BiRD: Using Bidirectional Rotation Gain Differences to Redirect Users during Back-and-forth Head Turns in Walking

Sen-Zhe Xu, Fiona Xiao Yu Chen, Ran Gong, Fang-Lue Zhang, and Song-Hai Zhang

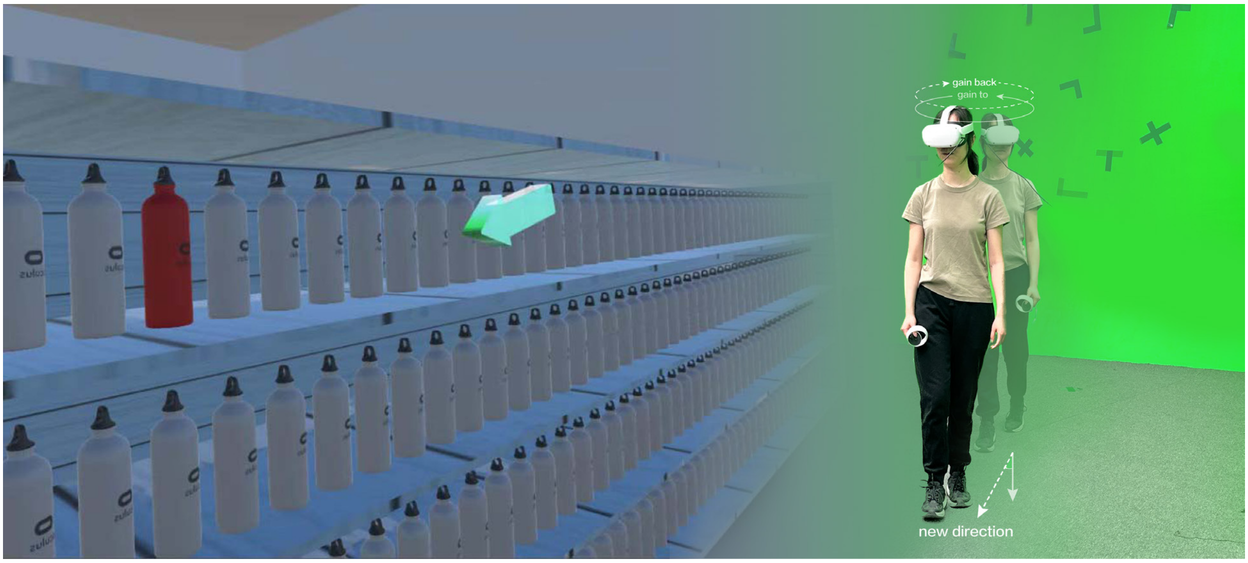

Fig. 1: **Left:** A virtual scene of a supermarket aisle that was designed for our studies. Participants could walk along a mostly straight trajectory and naturally pivot their heads left and right. A task pointer in the form of an arrow was employed to guide users in rotating their heads towards specific target objects. **Right:** By leveraging BiRD for redirection, users follow a novel physical path subsequent to a head rotation.

Abstract—Redirected walking (RDW) facilitates user navigation within expansive virtual spaces despite the constraints of limited physical spaces. It employs discrepancies between human visual-proprioceptive sensations, known as gains, to enable the remapping of virtual and physical environments. In this paper, we explore how to apply rotation gain while the user is walking. We propose to apply a rotation gain to let the user rotate by a different angle when reciprocating from a previous head rotation, to achieve the aim of steering the user to a desired direction. To apply the gains imperceptibly based on such a Bidirectional Rotation gain Difference (BiRD), we conduct both measurement and verification experiments on the detection thresholds of the rotation gain for reciprocating head rotations during walking. Unlike previous rotation gains which are measured when users are turning around in place (standing or sitting), BiRD is measured during users' walking. Our study offers a critical assessment of the acceptable range of rotational mapping differences for different rotational orientations across the user' s walking experience, contributing to an effective tool for redirecting users in virtual environments.

Index Terms—Redirected walking, virtual reality, rotation gain, detection thresholds, simulator sickness

1 Introduction

Over the past decade, virtual reality (VR) systems have experienced rapid development, providing users with unprecedented immersive and realistic experiences in various fields [42]. However, within this realm of impressive progress, challenges persist in the domain of VR interaction. One such challenge revolves around efficiently guiding users through expansive virtual environments (VEs) while confined to a limited physical space. Redirected walking (RDW) [36, 37], a cornerstone technology in VR interaction, addresses this challenge by a remapping between virtual and physical environments. RDW exploits the perceptual distinctions between human vision and proprioception—referred to as "gains", as elaborated upon by Steinicke et al. [45]— to achieve a navigation experience that seamlessly merges immersive quality with practical constraints. When VR users do inevitably run into obstacles in the real environment, RDW controllers will reset the user by overtly adjusting the user's physical orientation or position [59], helping them avoid the obstacle. However, resets often result in reduced immersion for the user within the virtual space, underscoring the importance to minimize their occurrence.

In redirected walking, common gain types include *translation gain* [17, 22], *rotation gain* [16, 35, 40, 54], and *curvature gain* [32, 38, 45]. Of these, the latter two are both effective in reorienting users. The successful application of these gains allows VR users to explore larger VEs than their physical space through natural walking without the need

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for additional input devices [12, 27, 34]. To ensure that gain-based redirection is imperceptible to the user, a significant amount of research is dedicated to measuring the detection thresholds for various gains. In general, literature asserts that *curvature gain* is only applied when a user is translating. On the other hand, prior research has not explicitly addressed whether *rotation gain* should affect a user's rotation when they are walking or in situ. According to the gain thresholds commonly utilized by RDW methods, *curvature gain* can only influence the user's path when the curvature radius exceeds 7.5 meters [15], which averages to a deviation of merely 7.64° per meter walked. On the other hand, *rotation gain* can alter rotations within a range of 0.67 to 1.24 [45]. Other works that also studied the detection thresholds of rotation gain had results of 0.59 to 1.1 [44]; 0.681 to 1.259 [4]; 0.82 to 1.2 [41]. Consequently, in terms of reorientation effectiveness, *rotation gain* evidently possesses a greater capacity to reorient the user.

Our approach is derived from the observation that in common VR applications, users tend to turn their heads while walking. When users explore the VE, especially an unfamiliar or new environment, their walking usually involves many rotational motion elements in addition to the forward motion component, such as head turns. This kind of head-turning to one side is usually followed by a reciprocating movement to turn their head back to their steering direction. If different rotation gains are applied when the user turns their head away and when they turn their head back, the user's physical orientation will change when the user turns back to their original virtual orientation. This can be used to redirect the user to a better physical orientation. We propose to apply different rotation gains in different directions, and use the bidirectional rotation gain difference to redirect users during their reciprocating head turns while walking. However, the rotation gain detection threshold measured in previous studies might surpass the detection threshold of the user for this specific purpose. First, conventional rotation gain only considers whether the user can perceive the remapping of angular velocity during the rotation process. It does not, however, consider the allowable difference of the gains applied to the adjacent rotation processes in different directions during reciprocating head movement. Therefore, when the user performs rapid reciprocating head turns, the large and high-frequency change of the gain may still be perceived by the user and may cause unnecessary sickness. Secondly, previous measurements of the rotation gain detection thresholds are usually conducted when the user is in a seated or standing position, but whether this detection threshold applies to reciprocating head turns during walking is unclear. Considering the difference between the head rotation during walking and the body rotation in situ, further investigation into rotation gain under these new conditions is warranted, as well as an exploration of how users perceive it.

It is worth noting that some previous RDW controllers may also contain strategies that apply different rotation gain values for different rotation directions. For instance, Thomas *et al.*'s (Push/Pull Reactive) P2R method chooses to use either the maximum or minimum rotation gain based on the user's rotation direction and the direction of the artificial potential field gradient [48]. However, these strategies are essentially different from our BiRD concept. **First**, previous RDW controllers did not distinguish whether the user's rotations are one-way rotations or reciprocating head turns. Thus, while they recommend different rotation gains for different directions, users may not experience both gain values over a brief time period unless they are engaged in reciprocating head movements. However, when the user is doing rapid reciprocating head turns, the high-frequency switching between rotation gains will be easier for the user to notice. Furthermore, previous RDW controllers only consider employing the existing gain range to reduce the number of resets, but do not consider the user's experience when the rotation gain changes for different directions. **Second**, previous RDW controllers did not distinguish whether rotation gain would be applied when the user is walking or rotating in place. Based on our observations, in simulation experiments, rotation gain is usually employed when the user is rotating in place; while in user experiments, the user's task generally is to walk directly towards given targets in a straight line without the need to turn their head left and right. Hence, the effect of rotation gain on frequent reciprocating head turning during walking remains to be studied.

In this paper, we introduce and evaluate a special implementation of rotation gains based on Bidirectional Rotation gain Difference (BiRD), which assigns different rotation remapping ratios to the bidirectional head turns during walking, thereby modifying users' walking direction in the physical environment (PE), as shown in Fig. 1. We conduct both measurement and verification experiments on the detection thresholds of the rotation gain difference for the reciprocating head rotations during walking. Compared to previous rotation gains, BiRD is measured during users' walking, rather than turning around in place (like standing or sitting [58]). In addition, BiRD mainly focuses on the bidirectional difference of the rotation gain in a reciprocating head rotation, instead of measuring the rotation gain detection threshold under constant mapping ratios, so as to redirect the user's physical direction with these head rotations during their walking. Our study offers a critical assessment of the acceptable range of rotational mapping differences for different rotational directions across the user's walking experience, contributing to an effective tool for redirecting users in VEs.

Our experiment results demonstrate that by applying rotation gains on the reciprocating head rotation during walking, we can steer the user imperceptibly and effectively. It suggests that BiRD has the potential to improve user navigation experiences in VR systems. It is worth noting that the proposed BiRD is different from curvature gain or bending gain. Although they all rotate the scene during the user's walking, curvature gain and bending gain only gradually adjust the virtual scene to change the user's trajectory; while BiRD can provide a direction change during the user's walking when the user rotates their head. By incorporating BiRD, it is possible to develop more effective redirection toolkits for users, reducing the number of resets.

2 Related Work

In the development of RDW technology, a lot of effort has been invested in exploring technologies that can help VR users make the most of limited physical space. Our study on the concept and application of BiRD, which redirects users in VEs by assigning different gain values to different rotation directions, is built upon previous research on gains and RDW algorithms; and hence strictly follows the relevant concepts of detection thresholds and its respective estimation methods.

2.1 Gains in Redirected Walking

The human body has evolved such that it has ability to maintain stable vision despite perturbations resulting from head/body rotations and/or movements [14]. Specifically, research has shown that despite inconsistencies between the perspective of a physical head movement and of an observed virtual movement, the environment is often still perceived as stable [18].

By exploiting such properties of the perceptual system, RDW is able to inconspicuously alter the ratio between real and virtual world movements using gains, allowing users to explore a wide VE within a limited PE. Common gain types include *translation gain*, *rotation gain*, and *curvature gain* [45]. Translation gain [17, 22] scales distance by adjusting the ratio between the user's virtual and physical speeds during walking. Similarly, rotation gain [16, 35, 40, 54] scales the angle by adjusting the ratio between virtual and physical angular velocity as the user turns. Curvature gain [32, 38] slowly rotates the virtual space frame by frame when the user is walking, causing the user to walk along a curve in physical space while walking straight in the virtual space. In recent years, some new types of gains have also emerged, such as bending gain [23, 39], jumping gain [29] and strafing gain [57]. The successful application of these gains allows VR users to explore larger VEs through natural walking without the need for additional input devices [12, 27, 34].

To reduce the obstruction of the user by obstacles, it is important to subtly adjust the physical orientation of users. Among the many types of gains, rotation gain can adjust the scaling between virtual and real world rotations [45]. Specifically, if the magnitude of the rotation gain is greater or less than 1.0, it signifies an increase or reduction on the amount of the virtual rotation that would be perceived by a user respective to their physical rotation in the real world. It is worth noting that measurement studies of rotation gain are conventionally conducted with subjects rotating whilst standing or sitting still in one spot and at constant gain values [4, 5, 50, 54, 58].

2.2 Detection Threshold Measurement of Gains

The detection thresholds of gains represent the extent to which the RDW controller can subtly alter the virtual world without the user noticing [36]. Steinicke *et al.* [45] adopted an iconic estimation technique in psychometric analysis which utilizes constant stimuli within a 2-alternatives-forced-choice (2AFC) task to measure detection thresholds [21]. In such a method, it is necessary to ensure that the sequence of the tested gain values are completely randomized whilst maintaining uniform distribution.

In a 2AFC task, users must choose one of the two given answers. To avoid bias towards choosing 'no' due to low-confidence in 'yes' or 'no' questions [28], questions are best tailored in the form: "Was the virtual movement smaller or larger than the physical movement?" so that users would choose from "Smaller" and "Larger" instead. The brilliance of this method is that since users are forced to choose from what is given, when they are unable to distinguish an answer and make a guess, they average to be correct in half of these trials.

After tallying the number of times users responded with "Larger", these results can be fitted into a psychometric function. The magnitude of gain at which participants answer "Larger" in half of the trials is noted as the point of subjective equality (PSE), i.e. users regard the physical and virtual movements as identical. However, due to the nature of psycho-physical experiments, the actual bounds of the detection threshold are stipulated by two other markers, the 25% mark and the 75% mark. Thus the detection thresholds would be the gain values when users had a 75% and 25% probability of answering "Larger". For gain values with chances of "Larger" responses higher than 75% or lower than 25%, it implied that most people would detect the existence of the gain. By adopting the 2AFC task and related analysis techniques, we aim to determine the acceptable range of BiRD that can be applied for users.

2.3 Reactive RDW Algorithms

While gains play a vital role in RDW controllers to remap virtual and physical movements, RDW algorithms combine and apply these gains in specific situations at various magnitudes to create a seamless interaction. Suma *et al.* [47] classified RDW methods into *overt* and *subtle* categories, depending on the perceptibility of the changes triggered by the method. Later on, Nilsson *et al.* [34] subdivided the controllers into four groups: *resetting*, *scripted*, *predictive*, and *reactive*. Here we mainly focus on reactive RDW methods, as they offer dynamic redirection based on the user's real-time state and are widely used.

Razzaque *et al.* [36] proposed three heuristic reactive algorithms, namely steer-to-center (S2C), steer-to-orbit (S2O) and steer-to-multiple-targets (S2MT). Hodgson *et al.* [15] proposed Steer-to-Multiple+Center. The idea of these methods is mainly to redirect users to predefined "safe" locations in the physical space. Utilizing artificial forces associated with the user positions and the PE layouts to redirect users is an effective way to avoid physical collisions. Li *et al.*'s method [26] utilized skeleton graph mapping to navigate users. Bachmann *et al.* [2] proposed to use artificial potential fields to push users away from obstacles and other users. Thomas *et al.* [48] proposed the Push/Pull Reactive (P2R), which pushes users away from obstacles and pulls users towards targets. Messinger *et al.* [30] subdivided the obstacle boundaries into smaller segments, with the force applied at the centre of each. Dong *et al.* [8] focused on prioritizing users based on the sum of the repulsion portion to reduce collision numbers. Another prevalent thought is to redirect users to align the PE and VE to avoid physical collisions. Thomas *et al.*'s [49] reactive environmental alignment method transitions the coordinate systems of the PE and VE from a misaligned state to an aligned state. Williams *et al.*proposed to align PE and VE based on distances to obstacles [52] and visibility polygons [53]. Reinforcement learning (RL) can also be used to design RDW controllers. Lee *et al.*leverages RL to calculate the optimal steering target for single and multiple users [24, 25]. Strauss *et al.* [46] utilizes RL to directly ascertain the optimal gain values to redirect users. Chang *et al.* [6] also harnessed the power of planning and versatility of RL to recommend gain values. Chen *et al.* [7] and Wang *et al.* [51] later combined RL with reactive alignment to provide users with passive haptic feedback when users interact with specific aligned objects.

With the diversification of VR applications, RDW techniques have gradually transitioned their attention from single-person experiences to multi-user interactions and specific scenarios. Bachmann *et al.* [3] and Azmandian *et al.* [1] proposed methods to prevent user collisions for two-user scenarios. For multi-user applications, researchers have introduced methods based on dynamic density [10], optimal space partitioning [19], and other strategies [9, 11] to avoid user collisions. There are also multi-user RDW methods that focus on the fairness issues in online multi-player VR games [55], and equalize the reset counts for users located in different PEs. For user comfort, POI-Aware RDW strategy [56] can ensure that resets occur far away from virtual targets whilst the number of resets are also minimized.

The above RDW methods generally involve strategies that assign different rotation gains to different user turning directions. In the simulation designs of these RDW methods, since simulated users typically walk in straight lines, rotation gain is only activated when the simulated user is spinning in place. In the user experiment scenarios of these RDW methods, participants are often instructed to traverse straight towards designated way-points, without the need to repeatedly turn their heads back and forth. However, such back-and-forth movement is common when users are naturally exploring unfamiliar environments. Regarding situations where rotations in two directions occur in succession, there is a lack of research examining whether users can perceive the differences in rotation gains under the current rotation gain thresholds, and whether these thresholds might cause user discomfort when applying the above methods.

3 Bidirectional Rotation Gain Difference

Our work presents BiRD, a novel rotation gain concept that assigns different gain values to the bidirectional head turns during walking and leverages the head movements in walking to modify the user's orientation in physical space.

Conventionally, the detection thresholds for rotation gain are measured with the participant either standing or sitting in place whilst a constant rotation gain is applied for each trial, as exhibited in studies [4, 5, 45, 50, 54, 58]. However, in actual VR applications, users will also frequently engage in cyclic head rotation movements to observe the surrounding environment, thereby inevitably triggering rotation gain. The concluded detection thresholds from the existing measurement experiments may be not appropriate for steering the user during walking.

Different from the conventional rotation gain, BiRD works by assigning different rotation remapping ratios to users' bidirectional head turns during walking, thereby modifying their walking direction in the PE. When users walk in the VR environment, they naturally look left and right to build a mental map of their surroundings. This instinctive behavior helps with the reorientation of users. We propose to apply a slight increase or decrease on their rotation mapping ratio when they return their head to their forward orientation during walking. These subtle changes prompt users to instinctively try to correct the discrepancies between their physical forward orientation and the orientation pointing to the original forward content in the VR environment, achieving the goal of orientation redirection. We define BiRD as follows:

$$BiRD = \frac{R_{back}}{R_{away}} \quad (1)$$

where R_{away} is the rotation gain when the user turns his head outward, and R_{back} is the rotation gain when the user turns back. We use their ratio to represent their difference. It's worth noting that BiRD is supposed to be applied to back-and-forth head turns, where the turns in two directions occur in succession. When BiRD equals 1.0, it indicates that there's no difference in the rotation gain when the user turns his head in both directions, meaning the user is under a constant

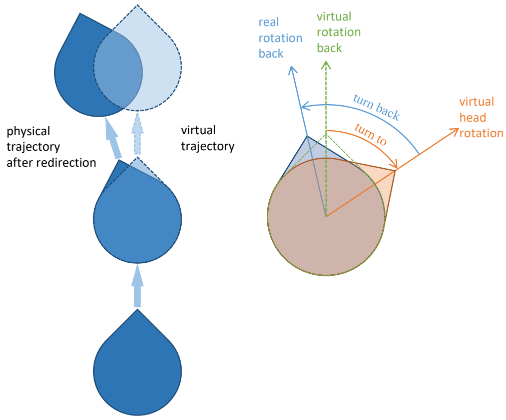

Fig. 2: Basic idea of BiRD. **Left:** Comparison of user's physical trajectory after redirection and their virtual trajectory using a BiRD gain smaller than 1.0. **Right:** Comparison of real and virtual rotation angles under a BiRD gain smaller than 1.0.

rotation gain. When BiRD does not equal 1.0, it is possible to change the physical direction through the user's back-and-forth head turnings. For instance, if a user turns their head to the *right* and we apply a BiRD less than 1.0 during their return rotation, they will over-rotate physically when turning back to their original virtual orientation. If the gain change happens unnoticed, the user's physical orientation will be redirected to the *left* as a result, as depicted in Fig.2 (Right). The contrast between the redirected virtual path and the resulting physical path is demonstrated in Fig.2 (Left). In contrast, applying a BiRD greater than 1.0 during the user's returning rotation would redirect the user to the *right*. We opted to use a ratio instead of a subtraction difference to represent the bidirectional difference in rotation gain, mainly because it simplifies the calculation of redirected angles. Consider a head turning action for observation during walking, where the user first turns their head to one side and subsequently turns back to the original direction. Suppose the user's rotation angle in the virtual space is α^V, the angle turned away in the physical space is α^P_{away} and the angle turned back is α^P_{back}, then based on the definition of the rotation gain, we have:

$$BiRD = \frac{R_{back}}{R_{away}} = \frac{\alpha^V/\alpha^P_{away}}{\alpha^V/\alpha^P_{back}} = \frac{\alpha^P_{back}}{\alpha^P_{away}} \tag{2}$$

Consequently, by simply multiplying the angle of turning away in the physical space by the employed BiRD, we can compute the angle of turning back in the physical space. Our objective is to measure the range of BiRD that users can accept. Due to the non-linearity in human perception of gain, the detection threshold of BiRD is evidently related to the value of R_{away}. Therefore, when discussing the threshold of BiRD, we annotate R_{away} as a subscript to indicate that the detection threshold is measured relative to a specific R_{away}. For example, when $R_{away} = 1.0$, we refer to the detection thresholds of BiRD as $BiRD|_{1.0}$.

We first investigate whether users can perceive the differences in conventional rotation gains in sequential head rotation movements under the current gain thresholds, and whether these thresholds cause discomfort. We conducted preliminary experiments (see Section 4) employing a typical RDW method, Thomas's P2R [48], as the RDW controller to validate this. It should be noted that P2R switches between the maximum and minimum allowable rotation gains depending on the relationship between the user's direction of rotation and the gradient of the potential function at the user's position. This could lead to frequent switches in rotation gain while the user turns their head for looking during walking. We then perform a measurement study (see Section 5) on the detection thresholds of BiRD, where we apply varying values of rotation gain on users as they perform reciprocating head turns in different directions while walking. We finally verify the detection thresholds of BiRD in a verification study (see Section 6).

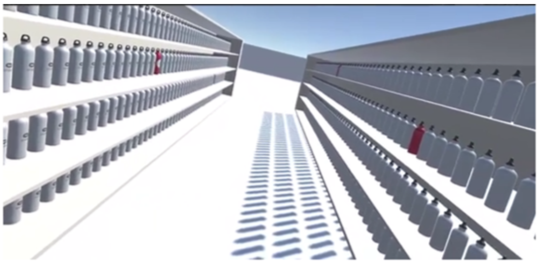

Fig. 3: Virtual scene utilized for pilot experiment.

4 Preliminary Studies

4.1 Pilot Experiment on Rotation Angles

Our work aims to determine the detection thresholds of BiRD, ensuring that we utilize the feasible degree of manipulation difference of bidirectional head rotation that users find comfortable. However, verifying whether users turn their heads while walking is a prerequisite for our BiRD. Therefore, our initial step was to quantify the natural magnitude of head rotation that people commonly undertake while walking. To achieve this, we conducted a straightforward pilot test.

Participants wore the Oculus Quest 2 head-mounted device and were immersed in a virtual supermarket aisle, as displayed in Fig. 3. This environment allowed them to walk along a relatively straight path and freely rotate their heads left and right. The pilot test involved five participants, with two males and three females, averaging an age of 21.8. All participants were right-hand dominant. Their task was to walk down a 7-meter long, 1.5-meter wide aisle 4 times (equivalent to a total of 28 meters in distance) as if they were visiting a supermarket, with no requirements asking them to turn their heads. The headset recorded the magnitude of their head rotations. Participants were not given any specific requirements or limitations regarding head rotations.

On average, each participant rotated their head 8.0 times during the test. To ensure that the rotations occurred during user walking, we only recorded rotations that were conducted whilst the user had a physical moving speed greater than $0.2m/s$. The observed rotation angles covered a wide range, spanning from 24° to 79°. The individual averages for rotation varied between 45° and 67°. In summary, the overall natural magnitude of head rotation while walking averaged around 53°.

4.2 Hypothesis on Detection Threshold Measurement

We hypothesized that the detection thresholds of rotation gains measured in situ and under constant stimulus condition might exceed the average user's detection threshold in a scenario involving walking and reciprocal head turning. To test this hypothesis, we designed an experiment to investigate whether utilizing rotation gains within the conventional detection thresholds leads to excessive discomfort when users are walking and making reciprocating head turns. In this experiment, participants are guided to walk and rotate their heads to observe salient objects. We utilized a commonly-used RDW controller to control the application of rotation gain. Specifically, we adopt the P2R method proposed in [48] to redirect the user in our experiment. We employ the detection thresholds used in the original P2R method (0.67 and 1.24) to apply the rotation gain. To exclude the influence of other gains on users, other gains output by the P2R method were not used to redirect users. We made a distinct change in our experiment compared to most previous user experiments with P2R: we intentionally incorporated various head-turning actions during users' walking. In contrast, earlier studies primarily only set clear targets directly ahead, leading users to rarely turn their heads while walking and only rotate in place upon reaching the target. To assess the appropriateness of the rotation gains, we measure whether the user's Simulator Sickness Questionnaire (SSQ) shows a significant increase after each trial.

4.2.1 Experiment Design

We constructed a virtual scene using Unity3D and employed the

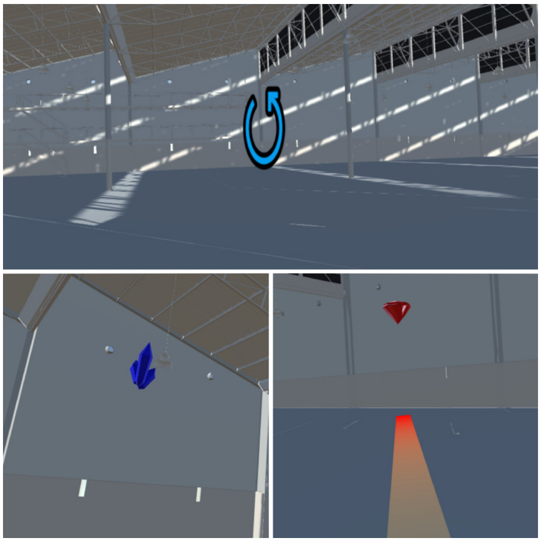

Fig. 4: Game objects utilized in the virtual scene.

Oculus Quest 2 headset as the HMD device for the experiment. Instead of the supermarket aisle, we utilized a "vacant warehouse" as our virtual scene in this experiment. This expansive virtual scene can provide users with greater freedom of movement. Participants commenced their journey at the central point of both the physical and virtual settings.

In this task, participants were tasked with advancing towards a recurring red diamond that appeared randomly between 2 to 6 meters away from them and at a random angle between $-\pi$ and π. Upon reaching the target, a new one would appear for them to pursue. Complementing this, blue crystals were occasionally positioned on either side of the pathway guiding the user to the red diamond, prompting users to periodically glance left and right as they moved. When a user spotted a crystal, it vanished, and a new one emerged. The task involved traversing 60 meters within the virtual space.

Participants completed the experiment in a tracked area of $5m \times 5m$, which is of course much smaller than our VE of $20m \times 20m$. Hence, to prevent users from stepping outside physical boundaries, we implemented [48]'s Reset to Gradient (R2G) reset method. When users were within proximity of the boundary, a 'reset sign' would appear, prompting the user to pivot in place until the sign disappeared. Consequently, by the end of this realignment process, the participant would be oriented in a direction conducive to safe navigation.

During each trial, we used the rotation gain output by the P2R method that adhered to the detection threshold (ranging from 0.67 to 1.24) to steer users during walking. Specifically, as users turned their heads to observe the target objects while walking, a rotation gain of either 0.67 or 1.24 was employed to map their physical rotation angle onto the virtual space, depending on the relationship between the rotation direction and the negative gradient of the potential function at the user's position. Notably, given that a rotation of the head is often consistently followed by a return rotation, the alternating of these two successive rotations induced gain changes between 0.67 and 1.24.

Before commencing the experiment, participants were required to complete an information form, providing essential information such as age, gender, VR experience, handedness, vision. Subsequently, we introduced the task to the participants, illustrating images of the game objects: reset sign, diamond, and crystal (refer to Fig. 4) that would be encountered during the trial. Before the trial, participants were asked to fill out the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [20]. After completing the task, participants were asked to fill out the SSQ again.

4.2.2 Results.

A total of 17 subjects participated in this study, of which seven were male and ten were female. The participants were between 19 and 28 years of age, with a mean age of 23 and a median age of 24, and all had normal or corrected normal vision. All 17 users who participated in this study are distinct from those in the pilot experiment (Section 4.1). Prior to the experiment, five participants had never experienced VR, 11 had experienced some VR before, and one had multiple VR experiences. All but one subject were right-hand dominant.

SSQ data were collected both before and after each trial to assess the increase in motion sickness. The results (as shown in Fig.7 "Traditional") revealed a significant increase in SSQ scores, with a median of 18.7 when the conventional rotation gain detection threshold was applied in our experiment. According to [43], the SSQ total score of this experiment surpasses the threshold for negligible symptoms (5.0) by a considerable margin. A Mann-Whitney U test indicated that there was no statistically significant difference between the SSQ score increases of the two genders ($p = 0.62 > 0.05$).

4.3 Study on Rotation Gain Transition

In the aforementioned experiment, we observed that the sharp increase in SSQ scores might be attributed to abrupt transitions between the maximum and minimum rotation gain thresholds. We conducted a supplementary study to assess whether implementing smoothing during gain changes could mitigate the fluctuation in SSQ scores following a VR experience.

4.3.1 Experiment Design

To control variables, all factors of this supplementary study were made consistent with that of the previous experiment in Section 4.2. The only feature that was changed was that a 20° range of smoothing was employed when switching between the rotation gains of 0.67 and 1.24. Specifically, the smoothing effect employs a Sigmoid function to gradually adjust the gain value to the target value within a 20° range. When the user's rotation angle is less than 20°, the rotation gain might not reach the maximum or minimum threshold by the end of the rotation due to the smoothing.

4.3.2 Results

We recruited the same participants as the experiment in Section 4.2. To assess motion sickness increases, we once again employed the SSQ to collect data both before and after each trial. The results (depicted in Fig.7 "Traditional+smoothed") once again revealed a significant increase in SSQ scores, with a median of 16.83 when Steinicke's threshold with a 20-degree angle smoothing was applied. The SSQ increases of this experiment also surpass the threshold for negligible symptoms (5.0) [43] by a considerable margin, i.e. the symptoms felt by the participants are concerning. A Mann-Whitney U test also indicated that there was no statistically significant difference between the SSQ score increases of the two genders ($p = 0.17 > 0.05$).

We also compared our results from the previous experiment in Section 4.2 and this supplementary study. It became evident by a Kolmogorov-Smirnov test that neither data followed a normal distribution ($p < 0.05$). Subsequently, a Mann-Whitney U test indicated no statistically significant difference ($p = 0.39 > 0.05$) between the two applications of the traditional rotation gain threshold.

4.4 Discussion

In the experiments mentioned above, although the rotation gains we applied were within the allowable range determined from previous detection threshold measurement studies, frequent head rotations during walking still significantly affected users, resulting in heightened discomfort. Furthermore, attempting to smooth the transition between rotation gains when changing directions did not alleviate this discomfort. This is primarily because users can detect excessive changes in rotation gain values over a brief time period, which cannot be addressed by smoothing. These findings support our hypothesis that the detection thresholds for rotation gain derived from previous measurement studies would exceed the average user's detection threshold for scenarios where users may frequently turn their heads while walking.

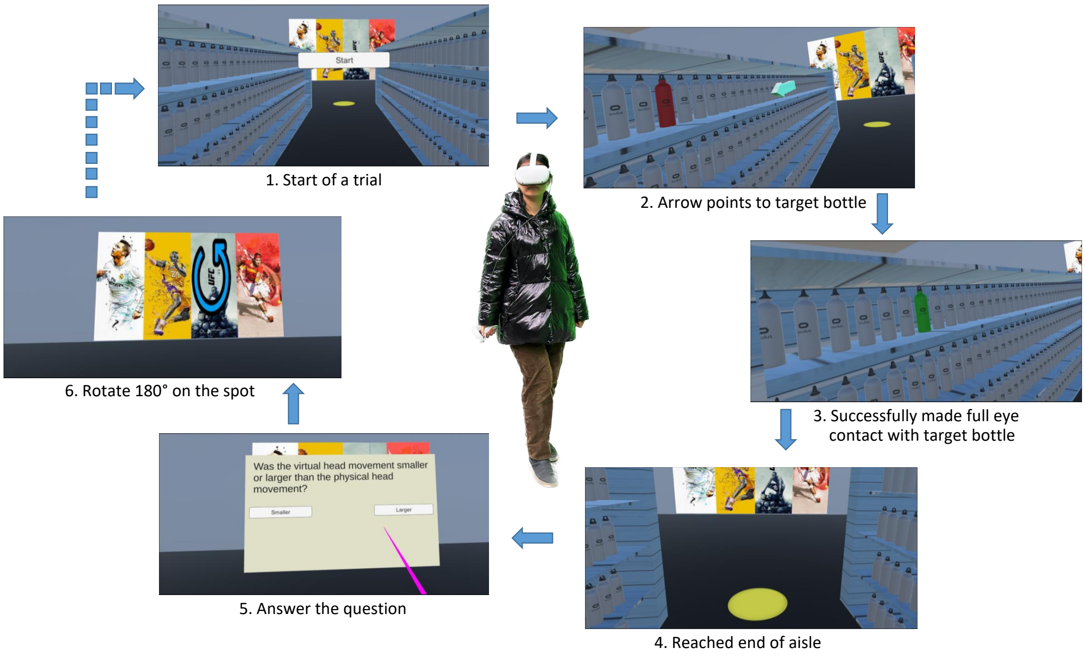

Fig. 5: First person view of the procedure of a trial in the measurement study.

5 Measurement Study

Building upon the findings of the preliminary studies, a new measurement study is needed to investigate the detection thresholds of BiRD. BiRD focuses on the largest bidirectional difference in rotation gain for successive head turns during walking. We undertake a comprehensive experiment aimed at assessing the imperceptible range of rotation gains when users execute bidirectional head rotations while walking.

5.1 Experiment Design

We constructed a VE resembling the setting of our preliminary experiments in Section 4.1, which is a supermarket aisle. The aisle has a length of 7 meters and a width of 1.5 meters. Both its dimensions and appearance are designed to closely mimic a real-world supermarket aisle, effectively replicating the experience of people walking between the shelves in an actual supermarket. The reason for using the supermarket aisle scene for the measurement experiment is that it is a place that we frequently visit in daily life and is natural for users to rotate their head left and right.

In the experiment, participants walked through the 7-meter aisle lined with white sports water bottles on both sides. Following a mint-colored arrow, they directed their gaze towards a red target bottle. Once the target bottle was centered in their field of vision, it automatically turned green. Then participants were supposed to shift their gaze back to the front. Based on the data obtained from the pilot test, the timing of the arrow's appearance was adjusted to enable participants to 'hit' the target bottle with a head rotation of approximately 50° to 60°. Based on the user's head-turning direction, we applied a rotation gain R_{back} to the returning head rotation after participants spotted the target bottle, which was different from the rotation gain R_{away} that was applied when participants initially turned towards the bottle. It should be noted that in our experiment we do not detect and predict reciprocating head turns from one-way rotations. Instead, we identify a user's rotation as a reciprocating head turn if the rotation to one side is quickly followed by a reciprocating movement to turn their head back. After locating all target bottles and reaching the aisle end, participants responded to a 2AFC question comparing the virtual angular velocity during their return turn process to that of their initial turn process towards the bottle: "Was the virtual head movement smaller or larger than the physical head movement?". Using the Oculus Quest 2's controller, participants selected either "Smaller" or "Larger" as their response. It was emphasized to the subjects that they should provide their best guess for an answer even if they were unable to accurately discern the stimuli. Moreover, since only one Quest controller was necessary to do the choice, participants had the flexibility to choose either the left or right Quest controller to use before the experiment based on their habit and handedness. Due to space limitations, we reset the participants to face the opposite direction after each trial (no rotation gain applied in the resetting process), so as to allow them to walk through the aisle again. A comprehensive visual representation of a trial within the study is provided in Fig. 5.

To avoid the complexity arising from simultaneous changes in R_{away} and R_{back}, we chose to fix R_{away} while varying R_{back} to determine how much R_{back} can change relative to R_{away}. In this study, we set R_{away} to 1.0. This decision was made because 1.0 is a centered gain value, allowing R_{back} to be either greater or less than R_{away}. Utilizing $R_{away} = 1.0$ instead of other biased gain values in this study helps reflect more general pattern regarding BiRD. A total of 15 values of BiRD, with increments of ± 0.05, were tested: 0.70, 0.75, 0.80, 0.85, 0.90, 0.95, 1.00, 1.05, 1.10, 1.15, 1.20, 1.25, 1.30, 1.35, and 1.40. They were tested in random order and repeated four times. Values less than 1.0 indicate that users would experience slower virtual movements when turning their head back than when turning away. Conversely, values greater than 1.0 imply that users would encounter faster virtual movements when turning their head back. When BiRD is set to 1.0, it means that the rotation gain applied when turning head back is the same as when turning head away, and because $R_{away} = 1.0$ in our experiment, no redirection is actually applied in this case. While we hypothesize that changes in R_{away} might influence the threshold of BiRD, the potential effects of R_{away} on BiRD could be a subject for future exploration.

Before the experiment, participants would fill out an information form that collects their basic information as in the Section 4.2, and receive a detailed briefing about their task in the experiment. Participants were instructed to keenly observe the changes in rotation speed that might occur before and after a head turn during walking. We adjusted the lens spacing on the headset for each participant according to their Inter-Pupillary Distance. To ensure a complete understanding of the task and the 2AFC question posed, participants were exposed to BiRD values of 1.0, 1.4, and 0.7 during the practice trials at the beginning. The selection of these two extreme values aimed to provide participants

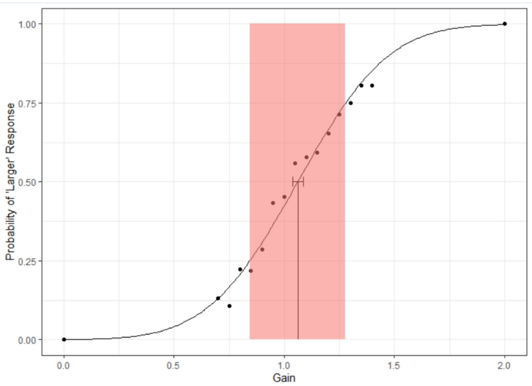

Fig. 6: Psychometric curve fit to our 2AFC data. The x-axis refers to the BiRD value utilized, whilst the y-axis represents the proportion of users that selected "Larger". The red interval highlights the range between the 25% threshold ($\text{BiRD}|_{1.0}$ = 0.84) and the 75% threshold ($\text{BiRD}|_{1.0}$ = 1.28), within which the BiRD values are considered imperceptible to users.

with a clearer sense of what comparatively smaller and larger gain difference would feel like. We made sure that each participant had a full apprehension of the task, question, as well as the meaning of its respective options before officially starting the experiment. Participants initiated the experiment by completing a SSQ. Each participant completed a total of $15 \times 4 = 60$ trials. We mandate participants to take a 10-minute break after completing half of the trials to mitigate the impact of user fatigue on the experiment. Participants were instructed to complete two additional SSQs during their break and at the end of the experiment. The entire experiment took approximately 70 minutes for each participant.

5.2 Results

5.2.1 Participants.

Participants comprised students recruited from both on-campus and off-campus locations. A total of 21 subjects were enrolled in our study, with 7 females and 14 males. The participants' ages ranged from 18 to 28 years, with a mean of 22.1 and median age of 22.0; all had normal or corrected normal vision. Out of the 21 subjects who participated in this study, only one overlapped with those who took part in our hypothesis experiment (Section 4.2). Prior to the experiment, 5 participants had no prior VR experience, 14 had some VR experience, and 2 had multiple VR experiences. All subjects were right-handed.

5.2.2 Detection Thresholds.

We fitted the likelihood of participants selecting "Larger" based on the data collected in the 2AFC task. Given that our task involved a binary response variable and a stimulus level [28], we opted to utilize a psychometric function, a widely employed and well-established psychological model. The function takes the following form:

$$\psi(x;\alpha,\beta,\gamma,\lambda) = \gamma + (1-\gamma-\lambda)F(x;\alpha,\beta) \tag{3}$$

F represents a continuous function with left and right asymptotes at 0 and 1, respectively, while γ and λ are utilized to adjust the positioning of the left and right asymptotes. Here, we utilized the cumulative normal function as F in our analysis, which takes the following form:

$$F(x;\alpha,\beta) = \frac{\beta}{\sqrt{2\pi}}\int_{-\infty}^{x} exp(\frac{-\beta^2(x-\alpha)^2}{2}) \tag{4}$$

The R package *quickpsy* [28] was employed to fit the psychometric function. The fitted curve is illustrated in Fig. 6. The curve demonstrated a goodness of fit with $p = 0.86$.

According to the fitted curve, the values of the thresholds are as follows:

25% : 0.84 PSE : 1.06 75% : 1.28

With a PSE slightly greater than 1.0 and a 75% threshold larger than the 25% threshold by ratio as manifested in the psychometric function, the results suggest that $BiRD|_{1.0} > 1.0$ tends to be less detectable than a $BiRD|_{1.0} < 1.0$. A Mann-Whitney U test also indicated that there was no statistically significant difference between the results of the two genders: $p = 0.13 > 0.05$ for the 25% threshold, $p = 0.78 > 0.05$ for the PSE and $p = 0.16 > 0.05$ for the 75% threshold.

5.2.3 Simulator Sickness Questionnaire.

The standard SSQ was sent to participants before the experiment, during their break, and after the experiment, allowing us to assess the practical impact of BiRD on users' experience. The mean scores and Total Symptom (TS) scores were as follows: 3.29 and 6.36 before the experiment, 12.07 and 19.75 during the break, and 17.94 and 29.99 after completing the entire experiment. A paired-samples t-test ($T = -4.19, p < 0.0002$ for TS score; $T = -3.86, p < 0.0005$ for mean score) demonstrated a significant relationship between the score increase and the completion of the experiment. This phenomenon is not unexpected, as it is also observed in other gain threshold experiments [13, 57]. This is primarily because users experienced some BiRD values that exceeded the detection threshold during the measurement. This also indicates that the range of BiRD values chosen for the study encompasses the users' detection threshold range.

5.3 Discussion

Our results indicate that participants were unable to discern applications of $\text{BiRD}|_{1.0}$ between magnitudes of 0.84 and 1.28. Taking into account the customary head-turning angles we measured, on average BiRD is able to redirect users' physical orientation by approximately -8.8° or +15.4°.

Compared to the detection threshold of 0.67 to 1.24 for conventional rotation gain [45], the detection range for BiRD is smaller. This is mainly due to the differing gain application manner. The conventional rotation gain study employed constant gain stimulus throughout each trial. However, BiRD intermittently applies different rotation gain values for different rotation directions. This intermittence increases the likelihood of gain detection, contributing to the observed narrower range in our study. This observation is further corroborated by the SSQ scores. The SSQ scores from participants in our experiment are slightly lower than those in some previous studies [50, 57]. As our gain is applied only briefly compared to studies where gain is consistently applied throughout, it would logically cause less impact on the user.

Compared to the seated rotation gain, which has a detection threshold range between 0.89 and 1.28 as reported by [50], our BiRD's detection range is relatively similar. This is most likely due to the fact that in our study, subjects are in motion and additional perturbations can disrupt their perception of rotation gains. This is consistent with the findings from [50], that the standing rotation gain also demonstrates a broader detection threshold range than seated rotation gain.

Due to the bidirectional difference of gain in BiRD, BiRD offers some features that might not be found in a constant gain stimulus. When the user turns their head back and forth during walking, BiRD can subtly modify the user's physical direction. However, although a constant rotation gain stimulus can adjust the user's virtual angular velocity to a larger degree, the physical direction will remain unchanged if the user returns to their original virtual direction.

Lastly, we want to emphasize that our findings regarding BiRD do not impact the traditional use of rotation gain. In past studies, rotation gain was primarily used for tasks where users would change their target points or directions; operations involving users swiveling their heads back and forth while walking were less common in user experiments. This kind of action might occur more frequently during a free exploration process in an unfamiliar VR space. However, our observations with BiRD suggest that when applying varying rotation gains for different directions during walking, the bidirectional difference of gains should be controlled within a range smaller than the conventional rotation gain's detection threshold to prevent users from VR motion sickness. In practice, BiRD is easy to implement: we simply need to

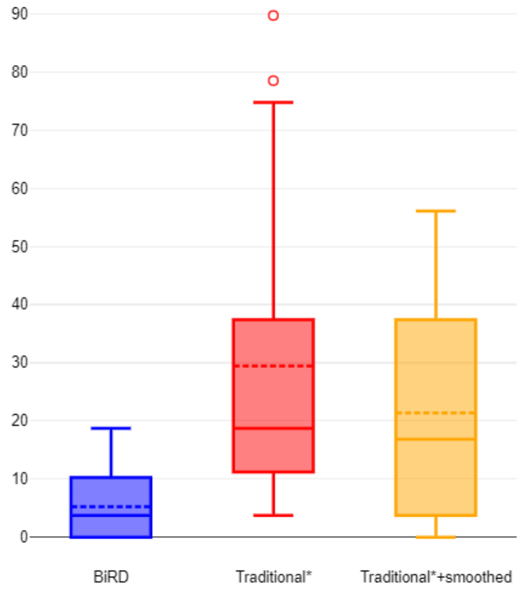

Fig. 7: A box and whiskers plot was employed to compare the increase in the total SSQ score resulting from the utilization of BiRD, Steinicke's threshold, and Steinicke's threshold with a 20-degree smoothing. In this plot, the solid line represents the median, the boxes symbolize the interquartile range, and the dotted line depicts the mean. *Notably, the term 'traditional' pertains to Steinicke's rotation gain threshold (0.67-1.24), which was employed in P2R [48].

calculate the movement speed of the headset to determine whether the user is walking, and then select an appropriate range for rotation gain.

6 Verification Study

After conducting the measurement study and determining detection thresholds for $\text{BiRD}|_{1.0}$, we validate those values in a final verification experiment. In this experiment, we tested whether the application of rotation gain within $\text{BiRD}|_{1.0}$'s detection thresholds would cause a significant amount of simulator sickness for users during a VR experience. We also use the P2R method as our RDW controller.

6.1 Experiment

To validate our experiment, we opted to compare the SSQ results of the preliminary experiments in Sections 4.2 and 4.3. To achieve this, we maintained the same virtual scene and user task. The sole modification was the selection of rotation gain values. Based on the measurement study of $\text{BiRD}|_{1.0}$, we identified that there are at least two mapping ratio ranges of rotation gain values that can be applied to reciprocating head turns during walking: a smaller ratio range spanning from 0.84 to 1.0 and a larger ratio range from 1.0 to 1.28. Consequently, we randomly chose a pair of gain values from these two ranges for utilization whenever head rotation occurred during walking.

Participants. Our goal was to compare the SSQ results from applying BiRD's detection thresholds, Steinicke *et al.*'s detection thresholds, and Steinicke *et al.*'s detection thresholds with transition smoothing. To control variables, we reenlisted the same participants who had taken part in our preliminary experiments in Section 4.2.

Simulator Sickness Questionnaire Results. The mean SSQ score of applying BiRD's mapping ratio ranges for head turns during walking had a median of 3.74. This median suggests a negligible level of sickness symptoms attributable to the application of BiRD [43]. A Mann-Whitney U test indicated that there was no statistically significant difference between the results of the two genders ($p = 0.34 > 0.05$). We conducted a Kolmogorov-Smirnov test and found that the resulting SSQ were not normally distributed. To compare the SSQ results with those from Section 4.2 and Section 4.3, we then conducted a Kruskal-Wallis H test. The Kruskal-Wallis H-test revealed a significant difference ($H = 11.90, p = 0.003$) among the results. Furthermore, post-hoc pairwise comparison Mann-Whitney U tests indicated significant differences between our method results and the two comparison methods results ($p = 0.001$ for "traditional" and $p = 0.023$ for "traditional+smoothed"). A graphical representation of the SSQ results from all three studies is presented in Fig.7.

6.2 Discussion

The results from our study support the idea that implementation of the P2R method with BiRD does not lead to excessive discomfort during VR experiences. This verifies our investigation into BiRD as well as the practicality of BiRD when utilized in RDW methods.

7 Limitations and Future Work

Our work has some limitations and possible future work. One drawback is the unexplored potential influence of ambulation speed on BiRD's detection thresholds. While we did not enforce any specific walking speed for our participants, different walking speeds may indeed affect the detection thresholds. Previous research has indicated a negative correlation between walking speed and gain thresholds [31,33]. Therefore, the impact of ambulation speed on BiRD's detection threshold remains to be explored. Besides, our measurement fixed the outward turning rotation gain R_{away} to 1.0 and measured larger and smaller thresholds of rotation gain difference of the inward turning process. In future studies, it would be beneficial to investigate the detection thresholds based on other R_{away}, thereby expanding the practicality of BiRD in practical applications. Additionally, it is crucial to acknowledge that our participant pool exhibited a notable gender bias within the participant samples. It would be beneficial and important to further expand participant diversity to enhance the reliability and validity of our findings as well as in future studies. Moreover, our current measurements of BiRD do not distinguish left and right sides. Given that individuals typically have a dominant hand, this could imply varied sensory sensitivities between the left and right sides. In future studies, the BiRD threshold range can be measured separately for the left and right sides, to further discover the influence of direction on BiRD threshold. Finally, another limitation of our study was that it did not explore the effects of combining BiRD with other forms of gain. A potential avenue for future research could involve investigating the impact of employing BiRD alongside traditional curvature gain.

8 Conclusion

In this paper, we identified that when the RDW controller applies alternating rotation gains within previously measured detection thresholds to back-and-forth rotations during walking, it can lead to a significant increase in simulator sickness. This phenomenon is primarily attributed to the disparity between the conditions under which the rotation gain detection thresholds are measured and the conditions of back-and-forth rotations during walking. We introduce a mechanism for controlling the difference between bidirectional rotation gains during successive back-and-forth rotations, which we refer to as BiRD. As the rotation gains in the two directions of rotations are different, BiRD can leverage the user's back-and-forth head movements during walking to alter their physical direction. We measured the detection threshold of BiRD in the walking state. Through a validation experiment, we verified that BiRD can significantly reduce the increase of simulator sickness during walking.

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REFERENCES

[1] M. Azmandian, T. Grechkin, and E. S. Rosenberg. An evaluation of strategies for two-user redirected walking in shared physical spaces. In *2017 IEEE Virtual Reality (VR)*, pp. 91–98, 2017. doi: 10.1109/VR.2017.7892235 3

[2] E. R. Bachmann, E. Hodgson, C. Hoffbauer, and J. Messinger. Multi-user redirected walking and resetting using artificial potential fields. *IEEE Transactions on Visualization and Computer Graphics*, 25(5):2022–2031, 2019. doi: 10.1109/TVCG.2019.2898764 3

[3] E. R. Bachmann, J. Holm, M. A. Zmuda, and E. Hodgson. Collision prediction and prevention in a simultaneous two-user immersive virtual environment. In *2013 IEEE Virtual Reality (VR)*, pp. 89–90, 2013. doi: 10.1109/VR.2013.6549377 3

[4] G. Bruder, V. Interrante, L. Phillips, and F. Steinicke. Redirecting walking and driving for natural navigation in immersive virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 18(4):538–545, 2012. doi: 10.1109/TVCG.2012.55 2, 3

[5] G. Bruder, F. Steinicke, K. Hinrichs, and M. Lappe. Reorientation during body turns. pp. 145–152, 01 2009. doi: 10.2312/EGVE/JVRC09/145-152 3

[6] Y. Chang, K. Matsumoto, T. Narumi, T. Tanikawa, and M. Hirose. Redirection controller using reinforcement learning. *IEEE Access*, 9:145083–145097, 2021. doi: 10.1109/ACCESS.2021.3118056 3

[7] Z.-Y. Chen, Y.-J. Li, M. Wang, F. Steinicke, and Q. Zhao. A reinforcement learning approach to redirected walking with passive haptic feedback. In *2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 184–192, 2021. doi: 10.1109/ISMAR52148.2021.00033 3

[8] T. Dong, X. Chen, Y. Song, W. Ying, and J. Fan. Dynamic artificial potential fields for multi-user redirected walking. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 146–154, 2020. doi: 10.1109/VR46266.2020.00033 3

[9] T. Dong, T. Gao, Y. Dong, L. Wang, K. Hu, and J. Fan. Free-rdw: A multi-user redirected walking method for supporting non-forward steps. *IEEE Transactions on Visualization and Computer Graphics*, 29(5):2315–2325, 2023. doi: 10.1109/TVCG.2023.3247107 3

[10] T. Dong, Y. Shen, T. Gao, and J. Fan. Dynamic density-based redirected walking towards multi-user virtual environments. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 626–634, 2021. doi: 10.1109/VR50410.2021.00088 3

[11] Z.-C. Dong, X.-M. Fu, Z. Yang, and L. Liu. Redirected smooth mappings for multiuser real walking in virtual reality. *ACM Trans. Graph.*, 38(5), oct 2019. doi: 10.1145/3345554 3

[12] L. Fan, H. Li, and M. Shi. Redirected walking for exploring immersive virtual spaces with hmd: A comprehensive review and recent advances. *IEEE Transactions on Visualization and Computer Graphics*, pp. 1–1, 2022. doi: 10.1109/TVCG.2022.3179269 2

[13] T. Grechkin, J. Thomas, M. Azmandian, M. Bolas, and E. Suma. Revisiting detection thresholds for redirected walking: Combining translation and curvature gains. In *Proceedings of the ACM Symposium on Applied Perception*, SAP '16, p. 113–120. Association for Computing Machinery, New York, NY, USA, 2016. doi: 10.1145/2931002.2931018 7

[14] J. Hamill, J. Lim, and R. van Emmerik. Locomotor coordination, visual perception and head stability during running. *Brain Sciences*, 10, 2020. 2

[15] E. Hodgson and E. Bachmann. Comparing four approaches to generalized redirected walking: Simulation and live user data. *IEEE Transactions on Visualization and Computer Graphics*, 19(4):634–643, 2013. doi: 10.1109/TVCG.2013.28 2, 3

[16] C. Hutton, S. Ziccardi, J. Medina, and E. S. Rosenberg. Individualized Calibration of Rotation Gain Thresholds for Redirected Walking. In G. Bruder, S. Yoshimoto, and S. Cobb, eds., *ICAT-EGVE 2018 - International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments*. The Eurographics Association, 2018. doi: 10.2312/egve.20181315 1, 2

[17] V. Interrante, B. Ries, and L. Anderson. Seven league boots: A new metaphor for augmented locomotion through moderately large scale immersive virtual environments. In *2007 IEEE Symposium on 3D User Interfaces*, 2007. doi: 10.1109/3DUI.2007.340791 1, 2

[18] P. M. Jaekl, M. R. M. Jenkin, and L. R. Harris. Perceiving a stable world during active rotational and translational head movements. *Experimental Brain Research*, 163:388–399, 2005. 2

[19] S.-B. Jeon, S.-U. Kwon, J.-Y. Hwang, Y.-H. Cho, H. Kim, J. Park, and I.-K. Lee. Dynamic optimal space partitioning for redirected walking in multi-user environment. *ACM Transactions on Graphics (TOG)*, 41(4):1–14, 2022. 3

[20] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and L. Mg. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology*, 3:203–220, 1993. 5

[21] S. A. Klein. Measuring, estimating, and understanding the psychometric function: A commentary. *Perception & Psychophysics*, 63:1421–1455, 2001. 3

[22] L. Kruse, E. Langbehn, and F. Steinicke. I can see on my feet while walking: Sensitivity to translation gains with visible feet. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 305–312, 2018. doi: 10.1109/VR.2018.8446216 1, 2

[23] E. Langbehn, P. Lubos, G. Bruder, and F. Steinicke. Bending the curve: Sensitivity to bending of curved paths and application in room-scale vr. *IEEE Transactions on Visualization and Computer Graphics*, 23(4):1389–1398, 2017. doi: 10.1109/TVCG.2017.2657220 2

[24] D.-Y. Lee, Y.-H. Cho, and I.-K. Lee. Real-time optimal planning for redirected walking using deep q-learning. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 63–71, 2019. doi: 10.1109/VR.2019.8798121 3

[25] D.-Y. Lee, Y.-H. Cho, D.-H. Min, and I.-K. Lee. Optimal planning for redirected walking based on reinforcement learning in multi-user environment with irregularly shaped physical space. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 155–163, 2020. doi: 10.1109/VR46266.2020.00034 3

[26] H. Li and L. Fan. Mapping various large virtual spaces to small real spaces: A novel redirected walking method for immersive vr navigation. *IEEE Access*, 8:180210–180221, 2020. doi: 10.1109/ACCESS.2020.3027985 3

[27] Y.-J. Li, F. Steinicke, and M. Wang. A comprehensive review of redirected walking techniques: Taxonomy, methods, and future directions. *Journal of Computer Science and Technology*, 37(3):561–583, 2022. doi: 10.1007/s11390-022-2266-7 2

[28] D. Linares and J. López-Moliner. quickpsy: An r package to fit psychometric functions for multiple groups. *R J.*, 8:122, 2016. 3, 7

[29] K. Matsumoto, E. Langbehn, T. Narumi, and F. Steinicke. Detection thresholds for vertical gains in vr and drone-based telepresence systems. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 101–107, 2020. doi: 10.1109/VR46266.2020.00028 2

[30] J. Messinger, E. Hodgson, and E. R. Bachmann. Effects of tracking area shape and size on artificial potential field redirected walking. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 72–80, 2019. doi: 10.1109/VR.2019.8797818 3

[31] C. T. Neth, J. L. Souman, D. Engel, U. Kloos, H. H. Bülthoff, and B. J. Mohler. Velocity-dependent dynamic curvature gain for redirected walking. *2011 IEEE Virtual Reality Conference*, pp. 151–158, 2011. 8

[32] C. T. Neth, J. L. Souman, D. Engel, U. Kloos, H. H. Bulthoff, and B. J. Mohler. Velocity-dependent dynamic curvature gain for redirected walking. *IEEE Transactions on Visualization and Computer Graphics*, 18(7):1041–1052, 2012. doi: 10.1109/TVCG.2011.275 1, 2

[33] A. Nguyen, Y. Rothacher, B. Lenggenhager, P. Brugger, and A. M. Kunz. Individual differences and impact of gender on curvature redirection thresholds. *Proceedings of the 15th ACM Symposium on Applied Perception*, 2018. 8

[34] N. C. Nilsson, T. Peck, G. Bruder, E. Hodgson, S. Serafin, M. Whitton, F. Steinicke, and E. S. Rosenberg. 15 years of research on redirected walking in immersive virtual environments. *IEEE Computer Graphics and Applications*, 38(2):44–56, 2018. doi: 10.1109/MCG.2018.111125628 2, 3

[35] A. Paludan, J. Elbaek, M. Mortensen, M. Zobbe, N. C. Nilsson, R. Nordahl, L. Reng, and S. Serafin. Disguising rotational gain for redirected walking in virtual reality: Effect of visual density. In *2016 IEEE Virtual Reality (VR)*, pp. 259–260, 2016. doi: 10.1109/VR.2016.7504752 1, 2

[36] S. Razzaque. *Redirected Walking*. PhD thesis, University of North Carolina at Chapel Hill, USA, 2005. 1, 3

[37] S. Razzaque, Z. Kohn, and M. C. Whitton. Redirected Walking. In *Eurographics 2001 - Short Presentations*. Eurographics Association, 2001. doi: 10.2312/egs.20011036 1

[38] M. Rietzler, J. Gugenheimer, T. Hirzle, M. Deubzer, E. Langbehn, and E. Rukzio. Rethinking redirected walking: On the use of curvature gains beyond perceptual limitations and revisiting bending gains. In *2018 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 115–122, 2018. doi: 10.1109/ISMAR.2018.00041 1, 2

[39] H. Sakono, K. Matsumoto, T. Narumi, and H. Kuzuoka. Redirected

walking using continuous curvature manipulation. *IEEE Transactions on Visualization and Computer Graphics*, 27(11):4278–4288, 2021. doi: 10.1109/TVCG.2021.3106501 2

[40] P. Schmitz, J. Hildebrandt, A. C. Valdez, L. Kobbelt, and M. Ziefle. You spin my head right round: Threshold of limited immersion for rotation gains in redirected walking. *IEEE Transactions on Visualization and Computer Graphics*, 24(4):1623–1632, 2018. doi: 10.1109/TVCG.2018.2793671 1, 2

[41] S. Serafin, N. C. Nilsson, E. Sikstrom, A. De Goetzen, and R. Nordahl. Estimation of detection thresholds for acoustic based redirected walking techniques. In *2013 IEEE Virtual Reality (VR)*, pp. 161–162, 2013. doi: 10.1109/VR.2013.6549412 2

[42] M. Sparkes. What is a metaverse, 2021. 1

[43] K. M. Stanney, R. S. Kennedy, and J. M. Drexler. Cybersickness is not simulator sickness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 41:1138 – 1142, 1997. 5, 8

[44] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Analyses of human sensitivity to redirected walking. In *Proceedings of the 2008 ACM Symposium on Virtual Reality Software and Technology*, VRST '08, p. 149–156. Association for Computing Machinery, New York, NY, USA, 2008. doi: 10.1145/1450579.1450611 2

[45] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Estimation of detection thresholds for redirected walking techniques. *IEEE Transactions on Visualization and Computer Graphics*, 16(1):17–27, 2010. doi: 10.1109/TVCG.2009.62 1, 2, 3, 7

[46] R. R. Strauss, R. Ramanujan, A. Becker, and T. C. Peck. A steering algorithm for redirected walking using reinforcement learning. *IEEE Transactions on Visualization and Computer Graphics*, 26(5):1955–1963, 2020. doi: 10.1109/TVCG.2020.2973060 3

[47] E. A. Suma, G. Bruder, F. Steinicke, D. M. Krum, and M. Bolas. A taxonomy for deploying redirection techniques in immersive virtual environments. In *2012 IEEE Virtual Reality Workshops (VRW)*, pp. 43–46, 2012. doi: 10.1109/VR.2012.6180877 3

[48] J. Thomas and E. S. Rosenberg. A general reactive algorithm for redirected walking using artificial potential functions. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 56–62, 2019. doi: 10.1109/VR.2019.8797983 2, 3, 4, 5, 8

[49] J. Thomas and E. S. Rosenberg. Reactive alignment of virtual and physical environments using redirected walking. *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 317–323, 2020. 3

[50] C. Wang, S.-H. Zhang, Y. Zhang, S. Zollmann, and S. Hu. On rotation gains within and beyond perceptual limitations for seated vr. *IEEE transactions on visualization and computer graphics*, PP, 2022. 3, 7

[51] M. Wang, Z.-Y. Chen, W.-C. Cai, and F. Steinicke. Transferable virtual-physical environmental alignment with redirected walking. *IEEE Transactions on Visualization and Computer Graphics*, pp. 1–14, 2022. doi: 10.1109/TVCG.2022.3224073 3

[52] N. L. Williams, A. Bera, and D. Manocha. Arc: Alignment-based redirection controller for redirected walking in complex environments. *IEEE Transactions on Visualization and Computer Graphics*, 27(5):2535–2544, 2021. doi: 10.1109/TVCG.2021.3067781 3

[53] N. L. Williams, A. Bera, and D. Manocha. Redirected walking in static and dynamic scenes using visibility polygons. *IEEE Transactions on Visualization and Computer Graphics*, 27(11):4267–4277, 2021. doi: 10.1109/TVCG.2021.3106432 3

[54] N. L. Williams and T. C. Peck. Estimation of rotation gain thresholds considering fov, gender, and distractors. *IEEE Transactions on Visualization and Computer Graphics*, 25(11):3158–3168, 2019. doi: 10.1109/TVCG.2019.2932213 1, 2, 3

[55] S.-Z. Xu, J.-H. Liu, M. Wang, F.-L. Zhang, and S.-H. Zhang. Multi-user redirected walking in separate physical spaces for online vr scenarios. *IEEE Transactions on Visualization and Computer Graphics*, 2023. 3

[56] S.-Z. Xu, T.-Q. Liu, J.-H. Liu, S. Zollmann, and S.-H. Zhang. Making resets away from targets: Poi aware redirected walking. *IEEE Transactions on Visualization and Computer Graphics*, 28(11):3778–3787, 2022. doi: 10.1109/TVCG.2022.3203095 3

[57] C. You, B. Benda, E. S. Rosenberg, E. D. Ragan, B. C. Lok, and J. Thomas. Strafing gain: Redirecting users one diagonal step at a time. *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 603–611, 2022. 2, 7

[58] S. Zhang, C. Wang, Y. Zhang, F.-L. Zhang, N. Pantidi, and S.-M. Hu. Velocity guided amplification of view rotation for seated vr scene exploration. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 504–505, 2021. doi: 10.1109/VRW52623.2021.00134 2, 3

[59] S.-H. Zhang, C. Chen, and S. Zollmann. One-step out-of-place resetting for redirected walking in vr. *IEEE Transactions on Visualization and Computer Graphics*, 29(7):3327–3339, 2023. doi: 10.1109/TVCG.2022.3158609 1