the back-right *rear large target* ($+179°$); select. (3) The arrow guided participants *back to front*; select the front home target again (mid-task offset sample). (4) Follow the arrow to the back-left *rear large target* ($-179°$); select. (5) The arrow returned participants to the front home target; select (end-of-task offset sample). The front realignment screen was then shown to reset the heading offset before continuing to the Head-Pointing Task.

Head-Pointing Task. This task was designed to assess precise head-pointing toward targets at varying horizontal angles. Each trial began with a *front home target*, which participants selected to establish a fresh baseline. Participants then selected a predefined sequence of *small pointing targets* positioned around the user (see Fig. 4b; Fig. 5). Initial positions were generated randomly within defined angular ranges using a Unity script and subsequently adjusted to ensure that target placement and activation order covered short-, medium-, and large-angle head turns.

Pointing target configuration:



(a) Rear large target (180° Rotation Task).

(b) Pointing target group with one *active* target (Head-Pointing Task).

Figure 4: Target types used across tasks: (a) rear large target; (b) pointing target group with one active target.

- **Pointing targets.** Each *target sphere* had a diameter of 0.095 m, positioned at heights $y \approx 2.2–2.5$ m and distances of $\approx 6–6.8$ m from the user. Targets were arranged in horizontal groups around the user.
- **Groups and counts (predefined).** Five groups with six targets each: front, right, left, right-rear, and left-rear. Mean distances were $\sim 6.06–6.83$ m and mean heights $\sim 2.22–2.48$ m. As an overview, Fig. 5 visualizes the distribution of small pointing targets around the participant.

Sequence and offset sampling. (1) Select the front home target (baseline). (2) The front group is spawned, and the guidance arrow directs participants to each *active target* (turns yellow when active) in a fixed order. (3) After completing the front set, the right and right-rear sets are spawned respectively and traversed in the same way. (4) Participants then return to the front home target to sample the mid-task offset. (5) The left and left-rear sets are spawned respectively and traversed in the same way. (6) Finally, they return to the front home target to sample the end-of-task offset.

Procedure

Participants were welcomed, received a brief introduction to the study, completed informed consent, and filled in a demographic form. To obtain a pre-exposure cybersickness baseline, they completed the CSQ-VR before donning the headset. Participants were then seated on a fixed chair, after which the experimenter demonstrated the controller mappings (`A` to confirm; `Trigger` used only in Interactive), and helped participants adjust the headset for comfort.

The front realignment screen (*"Please face forward..."*) was introduced (Fig. 3). Participants first experienced a 1:1 mapping and were instructed to rotate left/right, attempting to look "behind" them. The Static 2.5 mapping was then enabled to experience amplification; if needed, the experimenter toggled between 1:1 and 2.5 so the contrast was clear.

Because Interactive requires a mode-switching strategy, a dedicated training block preceded the main trials. Instructions emphasized "hold `Trigger` to deamplify for precise aiming; release to traverse." Participants practiced both the 180° Rotation Task and the Head-Pointing Task, including acquiring the front home target. A short, participant-paced rest followed. Before

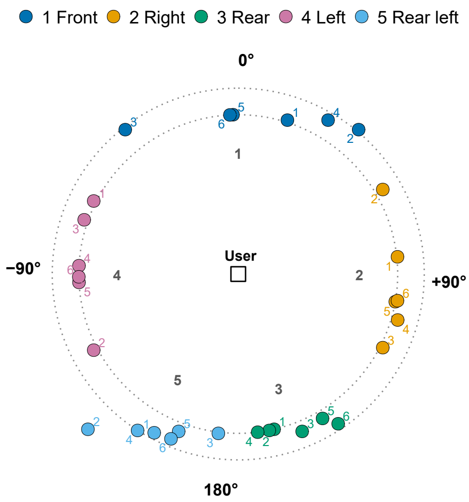


Figure 5: Schematic distribution of the small pointing targets in the Head-Pointing Task. Targets are grouped into five horizontal sectors relative to the participant's front (0°). Radii indicate approximate distances (~ 6.0–$6.8\,\mathrm{m}$)

starting the main trials, participants were instructed to (i) avoid random button presses (errors were counted), (ii) be reasonably quick without rushing (task time was recorded), (iii) prefer head rotations over torso rotation (small shoulder turns allowed if needed), and (iv) maintain a natural head speed.

Participants then completed three technique blocks in randomized order. Each block followed the same flow:

a) **Pre-block CSQ-VR.** Participants completed CSQ-VR immediately before the block.

b) **Reminder of controls.** Static: fixed gain, no trigger. Adaptive: automatic de/amplification; keep a natural head speed. Interactive: hold `Trigger` to deamplify for precise aiming; release to traverse.

c) **Tasks.** The 180° Rotation Task was run first, followed by the Head-Pointing Task as detailed under each task section.

d) **Post-block instruments and interview.** Immediately after each technique block, participants completed CSQ-VR, NASA-TLX, and the usability questionnaire, followed by a short, technique-specific mini-interview.

e) **Rest.** A participant-paced rest break was offered before the next block.

After the third block, a semi-structured interview elicited cross-technique comparisons and overall preferences, followed by a debriefing session.

Participants

We recruited 31 participants (9 female, 21 male, 1 non-binary) through a study poster, email, and word of mouth at the local university. Participants' age ranged from 22 to 43 years ($M = 29.19$, $SD = 5.98$). Prior VR experience, rated on a 4-point scale (1 = none, 4 = extensive), was distributed as 8 none, 17 limited, 5 moderate, and 1 extensive ($M = 1.97$, $SD = 0.75$). For additional context, self-reported gaming experience (1 = none, 4 = extensive) was 9 none, 10 casual, 5 moderate, and 7 extensive ($M = 2.32$, $SD = 1.14$).

Ethical Considerations

Informed consent was obtained from all participants. They received detailed information about the study's purpose, procedures, and potential risks and benefits, and were encouraged to raise concerns at any point. Participants were explicitly informed that they could withdraw from the study at any time without penalty. All data were treated confidentially, and anonymity was maintained throughout.

Apparatus

Participants wore a Meta Quest 3 HMD and completed the study *standalone* on-device. The experiment ran at a target refresh rate of 90 Hz with default runtime settings. Participants used the Meta Quest Touch Plus controllers; interaction details appear in Section 3.1. The experiment software was implemented in Unity 2022.3.13f1 (LTS), using the XR Interaction Toolkit 2.5.4 with the OpenXR plugin. We built a production Android (arm64) APK and sideloaded it to the headset. Participants were seated on a fixed chair within a stationary boundary.

3.3 Data Analysis Methods

We adopted a mixed-methods approach to pair the breadth and comparability of quantitative measures with the depth and nuance of qualitative accounts. Mixed methods can offset the limitations of any single strand—quantitative data may generalize patterns but miss lived experience, while qualitative data provide rich insight at the expense of generality—so combining them yields a more complete understanding than either alone (Creswell and Plano Clark, 2017).

Quantitative Analysis

We used a within-subjects design with *Technique* (Static, Interactive, Adaptive). Training trials were excluded. Trials lost to tracking were removed, and no participants were excluded. Objective outcomes (time, error, head movement) were analyzed after assessing normality with Shapiro–Wilk tests and Q–Q plots. As at least one condition deviated from normality for each measure, we used the *Friedman test*, with significant effects followed by pairwise *Wilcoxon signed-rank* tests. For Friedman tests, we report χ^2 and p. For Wilcoxon post hoc comparisons, we report z, p, and raw contrasts Δ in native units. All post hoc p-values were adjusted using the Holm–Bonferroni method. Subjective outcomes (NASA-TLX, usability items) were treated as ordinal and analyzed with the same non-parametric procedures. Offset was analyzed in a $2{\times}2$ within-subjects design with *Technique* (Adaptive, Interactive) and *Phase* (mid-task, end-of-task). Because distributions departed from normality, we applied an *aligned rank transform* ANOVA (ART) for main and interaction effects, with Wilcoxon tests (Holm-adjusted) for planned comparisons. Error rate was lightly winsorized to mitigate spurious button presses, while other measures (including offset and head movement) were left untrimmed to capture their full range. Figures display within-subject 95% confidence intervals.

Qualitative Analysis

We conducted short post-session interviews after each technique block and a final semi-structured interview to capture participants' experiences, strategies, and perceptions. Interviews were audio-recorded, transcribed locally on the researcher's machine using the Whisper speech-to-text model, de-identified, and accuracy-checked against the audio. Transcripts were then imported into QualCoder (open-source qualitative analysis software) for coding and memoing.

We followed Braun and Clarke's six-phase thematic analysis (Braun and Clarke, 2006) with an inductive, semantic focus. The process began with familiarization through full-text reading accompanied by brief analytic notes. Initial codes were then generated in QualCoder without a priori categories and subsequently collated into candidate themes. These themes were reviewed for internal coherence and mutual distinctiveness, with boundaries refined where needed. Finally, themes were defined and named with inclusion and exclusion notes, and the thematic account was produced with representative excerpts and, where appropriate, links to patterns observed in the quantitative results.

4 Results

4.1 Quantitative Results

Task Completion Time

Task completion time is defined as the time taken to complete the tasks (Figure 6). It was measured from the confirmation of the first target selection to the confirmation of the end target selection by the participant. The time taken for offset resetting and participant head realignment was excluded from this measure. Results are reported separately for the head-pointing task, the 180° rotation task, and the overall, which is calculated as the total time required to complete both tasks.

Overall The Friedman test revealed a statistically significant difference in overall task completion time across the three techniques ($\chi^2(2) = 26.39$, $p < .001$). Post hoc tests showed that Adaptive was significantly faster than Static ($Z = -4.57$, $p < .001$, $\Delta = -15.63$ s) and Interactive was also faster than Static ($Z = -3.78$, $p < .001$, $\Delta = -11.17$ s). There was no significant difference between Adaptive and Interactive ($Z = -1.78$, $p = .075$, $\Delta = -4.45$ s).

Head-Pointing Task A separate Friedman test on the head-pointing task also reached significance ($\chi^2(2) = 28.90$, $p < .001$). Post hoc tests showed that Adaptive was faster than Static ($Z = -4.64$, $p < .001$, $\Delta = -14.64$ s) and Interactive was faster than Static ($Z = -3.84$, $p < .001$, $\Delta = -10.84$ s), with no difference between Adaptive and Interactive ($Z = -1.74$, $p = .081$, $\Delta = -3.80$ s).

180° Rotation Task No significant differences were found for the rotation task ($\chi^2(2) = 4.71$, $p = .095$), and therefore pairwise contrasts were not followed.

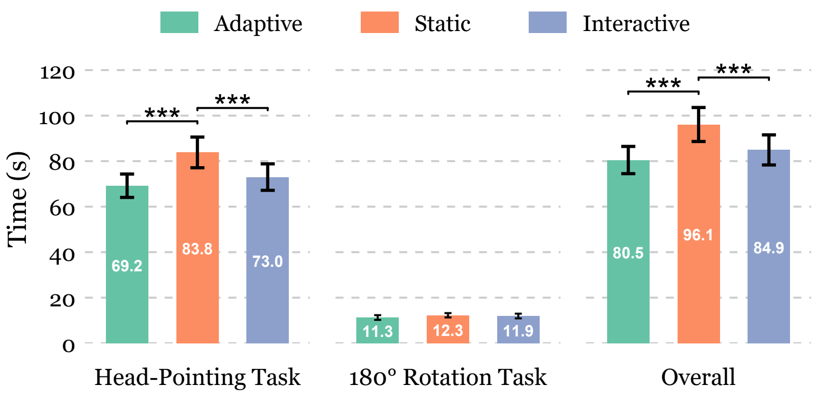


Figure 6: Task completion times across different head rotation gain techniques. Error bars represent the mean 95% confidence intervals. Statistical significance shown as asterisks (*$p < .05$, **$p < .01$, ***$p < .001$).

Error Rate

Error rate is defined as the instances where the cursor was positioned outside the target as the participant presses the A button to confirm the selection (Figure 7).

The Friedman test revealed a statistically significant difference in error rates across the three techniques ($\chi^2(2) = 22.12$, $p < .001$). Subsequent post hoc analyses were performed using Wilcoxon signed-rank tests with Holm's correction for multiple comparisons. The analysis showed that Adaptive had a significantly lower error rate compared to Static ($Z = -3.84$, $p < .001$, $\Delta = -6.05$). Similarly, Interactive had a significantly lower error rate compared to Static ($Z = -3.37$, $p = .002$, $\Delta = -5.48$). There was no statistically significant difference in error rates between Adaptive and Interactive ($p = .680$).

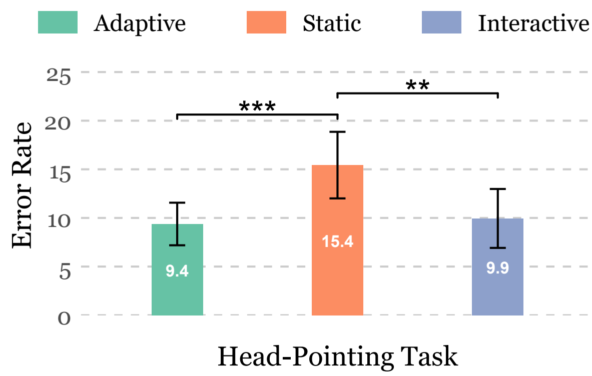


Figure 7: Error rates across different head rotation gain techniques. Error bars represent the mean 95% confidence intervals. Statistical significance shown as asterisks (*$p < .05$, **$p < .01$, ***$p < .001$).

Cumulative Head Movement

Cumulative head movement was defined as the total accumulated physical head angular difference from the start to the end of the task (Figure 8). Results are reported separately for the head-pointing task, the 180° rotation task, and the overall, which is calculated as the total cumulative head movement across both tasks. The Shapiro–Wilk test indicated that the assumption of normality was violated for the Adaptive–Interactive and Interactive–Static comparisons of cumulative head movement. Therefore, a Friedman test was conducted to compare cumulative head movement among the techniques.

Overall The Friedman test revealed a statistically significant difference in overall cumulative head movement across the three techniques ($\chi^2(2) = 40.52$, $p < .001$). Post hoc tests showed that Adaptive resulted in significantly more cumulative head movement than Static ($Z = 4.86$, $p < .001$, $\Delta = 258.13°$), and Interactive also resulted in significantly more head movement than Static ($Z = 3.72$, $p < .001$, $\Delta = 180.29°$). There was no significant difference between Adaptive and Interactive ($Z = 1.86$, $p = .063$, $\Delta = 77.84°$).

Head-Pointing Task A separate Friedman test on the head-pointing task also reached significance ($\chi^2(2) = 35.68$, $p < .001$). Post hoc tests showed that Adaptive resulted in significantly more cumulative head movement than Static ($Z = 4.80$, $p < .001$, $\Delta = 207.47°$) and Interactive ($Z = 2.14$, $p = .033$, $\Delta = 60.75°$), and Interactive also resulted in more head movement than Static ($Z = 3.70$, $p < .001$, $\Delta = 146.72°$).

180° Rotation Task For the 180° rotation task, the Friedman test also indicated a significant difference across techniques ($\chi^2(2) = 26.00$, $p < .001$). Post hoc tests showed that Adaptive resulted in significantly more cumulative head movement than Static ($Z = 4.35$, $p < .001$, $\Delta = 50.65°$) and Interactive ($Z = 2.72$, $p = .013$, $\Delta = 17.08°$), and Interactive also resulted in more head movement than Static ($Z = 2.61$, $p = .013$, $\Delta = 33.57°$).

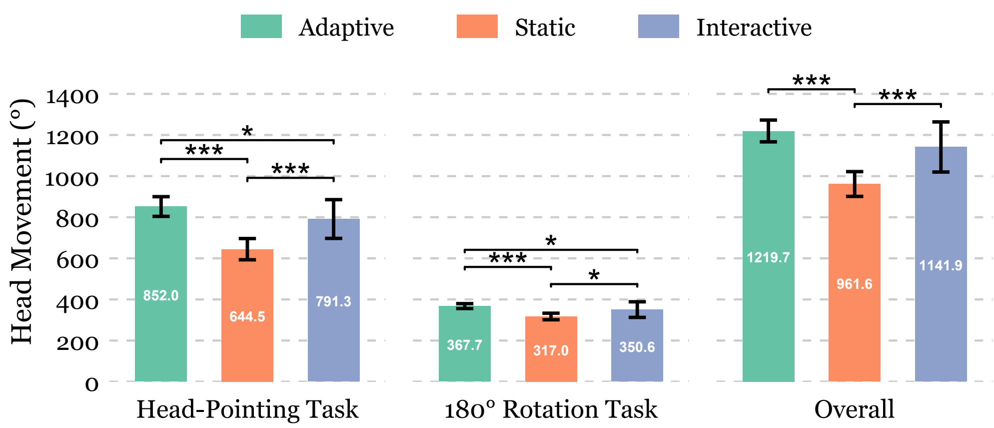


Figure 8: Cumulative head movement across different head rotation gain techniques. Error bars represent the mean 95% confidence intervals. Statistical significance shown as asterisks (*$p < .05$, **$p < .01$, ***$p < .001$).

Offset

Heading offset is defined as the absolute angular difference (in degrees) between (a) the participant's physical yaw heading, at baseline (recorded when the *front home target* is selected at trial start) and (b) their physical yaw heading when that same target is re-selected at a predefined checkpoint (mid-task or end-of-task). This metric quantifies any lasting virtual–physical heading misalignment accrued when asymmetric gains are applied across outward and return head-rotation segments.

Across techniques and tasks, average end-of-task offsets ranged from approximately 8° to 13° (see Appendix 1.1, Table 1; Figure 9). In the 180° rotation task, offsets averaged 13.2° at mid-task with Adaptive and 5.9° with Interactive, while at end-of-task values were 10.7° and 8.3°, respectively. In the head-pointing task, both techniques produced offsets of around 12°–13° at the end-of-task. Outlier cases were observed, with individual participants accumulating up to 64.8° (mid-task) under Adaptive and 54.8° (end-of-task) under Interactive.

Head-Pointing Task For the head-pointing task, there were no main effects or interaction (all $p \geq .126$). Within-technique comparisons (mid-task vs. end-of-task) were non-significant (see Appendix 1.1).

180° Rotation Task In the 180° rotation task, offset was larger with Adaptive than with Interactive. Under Adaptive, offsets decreased significantly from the mid-task to the end-of-task phase ($Z = 2.70$, $p = .007$, $\Delta = 2.14°$), whereas no reliable change was observed for Interactive ($Z = -1.42$, $p = .155$, $\Delta = -0.15°$). Overall, Adaptive yielded larger offsets, but these tended to be compensated for and reduced by the end of the task, while Interactive maintained lower offsets without significant phase-wise change.

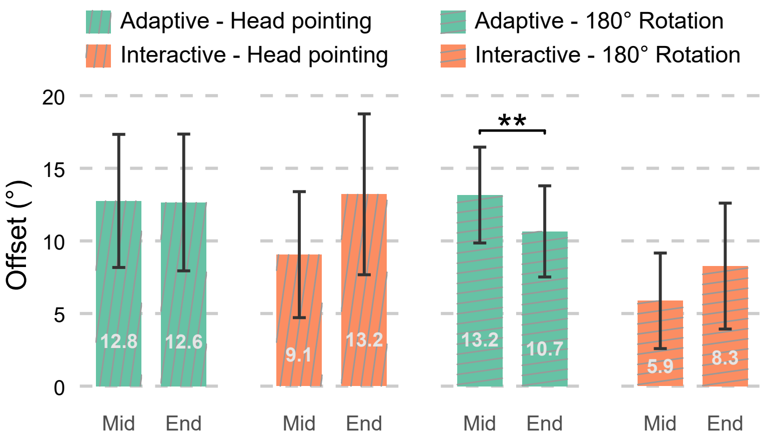


Figure 9: Mean absolute offsets in degrees (°) at the mid-task and end-of-task for Head-Pointing and 180° Rotation tasks, shown for both the 'Adaptive' and 'Interactive' techniques. Error bars represent 95% confidence intervals. Statistical significance shown as asterisks (*$p < .05$, **$p < .01$, ***$p < .001$).

Cybersickness (CSQ-VR)

CSQ-VR totals (range 6–42, lower = milder) stayed low across techniques. Means (Pre→Post) were: Adaptive 9.32→9.74, Static 9.29→10.70, Interactive 9.77→8.97 (SDs ≈3.6–4.9; see Appendix 1.2, Table 4). Post-block scores clustered at the low end of the scale (≈9–11), indicating very mild symptoms. *At the group level*, the tasks did not induce meaningful cybersickness, and no technique showed a practically relevant increase relative to its pre-block level.

NASA-TLX

Raw NASA-TLX metrics (Fig. 10) revealed no differences in Mental or Physical Demand, but participants reported significant differences in several other metrics. They perceived higher Overall workload with Static than with Interactive ($Z = 3.16$, $p = .005$, $\Delta = 9.02$) and with Adaptive ($Z = 2.45$, $p = .029$, $\Delta = 8.10$). Participants also reported higher Temporal Demand with Static than with Interactive ($Z = 3.24$, $p = .004$, $\Delta = 7.61$). Performance was reported to be better with both Adaptive ($Z = 3.53$, $p < .001$, $\Delta = 14.13$) and Interactive ($Z = 3.72$, $p < .001$, $\Delta = 16.77$) compared to Static. Frustration followed the same pattern, with higher Frustration reported for Static than for Adaptive ($Z = 2.48$, $p = .013$, $\Delta = 13.74$) or Interactive ($Z = 2.55$, $p = .011$, $\Delta = 13.84$). Although the Friedman test for Effort was significant ($\chi^2(2) = 9.13$, $p = .010$), Holm–Bonferroni-corrected post hoc tests showed that no pairwise contrast remained significant.

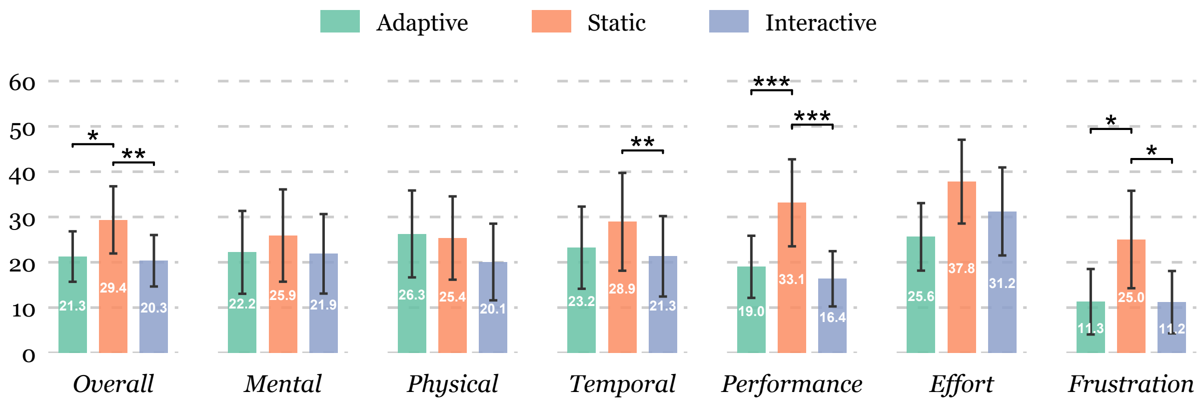


Figure 10: Mean NASA-TLX workload ratings for the three techniques across the seven subscales. For all subscales except Performance, lower scores indicate lower workload. Error bars represent 95% confidence intervals. Statistical significance is indicated by asterisks (*$p < .05$, **$p < .01$, ***$p < .001$).

Usability Questions

Self-defined usability questionnaire ratings (Fig. 11) showed several significant differences across techniques. Participants reported higher perceived control with Interactive than with both Static ($Z = 3.40$, $p = .002$, $\Delta = 1.00$) and Adaptive ($Z = 2.83$, $p = .009$, $\Delta = 0.77$). Comfort was rated higher for Interactive than for Static ($Z = 3.24$, $p = .004$, $\Delta = 1.26$); other comfort comparisons were not significant. For ease of use, participants favored Interactive over Static ($Z = 4.15$, $p < .001$, $\Delta = 1.84$); the difference between Interactive and Adaptive was not significant after correction. Precision was perceived highest for Interactive, with both Interactive ($Z = 4.40$, $p < .001$, $\Delta = 2.32$) and Adaptive ($Z = 4.00$, $p < .001$, $\Delta = 1.97$) scoring significantly higher than Static, and no significant difference between Interactive and Adaptive. Applicability was also rated higher for Interactive ($Z = 3.01$, $p = .008$, $\Delta = 0.84$) and Adaptive ($Z = 2.26$, $p = .047$, $\Delta = 0.58$) than for Static. No significant differences were found for naturalness ($p > .130$).

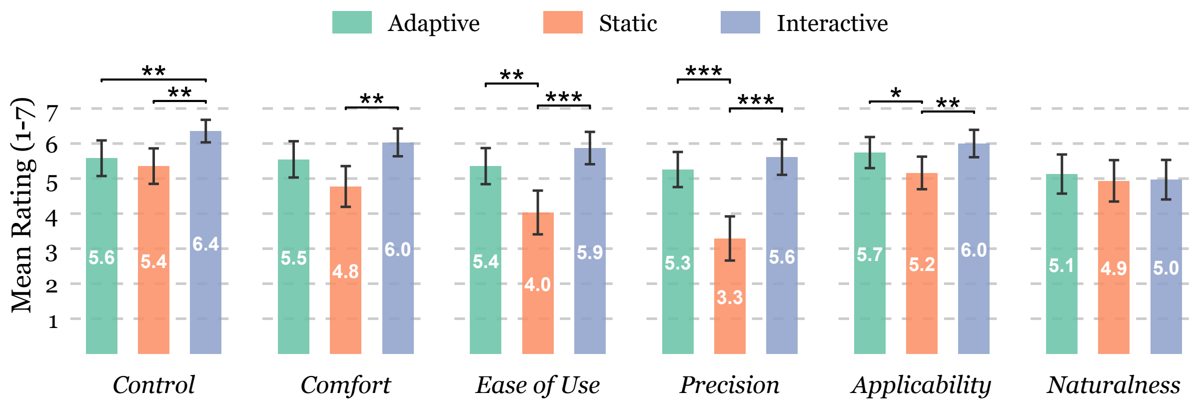


Figure 11: Mean usability ratings on a 7-point scale for the techniques across six self-defined usability questions. Error bars represent 95% confidence intervals. Statistical significance is indicated by asterisks (*$p < .05$, **$p < .01$, ***$p < .001$).

4.2 Qualitative Results

This section presents the results of the thematic analysis of participants' interview responses. Through iterative coding and analysis, several salient themes emerged that characterize users' experiences and perceptions of the techniques and of AHR in seated VR.

Theme 1. User Experience of Amplified Head Rotation

Preference for amplified head rotation A group of participants (P06, P13, P15, P25, P29) expressed a clear preference for AHR over the 1:1 mapping, often describing it as more *natural* or more *realistic* in VR. For them, amplification was better aligned with their expectations of how movement should feel in virtual space. P06 remarked, *"The amplification definitely... felt more natural... I thought it wasn't amplified,"* while P13 added, *"I never want to go back to the normal one... the amplification really helps, it makes me more engaged in this space."* P29 likewise described it as feeling more natural than the 1:1 mapping, saying, *"When I got used to it, it felt more natural for me than the slow one... with the amplification, I felt like I got something better."* P15 emphasized that the normal mapping seemed unnaturally slow or restrictive, explaining that without amplification they felt *"forced to move slower than I want,"* whereas the amplified mapping *"helped with that sensation."* P25 also found the amplified version *"more satisfying"* and felt slow with the 1:1 mapping, noting *"I felt like I didn't go anywhere with the first one."* P21 and P23 also preferred amplification for its efficiency and reduced physical strain, even though they found it less realistic.

Acceptance of visible amplification Additionally, some participants (P04, P11, P21, P22, P27) found amplified head rotation acceptable, practical, or beneficial in certain contexts. P04 emphasized its practicality, noting that amplification made it easier to look around while seated and reduced the strain of repeatedly turning the head. P11, P21, P22, and P27 preferred amplification for reducing physical effort, even if it felt less realistic. P22 described amplified rotation as *"not natural, but acceptable,"* and P11 stated, *"It's like riding an escalator—I think it's unnatural, but I accept it and I'm thankful for it... it saves me work and lets me look around more easily."* Among these participants, some further noted that amplification might be preferable depending on the task or VR context, and suggested, for example, offering it as an option in the *menu*.

Preference for 1:1 mapping (normal) rotation Some participants (P10, P16, P18, P20, P24, P31) preferred the normal rotation, mentioning that amplification felt unnatural, disorienting, or inconsistent with real-world movement. P20 described his preference and the mismatch between physical and virtual movement: *"I didn't really like the amplification... you move 180° with only 90° of motion, which messed with me a bit."* P24 reported the experience as *"wrong,"* stating, *"It felt weird. When it was amplified, it was like, whoa, that's wrong. I didn't like it."* Additionally, P18 emphasized that using her body to fully rotate enhanced immersion and embodiment, so she preferred normal rotation: *"Embodiment plays a big role for me... I can act more naturally if I use my body... I preferred the version where I rotate my body... it made me feel more immersed in the setting."*

Perceived as unnatural Eleven participants (P11, P16, P18, P20–P24, P26, P27, P31) explicitly described AHR as *unnatural* or *unrealistic*. For example, P22 noted that *"it is not natural..."* and P21 described it as *"a bit more unrealistic... not how real life works."* P26 found it *"a bit unnatural"* to look behind and unexpectedly find themselves back at the starting point. Similarly, P27 mentioned *"it didn't feel very natural... it moved way more than I expected."*

Theme 2. Sense of Agency and Control

Control and increased sense of agency Participants consistently valued being in control and described the Interactive technique as giving them *"more control,"* for deciding when amplification was active. In total, 19 participants (P01–P07, P10, P11, P13, P16–P17, P19, P21–P24, P27–P28) expressed this view. Several (P02, P03, P04) highlighted self-determination, noting that *"You yourself told it when you wanted to [slow it down]"* (P02), that they had the *"power to control"* (P03), and simply that they felt *"more in control"* (P04). Additionally, some participants mentioned having control over the timing of amplification, such as stating, *"You get to control when you want it to be faster or slower"* (P21) or *"I'm in control of when I want it to be assisted or natural"* (P22). Sense of control was sometimes linked to precision as P13 noted that *"It felt more precise to shoot the targets in this manner."* By contrast, the Adaptive technique was sometimes described as diminishing control and agency. For example, P27 reflected that *"It would speed my head movement up or slow it down on its own... I felt a little less in control."*

Adaptive technique and mismatched expectations Several participants (P06, P02, P21, P23, P15) also reported mismatched expectations with the Adaptive technique—moments when its automatic gain mode switch diverged from what participants expected. P06 described it as *"sometimes going slow when I wasn't expecting it, and then going fast when I was expecting it... it was very disorienting."* P02 noted a case where it felt *"a bit slower than I wanted, because it did the stabilizing when I was about to move my head quite fast to... turn,"* adding that *"overall... the speed was completely fine."* In a few instances, participants experienced unexpected jumps or sudden speed changes. P21 noted that *"the camera sort of jumped... I turned a bit, and I didn't expect it, but the camera shifted more than I did."*

P23 described the speed changes as *"almost like a surprise, oh, now it's slow… I didn't feel in control."* By contrast, with Interactive, P02 highlighted the predictable, user-timed speed-ups: *"You have the control, so you know when it's going to speed up… you don't feel it too fast or too slow."*

Theme 3. Spatial Orientation & Virtual–Physical Heading Offset

Spatial orientation and sense of direction Participants reported mixed effects of amplified head rotation on their spatial orientation and sense of direction in the virtual environment. Several participants (P04, P13, P29) reported improved environmental awareness and being able to see more of the scene with minimal head movement. P29, for example, felt *"much more aware"* and argued that amplification *"complements… natural awareness."* P15 reported *"about the same"* general awareness but noted better spatial understanding, as amplification felt closer to real head turning: *"it feels more like I'm turning my head in the real world."* However, many participants reported initial confusion when experiencing the amplified rotation for the first time. For some participants, this was the result of a relatively high rotation speed (gain of 2.5), such as P27, who noted, *"The first time… it felt a bit too high… I lost track of where I was looking, so I had to slow down and figure it out."* In other cases, when participants made an almost 180° physical rotation and looked back, they could see the start point again (a full 360° virtual turn). Several participants described this as surprising and initially disorienting. For example, P22 stated, *"I did 180° and saw the target in front of me, behind me, and I was like, there are two targets… but as time went on, I figured it wasn't two targets, it was one."* Notably, many participants indicated that as they became more familiar with the environment and adapted to the amplified rotation, their confusion lessened and their ability to orient themselves improved, for example, P27 reflected: *"as I got used to it, it felt more and more natural."*

P02, P06, and P28 reported difficulty understanding how much they were rotating in the virtual environment. For instance, P02 explained, *"I didn't really realize how far I was turning… if the tree was at 90°, I couldn't tell if it was 90, 100, or 130°."* Similarly, P06 described uncertainty when facing targets far to the right, unsure whether they were *"behind me or… 160° to my right,"* adding that *"where I was looking in the virtual space was a little obscured."* P23 noted that rapid turns sometimes revealed more of the scene than expected, "almost like the head is… an owl," leading to brief surprise about where they were looking. P20 noted that mismatches between physical turns and the resulting virtual view sometimes led to *"losing [my] global frame of reference,"* with spatial orientation feeling *"a little off, not enough to affect task performance, but… it just felt weird."*

Virtual–physical heading offset Regarding the offset, most participants (24; P02–P08, P10, P12–P13, P15–P19, P21–P25, P28, P30–P31) reported not noticing any mismatch when asked whether they perceived a heading offset between their physical and virtual head movement. Some participants who accumulated substantial offsets at the end-of-task phase (e.g., P03 and P22 with >40°) reported not noticing an offset. Among those who did experience larger offsets with Interactive (e.g., P14, P15, P27), offset was generally attributed to user error and trigger-timing rather than a technique issue—for instance, not yet mastering the button-press strategy or pressing and releasing the trigger at the wrong moment. As P27 explained, *"I kept the button held for too long sometimes... but that is a me issue more than a technique issue."* Notably, participants often compensated for the offset without explicitly labeling it as such, instead rotating further to complete the task. Their attention was directed primarily toward accomplishing the task, rather than to the offset itself; as P13 remarked, they *"didn't really care about"* the observed offset. However, eight participants (P01, P09, P11, P14, P20, P26–P27, P29) did explicitly recognize offset, for example, P20 described it with the Adaptive technique: *"In the interactive [targets] were at 90° to the left; they were almost directly in front of me in the adaptive."*

ViewShift: a user-initiated redirection strategy for view reorientation A key finding from our qualitative analysis was an emergent, user-initiated redirection strategy we term *ViewShift*. Six participants (P01, P05, P14, P19, P26, P29) discovered that they could deliberately reorient the virtual view—without rotating their torso—by exploiting the difference between high- and low-gain modes with Interactive, thereby creating an intentional offset in the desired direction. In practice, participants alternated high- and low-gain across an out-and-back head turn. This could be done in two ways: either "fast–out/slow–back" (turning toward the desired side in high gain and returning in low gain) or the reverse ("slow–out/fast–back"). Both variants produced a net scene shift toward the intended direction. For instance, P01 explained the reverse ordering as *"lock[ing] the background with the trigger, mov[ing] in the opposite direction, unlock[ing] it and mov[ing] back,"* effectively *"mov[ing] the world around me."* P05 described this as *"pull[ing] the vision a little bit to the right [or] to the left,"* noting that Interactive *"provides... more flexibility."* P19 reported using it to *"move the scene... more in front of me"* to keep aiming within a comfortable range, and P26 characterized it as "very intuitive... way nicer." P29 and P14 also used the same sequence to correct accumulated viewpoint offset when needed ("I... auto corrected it by having the button in again," P29). Notably, P14 engaged the same mechanism without explicitly realizing it, explaining, *"Because I realigned it by pressing again... maybe in the other direction or something like that."* This case suggests that additional participants may have engaged with the mechanism intuitively without being fully aware of it. In addition, this behavior emerged without instruction and provided in-situ realignment of the view. The mechanism is similar to redirected walking, where asymmetric scene rotations across successive head turns produce a net reorientation; in our study, however, this effect was user-initiated rather than system-controlled (Razzaque et al., 2001). The same effect is possible with Adaptive, but no participants reported discovering it during the study.

Theme 4. Technique Preferences and User Suggestions

Eighteen participants clearly preferred Interactive (P01, P03–P13, P16, P21–P22, P24, P27–P28), favoring it for the agency and precise aiming it afforded. In addition, eight participants (P02, P15, P17–P18, P23, P25–P26, P29) either did not have a clear overall preference or expressed mixed, task-dependent preferences, finding different techniques useful depending on context. Five participants (P14, P19–P20, P30–P31) preferred Adaptive for its reduced cognitive load and "more natural" feel. No participant mentioned Static as their overall favorite; while occasionally chosen for predictability in simple-looking tasks (e.g., P11, P23), it was often criticized as too sensitive and unsuitable for fine aiming (20 participants;

P01, P02, P05–P06, P10–P16, P19–P21, P23–P29). Some participants (P09, P24, P26) noted difficulty distinguishing between Adaptive and Static, though some (P24, P26) felt they made fewer errors with Adaptive.

Interactive Participants often preferred Interactive (18 participants) because they could decide *when* to slow down or amplify rotation, which supported both precise selection and rapid view rotation. For example, P09 remarked, *"I prefer manually... it's easier and faster to shoot the targets,"* and P13 explained that they felt *"In control of the entire process... I could choose fast or slow."* Several also described the technique as familiar or "game-like": *"I really liked it... it reminded me of the usual ways of interacting with targets in games... better control... I was better and faster."* (P10). At the same time, a few participants (P02, P06, P14, P31) found the trigger timing cognitively demanding. For instance, P06 noted, *"If I pressed the trigger too early... I'd strain my neck... but I could train and get better."* P15, P18, and P29 reported that the Interactive technique with button-triggered rotation often broke immersion. P15 noted that *"As soon as you press a button... you're suddenly aware you're in a virtual world."* while P29 found the button trigger *"didn't feel natural at all"* compared to the Adaptive technique, which *"didn't break the immersion."* P18 stated that *"when [you] use the trigger, it makes you feel like I'm not in the real world."*

Adaptive Some participants preferred Adaptive (5 participants) because it lowered cognitive load and provided a smoother, more natural flow, removing the need to manage mode switching explicitly. For example, P25 remarked, *"It was a lot easier... less mentally demanding because I didn't have more buttons to think about."* and P20 explained, *"I could focus more on the game as opposed to the motions."* Others highlighted its natural and immersive feel: P02 noted that *"it stabilizes as you slow down,"* P18 said they *"preferred it because it felt more natural,"* and P29 remarked that *"it was more immersive because I didn't have to think about it."* At the same time, several participants reported mismatches when the system's automatic adjustments did not align with their intentions, such as slowing when they wanted speed or amplifying when they wanted precision (see Section 4.2). Additionally, three participants (P04, P10, P23) reported increased cybersickness during the Adaptive block. P04 reported *"a bit of dizziness,"* relating it to the greater physical movement required to reach rear targets (180°) with Adaptive. For P10, Adaptive occurred in the first block, which may partly explain the reported symptoms, as several participants noted stronger sickness effects in earlier blocks that diminished over time. P23 linked their cybersickness to the mismatched expectations (see Section 4.2), remarking, *"If I were in there longer, I think I'd start to feel motion sickness, because you're rotating your head one way, but then it adjusts for you."*

Static Static was sometimes valued for its predictability and non-surprising behavior (P04, P05, P11, P22, P23), and some participants further noted that it might suit simple or coarse tasks, such as scene exploration, or aiming at larger targets (P05, P11, P23, P29). P11 remarked, *"It is the most predictable... I was never disoriented."* However, it was widely criticized (20 participants) as difficult for precise selection due to sensitivity to micro-movements. P15 described it as *"easily the worst one... hard to focus exactly on targets,"* while P06 found it *"hard... very sensitive... a bit more straining."* Similarly, P27 explained that *"with Static I had* *to keep making micro-adjustments,"* which made the technique effortful and less comfortable for pointing tasks. In addition, some participants (P01, P16, P24) explicitly reported mild cybersickness during the Static block, typically described as dizziness or slight nausea.

User suggestions Participants requested *adjustable settings* to personalize gain, such as an options menu with sliders (*"a slider... low to high or... turn it off completely"*; P15) and, for some, calibration of Adaptive (P11). P01 also wanted a slightly higher high-gain to reduce physical turning. For precision, P14, P06, and P29 requested a lower low-gain during fine aiming. Additionally, P15 and P31 suggested a target-assistance variant of Adaptive, where gain would adjust dynamically based on target position to support fine aiming. To improve Adaptive, participants proposed *more transparent switching*, noting that gain shifts should feel smooth and seamless rather than algorithmic or surprising (P15, P21, P23). P11 also suggested *easy mode switching between techniques* based on the task. P29 preferred reversed trigger mapping for the Interactive (*"it might be more intuitive to have it press for speed rather than the opposite"*). P19 suggested a *combined technique*, where Adaptive would serve as the base that adapts automatically, but users could still intervene manually as in Interactive. P14 further requested a simple *reset function* (e.g., a double tap) to realign the view and reset accumulated heading offset.

5 Discussion

Head movement is the default input for viewport control in HMDs, typically implemented as a 1:1 mapping between physical head rotation and the virtual view. In seated VR, where large physical turns are limited, altered mappings can amplify head rotation, enabling efficient view control with reduced physical effort. This work introduces two novel techniques that alter the mapping to amplify head rotation. *Interactive* allows users to switch manually between low- and high-gain modes, whereas *Adaptive* switches automatically based on head-movement kinematics. Both techniques were evaluated against a *Static* gain 2.5 baseline.

The following discussion interprets the findings in relation to the research questions. We begin by summarizing the key findings and then discuss their significance for task performance, cumulative head movement, user experience, control, cybersickness, workload, acceptance, and virtual–physical heading offset.

Summary of key results

In terms of quantitative results, across tasks, both Interactive and Adaptive improved performance compared to Static. They resulted in faster times and fewer errors in the head-pointing task, though no differences were observed in the 180° rotation task. Both techniques, however, led to more cumulative head movement than Static, with Adaptive typically producing the highest cumulative movement. On average, virtual–physical heading offsets were generally modest, though occasional larger cases were recorded. CSQ-VR scores remained low across techniques. In subjective ratings, both novel techniques were perceived as less demanding than Static in overall workload, with Interactive also rated lower in temporal demand. Participants further reported higher performance and lower frustration with Interactive and Adaptive than with Static. In terms of usability ratings, Interactive scored highest for control, being rated significantly higher than both Adaptive and Static. It was also rated significantly higher than Static on comfort. For ease of use, precision, and applicability, both Interactive and Adaptive were rated significantly higher than Static, with no significant differences between them on precision or applicability. Perceived naturalness did not differ reliably across techniques.

In terms of qualitative results, amplified rotation sometimes caused initial confusion, particularly at higher gains, but participants reported adapting quickly. Participants strongly valued control and predictability, most often favoring Interactive for user-timed switching that supported both rapid turning and precise aiming. Adaptive was appreciated for lower cognitive load and a smoother, "more natural" flow, but occasional mistimed speed changes reduced the sense of control. Static was predictable yet widely criticized for fine aiming due to sensitivity to micro-movements. Perceptions of naturalness were divided: some found amplification more intuitive and even more realistic after adaptation, while others preferred a 1:1 mapping for its closer alignment with real-world movement and a stronger sense of embodiment. Most participants did not explicitly notice virtual–physical heading offset during tasks, instead compensating implicitly while completing the task. Several participants discovered and used Interactive to deliberately recenter the view (fast–out/slow–back), actively managing heading offset; no one reported discovering an equivalent strategy with Adaptive.

5.1 Task performance & Cumulative Head Movement (RQ1)

Both Adaptive and Interactive improved head-pointing performance over Static, with shorter completion times and fewer errors. However, Static still required less physical head movement to complete the tasks. This pattern suggests that while Static supported the ballistic phase of pointing, it left users struggling in fine-aim corrections, causing more overshooting/undershooting, and resulting in higher errors and higher task time. In contrast, the novel techniques better supported both rapid rotation and precise aiming, explaining their enhanced performance. This aligns with motor-control and gain literature: high gain accelerates the ballistic phase, whereas low gain supports corrective fine-aim (Deng et al., 2024).

In terms of cumulative head movement, both Adaptive and Interactive required higher head movement than Static across tasks. Within each task, Adaptive exceeded Interactive; however, when aggregated across tasks (Overall), the Adaptive–Interactive contrast was not significant. This increase was partly due to the heading offset introduced by both novel techniques, which required compensatory head rotations and thereby contributed to their higher head movement relative to Static. In addition, in the head-pointing task, both techniques used a low gain for fine aim, but Adaptive's velocity-triggered smooth transfer kept gain near the low end more often as participants decelerated, increasing physical rotation relative to Interactive. In the 180° rotation task, participants rarely switched to the low-gain mode with Interactive, making it effectively a constant high-gain mapping, whereas Adaptive occasionally transitioned to low gain during slower segments of the turn, leading to additional head movement. Moreover, higher cumulative head movement with Adaptive reflects the chosen variant of this technique and its parameterization: the smooth transfer and moderate g_{high} were selected to avoid overshoot and precision loss, which also reduced the average applied gain and thus increased head movement. Alternative variants without a smooth transition function or with higher

g_{high} values could reduce head movement, but would risk larger offset and reduced pointing precision.

Taken together, for *performance*, the gain mode switching with novel techniques improved speed in the Head-Pointing Task without an accuracy cost, whereas this advantage does not extend to the 180° Rotation Task. In terms of *movement effort*, the dual gain modes of the novel techniques come with increased physical head movements, most pronounced for Adaptive. In contexts dominated by broad scene exploration without precise selection, the lower movement and predictability of Static can therefore be advantageous when minimizing physical rotation is the primary goal. By contrast, for mixed navigation and precise head-pointing, the novel techniques are preferable. Interactive typically required less cumulative movement than Adaptive within each task, a pattern attributable to the specific Adaptive variant and parameterization used in the experiment (threshold + smooth transfer; moderate g_{high}).

5.2 User experience: control, cybersickness, workload, acceptance (RQ2)

Both quantitative and qualitative findings indicated that participants strongly valued agency over rotation gain switching. Qualitatively, 19 participants explicitly praised the control afforded by the Interactive technique, aligning with the quantitative finding that Interactive received significantly higher usability ratings on perceived control. This is consistent with sensorimotor models of VR illusion, which propose that illusions are strongest when the sensory consequences of an action align with the user's predicted next state (Gonzalez-Franco and Lanier, 2017). When users move their head or limbs, and the predicted state in the brain matches the incoming sensory feedback, the illusion is sustained. Additionally, agency further strengthens the illusion through the sense that *I am the initiator of the action* (Gonzalez-Franco and Lanier, 2017; Haggard et al., 2002).

In our study, the user-timed switching in Interactive reinforced the match between the user's action and their predicted next state, as gain changes occurred precisely when users intended them, ensuring that the altered visual rotation aligned with their predictions. By contrast, in Adaptive, automatic switching sometimes diverged from user intent, reducing perceived control and leaving participants feeling disoriented or surprised by sudden speed changes. According to models of VR illusion, such mismatches undermine agency and may also disrupt presence, or place illusion (PI), since sensorimotor contingencies are no longer consistent (Slater, 2009). Taken together, the findings suggest that gain switching should be designed to respect user intention: either by enabling *user-triggered control*, as in Interactive, or by ensuring that automatic switches are tightly aligned with user expectations. Otherwise, mismatches risk weakening the VR illusion and negatively affecting user performance on the task.

Cybersickness is commonly attributed to *sensory conflict theory*, which states that adverse symptoms arise when visual feedback diverges from vestibular and proprioceptive signals. In VR, such conflicts occur when system-generated visual motion does not align with the user's physical head or body movements (LaViola, 2000). In our study, CSQ-VR scores remained low on average across techniques (see Section 4.1), indicating very mild levels of cybersickness.

Nevertheless, interview data revealed technique-specific reports. With Static, some participants reported cybersickness, possibly due to the high rotation speed ($g = 2.5$).

High gains increase visual angular velocity relative to vestibular and proprioceptive signals, especially during rapid turns, which can cause visual–vestibular mismatches and induce cybersickness (LaViola, 2000; Ragan et al., 2017). A further contributing factor may have been the sensitivity to micro-movements during the head-pointing task, where repeated fine adjustments under high gain were often described as straining or uncomfortable.

With Adaptive, participants occasionally reported mismatched expectations when automatic gain changes diverged from user intent as P23 remarked, *"it adjusts for you."* From a *sensory-conflict perspective*, this divergence from users' intent introduces prediction errors (i.e., unexpected visual feedback) relative to vestibular and proprioceptive input, which can induce cybersickness (LaViola, 2000). In our case, Adaptive employs a sigmoid-based smooth transfer for rotation gain. When a participant initiates and intends a rapid turn, the visual scene can momentarily lag during the low-to-high transition, causing visual angular velocity to fall short of the vestibular and proprioceptive estimate of head motion. This transient mismatch may induce cybersickness.

Additionally, the mechanism behind the Adaptive technique (where gain was modulated based on head velocity and acceleration) was not explicitly explained or trained with participants during the experiment. This lack of transparency may have contributed to mismatched expectations, as participants could not anticipate when or how the system would adjust their rotation. It is plausible that if participants had been informed of, and practiced with, the underlying mechanism, they might have perceived the behavior of Adaptive as more consistent with their intent, thereby reducing surprise and aligning better with their expectations.

Some participants noted that trigger timing in Interactive could increase cognitive load and affect presence. However, the absence of differences in *Mental Demand* (Raw NASA-TLX; Fig. 10), together with the significantly higher *Comfort* and *Ease of Use* ratings for Interactive in the usability questionnaire (Fig. 11), suggests that any cognitive cost was small or offset by the enhanced precision and control from user-timed switching. While not statistically significant, Adaptive showed a slight trend toward lower *Effort* than Interactive (Fig. 10), which we may interpret as a possible indication of the added effort of timing the trigger button. In addition, *Physical Demand* did not differ significantly across techniques (Fig. 10), indicating that reductions in head movement with Static were not reflected as lower physical workload in the raw NASA-TLX ratings, possibly because the frustration participants experienced with Static influenced their perception of physical effort.

Beyond preferences for specific techniques, many participants reflected positively on amplified head rotation (AHR) in general. Several explicitly favored AHR over a normal 1:1 mapping in seated VR, describing it as more natural once adapted, more engaging, or simply more practical for the task demands. Others did not necessarily prefer AHR but still regarded it as useful in contexts where frequent head turning would otherwise be effortful or uncomfortable, framing it as "not natural, but acceptable" when it reduced physical strain.

These accounts converge with the relatively high *Applicability* ratings across techniques (Fig. 11), suggesting that, even when perceived as less natural, participants recognized the practical value of amplification for seated VR. At the same time, a subgroup preferred the normal 1:1 mapping, often grounding their preference in realism, embodiment, or a desire to "use the body" for presence. Taken together, the results highlight that acceptance of AHR in seated VR is shaped less by a single notion of naturalness than by the balance between effort reduction, task demands, and users' expectations for how movement *should* feel in a virtual environment. These findings are consistent with prior work showing that even overt gains beyond perceptual thresholds (≈ 0.89–1.28) can still be considered applicable by users up to values around 2.5 in seated VR (Wang et al., 2022).

5.3 Virtual–physical heading offset (RQ3)

One important trade-off of the Interactive and Adaptive is the heading offset that arises from applying asymmetric gains during out-and-back head turns.

Not all gain techniques accumulate virtual–physical heading offset. When gain depends only on head yaw (e.g., a constant-gain mapping), a given physical turn (e.g., 30°) always produces the same virtual rotation; thus, an out-and-back movement realigns the view without offset. Dynamic mappings that vary gain solely with yaw angle likewise apply the same gain in both directions, ensuring that outward and return movements cancel out.

By contrast, techniques that (i) modulate gain from temporal kinematics, such as Adaptive, velocity-guided amplification (Zhang et al., 2021), and HeadShift (Wang et al., 2024), (ii) involve user-timed mode switching, such as Interactive, or (iii) specify gain based on target position (Langbehn et al., 2019), can apply asymmetric gains between outward and return turns, accumulating offsets across repetitions.

On average, Interactive and Adaptive accumulated offsets in the range of 9°–13°, though occasional extreme cases were recorded. These outliers highlight that while average offsets remain moderate relative to the rotations performed, occasional extreme cases can arise and may conversely affect both task performance and user experience.

In addition, Offset dynamics depended on both the task and how each technique was used. In the 180° rotation task, Interactive remained relatively stable, as participants rarely switched modes during continuous, large-angle turns and when interacting only with the large targets, effectively making it close to a constant high-gain mapping and thereby yielding less offset. Adaptive, by contrast, often transitioned into the low-gain state as head velocity decelerated. This produced an offset in one direction during rotations on the right side and an opposing offset during rotations on the left side, which partly canceled across task halves by the end. While this explains the observed mid-to-end reduction, it also shows that Adaptive exposes users to offset during rotation tasks that may be less apparent in endpoint averages yet remain important for spatial orientation, task performance, and user comfort. In addition, if the task were asymmetric, this pattern of offset generation and cancellation might differ from what was observed.

In the head-pointing task, both techniques produced a similar amount of offset, with no reliable differences between them. This suggests that the task structure with short rotations and pauses prevented the kind of cumulative offset observed in continuous turns. In addition, fine-aim corrections were typically performed in low gain under both techniques, which further aligned their comparable offset outcomes in which, heading offset remained relatively similar across techniques. Adaptive in the head-pointing task offsets also stayed at a similar level from mid-task to end-of-task, suggesting that the cancellation effect observed in the 180° rotation task was less evident under this task structure.

Despite measurable offsets of around 10° on average, most participants did not explicitly report noticing a mismatch, even those who accumulated larger offsets. Instead, participants' attention appeared target- and goal-directed, and they typically compensated by rotating further to complete the task. This suggests that offset often remained implicit within task execution rather than being noticed as a distinct phenomenon. A possible explanation is that participants engaged with the task for a short duration, and longer exposure may have made the offset and its effects more explicit. Additionally, when offset was noticed with Interactive, participants often attributed it to their own trigger timing rather than to the technique itself. This placed responsibility for both accumulating and correcting the offset on the user, suggesting that the sense of control and agency influenced how participants perceived it. It may also have made the offset more explicit, allowing users to avoid or recover from it when needed.

Several participants discovered *ViewShift*: deliberately managing virtual–physical heading offset in Interactive by alternating high- and low-gain across an out-and-back head turn (e.g., high gain toward the desired side followed by low gain back), effectively shifting the virtual view to the desired side and bringing targets into a more comfortable position. We formalize ViewShift using a *user-initiated two-gain model*. In Interactive, rotational gain is user-toggled between two constant states: a high ("fast") gain g_{H} and a low ("slow") gain g_{L}, with $g_{\mathrm{H}} > g_{\mathrm{L}}$. Consider an out-and-back head turn of equal physical magnitude $\Delta\theta$ (take $\Delta\theta > 0$ toward the intended direction). The net virtual–physical heading offset is

$$\Delta\varphi \;=\; g_{\mathrm{H}}(+\Delta\theta) \;+\; g_{\mathrm{L}}(-\Delta\theta) \;=\; (g_{\mathrm{H}} - g_{\mathrm{L}})\,\Delta\theta.$$

Applying the high gain on either the outward segment ("fast–out/slow–back") or the return segment ("slow–out/fast–back") yields the same net offset $(g_{\mathrm{H}} - g_{\mathrm{L}})\,\Delta\theta$ toward the intended direction; the two ViewShift sequences differ only in *when* the larger portion of the virtual rotation occurs (outward vs. return).

This follows the same asymmetric scene-rotation principle underlying redirected walking (RDW), which subtly rotates the virtual scene to redirect the physical walking path (Razzaque et al., 2001). In RDW, such asymmetries produce a net change in *physical* orientation during locomotion; here, the same idea is repurposed to yield a net shift of the *virtual view* that recenters content without torso rotation. A similar approach is implemented by Sargunam et al. (2017) with *Guided Head Rotation*, a system-initiated variant that gradually rotates the virtual scene during travel to encourage the user's physical head to return toward the real-world forward (neutral) orientation. A key distinction is that ViewShift exposes the rotational-gain "lever" directly to the user: rather than the system steering implicitly, users themselves initiate, time, and apply the fast–slow sequence to redirect the view to a desired position. This suggests a complementary lens: a user-initiated redirection strategy, in which outward–return gain asymmetries are surfaced as an affordance for on-demand recentering rather than hidden as a background locomotion aid.

Although no participants reported discovering *ViewShift* with Adaptive, the same asymmetric fast–slow sequence is, in principle, achievable: Adaptive enters high gain during rapid rotations and reverts to low gain as the head decelerates (i.e., slow rotations engage low gain; fast rotations engage high gain), so a deliberate fast–out/slow–back sequence would likewise produce a net view shift. As discussed in Section 5.2, the mechanism behind Adaptive (velocity- and acceleration-based switching) was not made explicit or trained, which likely reduced discoverability of this affordance.

ViewShift may increase discomfort and cybersickness risk if the low-gain state is set too low, as strongly reducing visual speed during rotation can worsen visual–vestibular conflict. In our implementation, the low-gain state was set to $g_{\mathrm{L}} = 1$ (i.e., normal 1:1 mapping), but further experiments are needed to evaluate its usability and potential to induce cybersickness.

Taken together, virtual–physical heading offset arises from asymmetric gain across outward and return head turns. With Interactive and Adaptive, offsets were typically moderate on average but occasionally large, and shaped by task structure and by how the techniques were used. Our results also demonstrate *ViewShift*, which participants used to deliberately recenter the virtual view, treating offset as a controllable resource when needed. To keep offset within acceptable bounds and support recovery in practice, systems can make offset and gain state visible (e.g., a heading marker with an optional arc showing the offset angle) and provide simple recovery actions (e.g., a one-tap micro-recenter or a full reset); these are preliminary design suggestions that require empirical investigation. In contexts where tight alignment between physical and virtual forward is critical, constant gains may be preferable to mappings such as Interactive and Adaptive.

5.4 Limitations and Future Work

A rigorous, controlled evaluation of the two techniques for selection and pointing (using a standard Fitts' Law task to quantify movement time (MT), throughput (TP), error rate, and effective width) was not undertaken within the scope and resources of this project. Such a study, with systematically varied angular amplitudes and angular target widths, would provide stronger evidence on comparative performance and would align with related work that employs controlled Fitts' tasks to assess selection and pointing techniques.

Similarly, identifying optimal parameters for the Adaptive technique would ideally involve an iterative, empirical tuning procedure conducted on controlled pointing tasks. In the present work, parameters were set through researcher testing and a small pilot; they should therefore be regarded as preliminary rather than fully optimized. A more comprehensive comparative study of all three Adaptive variants would help clarify their trade-offs and suitability across contexts.

Additionally, this study adopted a constant high-gain value of $g = 2.5$ for the Static baseline and as the upper bound for the dynamic techniques. While a more conservative value, such as $g = 2.0$ might better reflect practical deployment scenarios and reduce potential disorientation, the higher gain ensured that amplification was clearly visible in the experiment and that its effects could be observed more prominently. Future work may assess the impact of varying gain magnitudes, including more moderate settings, to balance amplification in terms of user comfort, spatial orientation stability (virtual–physical heading offset), and cumulative head movement.

The training block was conducted with Interactive to introduce both tasks and the mode-switching strategy. Although the main-phase technique order was randomized, this asymmetric familiarization may have influenced outcomes by providing Interactive with additional practice or by front-loading effort with that technique.

For Adaptive, the underlying mechanism (gain modulation based on head velocity and acceleration) was not explicitly explained or trained with participants. This may have contributed to mismatched expectations, suggesting that clearer instructions and familiarization could alter how the technique is perceived.

The choice of environmental references may also have limited spatial orientation fidelity. More distinctive or varied landmarks (e.g., trees with different colors or shapes) could have provided clearer reference points and potentially improved participants' orientation. Furthermore, the tasks employed in this study were symmetric by design. Asymmetric task structures might have resulted in different patterns of offset accumulation, and more naturalistic task designs could yield additional insights into how amplified head rotation is experienced in everyday seated contexts.

Based on participant suggestions and study findings, future work may explore adjustable settings to personalize gain, along with more transparent and visible indicators of gain states and mode switches. Another direction is to make the *ViewShift* affordance more explicit as a feature and evaluate its usability and potential effects on cybersickness. Hybrid approaches also appear promising, such as a *combined technique* where Adaptive provides automatic switching by default while manual intervention remains available. In addition, alternative triggers beyond a button press (e.g., gesture-based input) could be investigated to improve ergonomics and intuitiveness.

6 Conclusion

In summary, this thesis introduced two novel AHR techniques for seated VR: the Interactive technique, which enables user-timed switching between high and low gain, and the Adaptive technique, which automatically adjusts gain based on head-motion kinematics. In a mixed-methods study ($n = 31$), compared with a Static constant-gain baseline ($g = 2.5$), both techniques improved head-pointing performance while maintaining low cybersickness and generally modest heading offsets. Interactive afforded the strongest sense of agency through user-timed switching, whereas Adaptive offered reduced cognitive load by automating the timing.

In the head-pointing task, both Interactive and Adaptive yielded faster times and fewer errors than Static. Switching gain modes increased *physical* head movement for both novel techniques, with Adaptive typically producing the highest cumulative movement. By contrast, Static minimized physical rotation. Taken together, when the primary objective is broad scene exploration with minimal physical rotation, Static can be advantageous, whereas for mixed navigation and precise head-pointing tasks, Interactive and Adaptive are preferable.

Participants strongly valued control and agency over rotational gain, and Interactive was most consistently associated with a heightened sense of control. Both Interactive and Adaptive reduced perceived workload compared to Static. Acceptance of visible amplification was also generally high, even though participants expressed mixed views on naturalness.

Offsets were moderate on average, though occasional extreme cases were recorded. Most participants did not explicitly notice virtual–physical heading offset mismatches, instead compensating implicitly during task execution. When offset was noticed in Interactive, it was often attributed to participants' own trigger timing rather than to the technique itself, suggesting that accumulated offset was perceived as a consequence of their own actions. In contexts requiring strict alignment of physical and virtual forward, constant gains may remain the better choice.

Notably, several participants discovered that Interactive could be used to *deliberately* recenter the view by alternating high and low gain across an out-and-back turn. This produced a controlled offset that shifted the virtual view without requiring torso rotation. We term this behavior *ViewShift*, a user-initiated redirection strategy in which bidirectional gain asymmetries are surfaced as an affordance for on-demand recentering rather than experienced only as an unintended side effect.

Overall, the findings highlight the promise of giving users agency in controlling rotational gains. Gain switching should be designed to respect user intention, either by enabling *user-triggered control*, as in Interactive, or by ensuring that automatic switches remain tightly aligned with user expectations.

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1 Additional Statistical Results

1.1 Offset analyses

Table 1: Absolute offsets (degrees) by technique, task, and phase ($n = 31$). Values are means (M) and standard deviations (SD).

Technique	Task	Phase	M	SD
Adaptive	Head-Pointing Task	mid-task	12.75	12.49
Adaptive	Head-Pointing Task	end-of-task	12.65	12.84
Interactive	Head-Pointing Task	mid-task	9.05	11.83
Interactive	Head-Pointing Task	end-of-task	13.21	15.10
Adaptive	180° Rotation Task	mid-task	13.16	8.99
Adaptive	180° Rotation Task	end-of-task	10.65	8.56
Interactive	180° Rotation Task	mid-task	5.87	8.97
Interactive	180° Rotation Task	end-of-task	8.27	11.82

Table 2: ART ANOVA (Technique × Phase) for absolute offset. Kenward–Roger degrees of freedom.

Task	Effect	F	df_1	df_2	p
Head-Pointing Task	Technique	2.38	1	90	.126
	Phase	0.09	1	90	.771
	Technique:Phase	0.79	1	90	.376
180° Rotation Task	Technique	22.05	1	90	$< .001$
	Phase	1.58	1	90	.212
	Technique:Phase	2.74	1	90	.102

Table 3: Paired Wilcoxon signed-rank tests (Mid vs End) for absolute offset, by technique. z = standardized test statistic; Δ = median(Mid − End) in degrees.

Task	Technique	z	p	r	Δ (°)
Head-Pointing Task	Adaptive	0.54	.590	.10	+1.50
	Interactive	0.27	.791	.05	+0.31
180° Rotation Task	Adaptive	2.70	.007	.48	+2.14
	Interactive	-1.42	.155	.26	-0.15

1.2 Cybersickness (CSQ-VR)

Table 4: CSQ-VR totals (range 6–42) by technique and time. Values are means with standard deviations in parentheses.

Technique	**Pre**	**Post**
Adaptive	9.32 (4.48)	9.74 (3.89)
Static	9.29 (3.55)	10.70 (4.91)
Interactive	9.77 (4.52)	8.97 (3.98)