Virtual Reality (2024) 28:35
https://doi.org/10.1007/s10055-023-00935-4

ORIGINAL ARTICLE

Effect of optical flow and user VR familiarity on curvature gain thresholds for redirected walking

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Received: 7 February 2023 / Accepted: 18 December 2023 / Published online: 29 January 2024

Abstract

Virtual reality (VR) locomotion should allow users to move freely in the virtual space while staying within the tracking area in the real space. The redirected walking (RDW) technique enables users to walk naturally in an unlimited virtual space within a limited tracking area by rotating the virtual scene view. However, conflicting visual and vestibular signals during RDW can lead to user discomfort and decreased immersion. To avoid user discomfort, an RDW gain should be within the detection threshold (DT) range. However, a large angle of walking redirection is required when physically avoiding obstacles or escaping from a narrow space, so DT expansion is necessary. In this study, to change the curvature DT range and enhance RDW performance, we proposed an optical flow (OF)-generating vection in a virtual environment. Further, we investigate methods to reduce user discomfort and increase RDW efficiency considering familiar and unfamiliar VR users. The findings showed that the introduction of OF led to a reduction in the DT range for all users, irrespective of the OF's direction. However, conditions with OF resulted in an extended DT range for users familiar with VR while concurrently diminishing the DT range for those who were VR unfamiliar. To delve further, our analysis indicated that when both the OF and redirecting directions were identical, the RDW performance was robust to VR familiarity, whereas in opposing directions, the DT range increased for VR-familiar users. Our study findings suggested using OF for the RDW technique and extending its applicability in virtual environments.

Keywords Virtual reality · Redirected walking · Detection thresholds · Optical flow · VR familiarity

1 Introduction

Virtual reality (VR) technology provides virtual spaces where humans can move and interact. These virtual environments can be larger than real space. Because the walkable space of VR users is limited, a VR locomotion technology that allows the user to naturally walk in the virtual space without limiting its size is critical (Nilsson et al. 2018b; Suma et al. 2012). VR locomotion techniques include redirected walking, teleportation, walking-in-place, and hand controllers (Bowman et al. 1997; Peck et al. 2011; Razzaque et al. 2001; Usoh et al. 1999). Redirected walking has demonstrated effectiveness in delivering a seamless VR movement experience. Unlike other techniques, it does not need extra locomotion training or the use of additional devices, enabling users to engage in natural and unconstrained walking within VR (Peck et al. 2011; Usoh et al. 1999). Redirected walking (RDW) technology can change the user's walking trajectory by providing visual information that does not match the vestibular information generated when the user walks through the VR scene (Razzaque et al. 2001). RDW techniques involve the application of gains to manipulate the user's visual perception of movement within a VR environment. The RDW gain is usually expressed as a multiplier that affects the virtual movement of the user's viewpoint (VR camera) relative to the actual physical movement. For example, if a curvature gain of 2 × is applied, it means that

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for every physical step the user takes, the VR scene rotates twice as much. This technology enables users to walk almost unlimitedly in the virtual space while ensuring that they stay safely within the tracking area without colliding with obstacles in the physical space (Nilsson et al. 2018a). However, the high mismatch between visual and vestibular signals due to excessive application of gain reduces user immersion, increases VR motion sickness, and causes temporary disorientation (Akiduki et al. 2003; Stanney et al. 2003). Therefore, to change a user's walking direction without the user detecting the disparity between the visual and vestibular signals, a fitting RDW gain value is used within the experimentally estimated detection threshold (DT) (Steinicke et al. 2008a ; Steinicke et al. 2009). The RDW gain should not exceed the DT range (the range where the user will not be aware that the RDW gain has been applied, even if there is a redirection manipulation). However, in cases in which the user must escape from a tight space or avoid obstacles, a large RDW gain exceeding the DT value is required to considerably change the user's walking direction. Therefore, the DT range should be extended. An alternative to DT range extension is the reset technique, which is often used to redirect users who have reached the tracking area boundary (Nilsson et al. 2018a). This method encompasses diverse strategies, such as applying a doubled rotation gain to the user, momentarily pausing the VR scene, adjusting the angle of the VR camera (which simulates the user's viewpoint), or introducing visual distractors (Peck et al. 2009; Williams et al. 2007). The resetting mechanism acts as a safeguard, and has shown effectiveness across tracking areas of varying sizes. However, as the size of the tracking area decreases, frequently repeated interventions expose users to frequent visual-vestibular discrepancies, which can negatively affect immersion and distract their virtual experience (Sra et al. 2018). For this reason, the possibility of increasing the DT range to seamlessly manipulate the user's walking trajectory needs to be examined and explored. This study aims to reduce reliance on resetting.

In this study, we attempt to increase the DT range by applying an optical flow (OF) that can generate vection in the RDW technique. OF represents a visual signal pattern that emerges during the perception of movement within the surrounding environment, and vection refers to the perceptual illusion of self-motion induced by the observation of this OF. These illusions of movement can be experienced without physical movement (Patla 1997). Thus, virtual motion is induced because of the visual-vestibular signals mismatch. Therefore, OF provides a sense of speed and direction to improve presence in virtual environments. As shown in the previous study, when sitting subjects swiftly recognized the OF and felt the vection, their perceived presence was evaluated as high (Riecke et al. 2006). In another study, the magnitude of vection revealed a positive correlation with presence (Keshavarz et al. 2019). Among the vection types of directional OF, circular vection rotates the environment of the user; this causes visual-vestibular signal mismatch, allowing manipulation of the physical walking direction of the user and inducing the user to feel as if they are maintaining their original walking direction (Rothacher et al. 2018). The results of circular vection are similar to those of the RDW technique. The locomotion direction of the OF observer can be changed according to the direction of the OF (Prokop et al. 1997; Warren et al. 2001). Within the RDW domain, previous studies manipulated visual density by introducing static objects and modified OF patterns by textural and lighting adjustments within virtual spaces to explore the DT range change. However, these results did not find a link between OF and DT (Paludan et al. 2016; Waldow et al. 2018). It is worth noting that in environments where static OF is passively presented within a virtual space, users may not readily perceive subtle differences in OF patterns. Furthermore, few studies have considered the dynamic OF and direction to increase the DT range. The possibility that adding an OF that is mismatched or opposite to the reorientation manipulation to the RDW technique could extend the DT range by offsetting the mismatch between visual and vestibular signals caused by RDW needs to be explored.

The DT range was measured according to the characteristics of users to understand the perception of the RDW and investigate the possibility of increasing the DT range. The redirection perceived could differ depending on the characteristics of the participants. For example, women tend to notice the application of the RDW technique less than men (Bruder et al. 2009a; Nguyen et al. 2018b; Nguyen et al. 2020). Previous research found that users with high visual dependence were less aware of redirection manipulation (Rothacher et al. 2018), and the DT could vary depending on the sensitivity to visual-vestibular collision and internal body changes such as posture shake (Ngoc et al. 2016). Participants who have previously experienced CAVE systems or 3D video games felt low VR motion sickness and spatial recognition ability did not deteriorate even when rotation gain was applied (Freitag et al. 2016; Sargunam et al. 2017). Therefore, they could be unaware of RDW manipulation. Intrinsic factors, such as gender, visual dependence, sensitivity, or similar experience (e.g., familiarity with VR technology), could affect the user's perception of redirecting manipulation. Unlike intrinsic factors, familiarity with VR technology is based on the experience of an individual. Confirmation through human experimentation is required, and a user-adaptive RDW technique is important to explore. Furthermore, because users with similar experiences tend to feel stronger and faster vection caused by the OF (Pöhlmann et al. 2022), the DT range may increase according to the influence of the VR familiarity of the user when additional OF is provided. To investigate whether the VR familiarity factor can increase the DT in an OF-added virtual environment and support different walking experiences of users in a virtual space, it is necessary to pre-emptively measure and compare DT values according to the user's VR familiarity. The user-adaptive RDW technique design strategy needs to apply RDW considering RDW performance change prediction, which is based on the effect of OF and user VR familiarity on DT.

In this study, we designed independently moving objects (IMOs) independent of the background of the virtual environment, flying in the air in a virtual space. We investigated how the directionality of OFs, a pattern of visual signals generated by directionally moving IMOs, changes the user's DT range (see Fig. 1). By comparing the effect of the user's VR familiarity on the DT range, we explored the OF conditions that can reduce user discomfort and increase RDW efficiency based on VR familiarity of users. We set the following research questions:

RQ1. When using the RDW technique, how does the OF with different directions added to the VR scene change the DT range?

RQ2. How does applying OFs in VR affect the DT range between VR-unfamiliar and VR-familiar users?

2 Related work

In this section, we summarize previous research work related to RDW in VR, estimation of detection threshold, and vection for redirection.

2.1 Redirected walking techniques

Visual signals are used as the primary sources of information because of visual dominance in recognizing space and locomotion decisions even when discrepancies exist between visual and vestibular signals (Akiduki et al. 2003). RDW is a visual technology in which the entire virtual environment map is rotated or the movement speed is modulated so that a user moves only within the tracking area and experiences unrestricted movement in the virtual environment (Razzaque et al. 2001; Sun et al. 2020). For example, the RDW technique rotates the virtual environment map, which causes the user to walk in a curved path in the real space without leaving the tracking area, whereas the user can feel as if they are walking on a straight path in the virtual space. In particular, the method of changing the direction by applying a redirection gain to the user's physical movement value of the user in a virtual environment was studied. RDW gain is classified into rotation, translation, and curvature gain (Steinicke et al. 2008a; Steinicke et al. 2009). Rotation gain is a technique in which a gain is used to control rotational movement in real space so that the user in the virtual space experiences a larger or smaller rotation than the actual space (Bruder et al. 2009b). Translation gain is a technique in which the user walks more or less than the actual amount of walking in the virtual space by providing a gain to the movement of the user walking in a straight line in the real space (Interrante et al. 2006). Curvature gain causes a user moving in the forward direction to turn left or right. This gain continuously rotates the map based on the user going straight, causing the user to move in an arc (Steinicke et al. 2008b). Another technique within the domain of redirected walking is commonly referred to as 'reset.' These procedures are frequently employed to halt users and change their orientation, typically when they approach the boundary of the tracking area (Suma et al. 2012). Reset techniques involve the suspension of the user's ongoing motion followed by a reorientation. Examples include the '2:1 turn technique,' which entails rotating the virtual space at twice the rate of the user's physical rotation, the 'freeze-turn technique,' which involves temporarily freezing the virtual scene, reorienting the user toward the center of the tracking area, and then resuming the scene, as well as the use of 'visual distractors' that divert the user's

Fig. 1 Concept of redirected walking technique integrated with optical flow overlaid with lines (invisible to the user). In a virtual space, objects moving independently of the background can create optical flows to manipulate the user's walking trajectory

attention to specific visual objects while concurrently rotating the virtual space to a greater extent relative to the user's physical rotation (Peck et al. 2009; Williams et al. 2007). These reset techniques effectively serve their purpose as safety mechanisms and exhibit efficacy across diverse tracking area scales (Nilsson et al. 2018a). However, these resets can disrupt the overall user experience through overt user intervention and redirection. Our exploration centers on curvature gain, a technology designed to facilitate directional changes in scenarios where users are engaged in continuous movement and can enhance user experience before the need for reset interventions (Neth et al. 2012; Williams et al. 2007). This study focuses on how the OF affects curvature gain before verifying other RDW gains.

2.2 Detection threshold (DT) estimation and individual difference

RDW technology can overcome physical limitations by creating an inconsistency between the movement of users in the virtual space and real space (Nilsson et al. 2018a); however, this causes visual-vestibular inconsistency for the user. Assume that the user is controlled at a larger angle to avoid obstacles efficiently and move out of a narrow space. In this case, the difference between the virtual and the real movement increases, which creates a difference between the visual and vestibular information of the user. The collision of this visual and vestibular information causes motion sickness and decreases presence by causing the user to notice the RDW manipulations (Akiduki et al. 2003; Stanney et al. 2003). The RDW technique has a limitation on RDW gains and is defined as a DT (Bölling et al. 2019; Rietzler et al. 2018). Because the DT range restricts the RDW gain values, RDW technology has limitations in spatial expansion and obstacle avoidance. Consequently, many studies have focused on DT expansion.

A novel method for measuring DT was first proposed by Steinicke et al. (Steinicke et al. 2008a; Steinicke et al. 2009). In this study, DT was measured through two-alternative forced-choice (2AFC) by randomly changing the rotation gain, translation gain, and curvature gain of participants. In the environment in which RDW gain was applied, participants were asked, 'Was the virtual movement smaller or greater than the physical movement?' or "Did the physical path turn left or right?". Participants were requested to select one of the smaller/greater or left/right answers to these questions, respectively. There are two response options that participants who have experienced unknown RDW gain can choose from, and Steinicke et al. defined the gain value when the proportion of participants who choose each response is 50% as the point of subjective equality (PSE). As the gain decreases or increases from this point, it becomes easier for the participant to notice the difference in movement between virtual space and real space, creating a psychometric curve for the performance in identifying this difference. In psychophysical experiments, it is customary to identify the threshold as the point where the curve reaches a midpoint between the chance level and 100%. The points at which movement in the virtual and real space can be distinguished into a 75% range are defined as lower DT (LDT) and upper DT (UDT), respectively. In this study, the DT was measured by randomly applying nine curvature gains ($\pm\pi/180, \pm\pi/90, \pm\pi/60, \pm\pi/45, 0$) to participants, five times each.

Because DT indicates the threshold at which the user recognizes a redirecting manipulation, measuring and comparing the DT according to the characteristics that the user recognizes as redirecting manipulation are crucial. Women have a wider field of view than men (Schmitz et al. 2018) and tend not to notice redirecting manipulation (Bruder et al. 2009a; Nguyen et al. 2018b). The participant with high visual dependence on visual cues or low susceptibility to visual–vestibular conflict and internal body changes, such as postural sway, tended to notice less redirecting manipulation (Rothacher et al. 2018). Intrinsic factors, such as gender, visual dependence, and sensitivity, can increase the DT range by preventing users from noticing the redirecting manipulations. Users with experience in the past virtual environment system or 3D space did not have any difficulty in adapting to the virtual environment, felt limited motion sickness, and performed better spatial perception-related tasks than users without experience (Freitag et al. 2016; Sargunam et al. 2017). Users with similar VR experiences would not easily detect redirecting manipulation. However, DT was not measured according to this property (e.g., familiarity with VR). Familiarity with VR technology is formed based on personal experience, so variations in familiarity are more likely than intrinsic factors. User-adaptive RDW technology through DT estimation is required based on the effect of VR familiarity of users on DT. Therefore, this study measured the curvature DT for a user group according to familiarity with the VR and investigated the possibility of increasing the RDW performance with a large curvature while reducing user discomfort.

2.3 Optical flow (OF) generating vection for redirection

OF observers experience a vection, which is an illusion of self-motion that the user is moving even though there is no physical movement (Heckmann and Howard 1991). An example of vection is when a person sitting on a stationary train sees a train departing from the opposite side of the platform. That person experiences an optical illusion as if the train he is riding on is departing. When the human is moving physically, the vection can affect quickly and strongly, so it is likely to change the walking direction of the user (Bubka and Bonato 2010). If the display modulated the speed and direction of the OF by moving the ground faster or slower than the participant's walking speed, then the participant slows or accelerates the walking speed (Baumberger et al. 2000). Artificially inserting OF in a direction opposite to the OF generated by the vehicle motion in the first-person image of riding a spaceship or roller coaster revealed the effect of reducing motion sickness (Park et al. 2022). Studies have revealed the potential that the direction of the OF could change the perception of motion. Modulated OF, such as the RDW technique, confuses the real motion with illusion motion and allows the user to change the walking direction in the virtual environment without recognition of visual–vestibular discrepancy.

Studies have investigated the changes in DT with the amount of OF to determine the potential for an increase in the DT range (Paludan et al. 2016; Waldow et al. 2018). Translation gain thresholds were measured in the condition in which the amount of OF increased using global lighting and texture rendering of furniture placed in the virtual space, but the DT value did not differ from the DT value in the condition in which OF was not increased (Waldow et al. 2018). Another research group observed the DT of rotational redirection when the visual density was increased by changing the number of objects placed in the virtual space, but the DT did not increase according to the visual density (Paludan et al. 2016). In previous studies, participants would have perceived modulated OF conditions (e.g., background texture change and object count change) as different visual effects. In addition, the modulated OF only increased the amount of the total OF in the same direction as the RDW manipulation, did not affect the change in DT. However, as the user's walking pattern can be manipulated according to the direction of OF (Baumberger et al. 2000; Warren et al. 2001); therefore, it is necessary to explore the effect of directional OF, with motion independent of the virtual background, on the user's perception of redirection. Accordingly, employing OF in VR may change the DT range. We investigated the effect of applying OF on users' perception of redirection manipulation and perceived user experience. We designed IMO to generate different OF directions in a virtual environment.

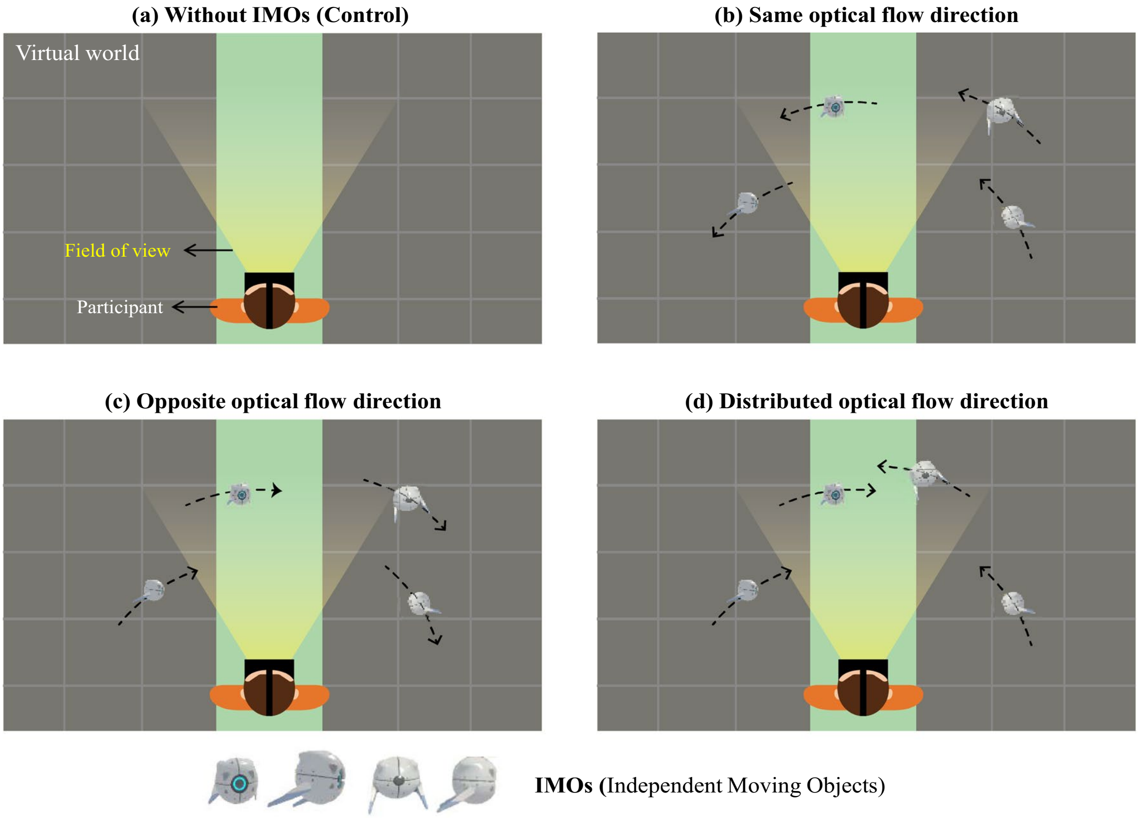
3 Experiment

Our experiment aimed to extend the curvature DT using OF in the virtual environment and explore the change of the curvature DT range according to the user's VR familiarity and varying OF directions.

3.1 Design

The experiment was conducted in a physical space with a 7 m × 7 m size, and Unity3D was used to design the virtual environment. We used an Oculus Quest 2 which provides a resolution of 1832 × 1920 pixels per eye and two controllers. The fundamental experimental environment and method were established based on the DT measurement environment of Steinicke et al. (Steinicke et al. 2009). Curvature DT was measured under four OF conditions (Control, Same, Opposite, and Dispersion) by varying the presence or absence of IMO and its moving direction. A green path was placed for participants to walk along in a virtual environment. We applied nine curvature gains ($\pm\pi/180, \pm\pi/90, \pm\pi/60, \pm\pi/45$, 0) for each of the four experimental conditions. In one experimental condition, each curvature gain was randomly applied 45 times; five times per gain. To prevent the participant from noticing the curvature gain immediately after departure, the curvature gain was applied after the participant moved straight for 1.5 m. The participants walked along the path to which a curvature gain of 5 m was applied (a total of 6.5 m walking) and stopped when the 2AFC questionnaire screen appeared to indicate whether the physical path was bent to the left or right. After the participant answered 2AFC through the controller, we guided the participant to the starting location from which the participant started and then repeated the same task. Music was played at 100 beats per minute so the participants could walk at a constant speed (Nguyen et al. 2018a). The four experimental conditions were conducted in the order of counterbalanced Latin Square design.

We designed a condition without IMO (Control) as shown in Fig. 2a and three conditions with IMO; the direction of OF by IMO was set based on the curvature redirection to the same direction (Same condition, see Fig. 2b), opposite direction (Opposite condition, see Fig. 2c), and distribution direction (Distributed condition, see Fig. 2d). The IMO moved in four ways to orient the OF. The OF was induced by the movement of IMO, which was a spherical drone with a diameter of 0.4 m that orbited around the participant at an average distance of 3 m and a speed of 2.3 rad/s so that the participants could observe the IMO. Each drone appeared when the curvature gain was applied and disappeared when the curvature gain application ended. To compute the optical flow between consecutive frames, we employed the Farneback method as implemented in the OpenCV library (Farnebäck 2003). This method approximates the flow based on polynomial expansion and can capture both the translational and rotational movements within the scene. Each pair of x and y values in the OF represents a movement of one pixel in the VR scene. For our experiment, we excluded the background and analyzed the OF caused by the IMO when participants walked at a speed equivalent to 100 beats per


(a) Without IMOs (Control)

(b) Same optical flow direction

(c) Opposite optical flow direction

(d) Distributed optical flow direction

Fig. 2 Schematic of the experiment with various IMOs moving conditions when the curvature gain direction is to the left. **a** Curvature redirected walking manipulation condition without the IMOs (Control). **b** and **c** With the IMOs that rotate in the same (Same condition) and opposite direction of redirecting manipulation (Opposite condition). **d** Two groups of IMOs, each rotating in the same and opposite direction of manipulation (Distributed condition)

minute. The resulting vectors, which indicate the amount of pixel movement, are as follows: OF in the Same condition (flow x: 603.635, flow y: 113.659), OF in the Opposite condition (flow x: -769.170, flow y: 121.591), OF in the Distributed condition (flow x: -18.6856, flow y: 125.278). The symbol illustrates direction with + on the x-axis indicating right and—indicating left. On the y-axis, + represents the top, and—represents the bottom.

3.2 Participants

Twenty participants were recruited for this study (age: $M = 23.35$ ($SD = 3.70$)), 10 males and 10 females). Before participation, a peripheral vision (Min = 1 and Max = 5) as a sub-scale of the peripheral vision-related visual activity questionnaire was conducted to confirm that participants did not have any difficulty in recognizing the IMO (Sloane et al. 1992). Participants had an average of 1.46 ($SD = 0.65$), indicating that participants did not have any problem recognizing IMO. Participants did not have any difficulty walking for a long time while wearing a VR HMD, and no motion sickness symptoms related to 3D games were observed.

VR familiarity was measured through a question about previous VR experience, a sub-item of the demographics questionnaire, before participation in the experiment. All participants were asked about their familiarity with VR, and participants responded to the question 'I am familiar with using VR' on a five-point Likert scale (1 = Strongly disagree, 3 = Neither disagree nor agree, and 5 = Strongly agree). Because VR familiarity was answered subjectively by participants, to reduce the ambiguity of VR-familiar group classification, we considered only participants who answered 'agree' or 'strongly agree' as familiar with VR. A score of 4 (agree) or higher was assigned to the group familiar with VR technology (VRF (VR Familiar) group, 10 participants (5 males and 5 females), and a score of less than 4 was assigned to the group unfamiliar with VR (VRUF (VR UnFamiliar) group, 10 participants (4 males and 6 females)).

3.3 Measurement

We measured curvature DT by using the 2AFC question ('Does the physical path curve left or right?') in the VR scene after participants had walked 6.5 m. Participants used a handheld VR controller to answer this question. After completing each experimental condition, the participant took off the head-mounted display (HMD) and answered the questionnaires. We used NASA-TLX questionnaires to measure the workload (Hart 1986), the Slater-Usoh-Steed presence questionnaire (Slater et al. 1994) to measure presence, and the VR sickness questionnaire (Kim et al. 2018) to measure VR sickness. We surveyed the attraction IMO led in two sub-scales: gaze attraction and body attraction. Participants were asked, 'While walking, the gaze followed a moving object (drone)' and 'My body tried to follow a moving object (drone) while walking.' Both questions were answered on a five-point Likert scale (1 = Strongly disagree, 3 = Neither disagree nor agree, 5 = Strongly agree).

3.4 Procedure

We conducted a within-subjects experimental design. Before the experiment, participants were asked to fill in a demographics questionnaire. They watched a video recording showing both the execution of the experiment by the actor and the corresponding VR environment experienced by the actor. The participants moved to an obstruction-free experimental place and then put on VR HMDs. We gave them time to familiarize themselves with the VR environment. We then had them do a series of practice sessions where they walked and answered 2AFC questions with curvature gain applied. Each practice iteration was repeated three times. The participant proceeded with the DT measurement experiment described in Sect. 3.1. They were informed that they could end the experiment at any time if they felt uncomfortable. After completing one experimental condition, the participant took off the VR HMD and answered user experience questionnaires. We provided a rest time of at least 5 min after the questionnaire, and additional sufficient rest time was provided if the participant desired. After resting, the next sequence of experimental conditions was performed. The experiment was approved by the Institutional Review Board (IRB No. 20210806-HR-62-01-02). The total duration was approximately two hours, and a $50 reward was paid for their time.

4 Results and discussion

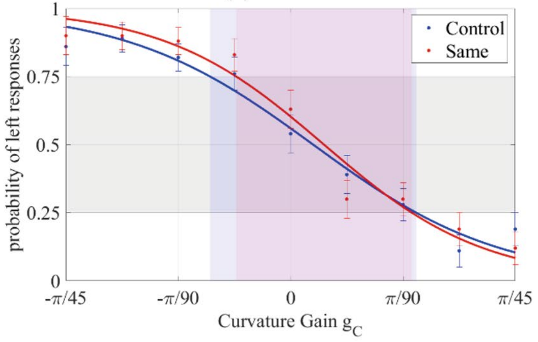
We analyzed and discussed the change in DT range under different OF conditions in terms of IMO and perceived user experience. A repeated measures analysis of variance (ANOVA) with a post hoc test was conducted for each measurement.

4.1 Redirected walking performance

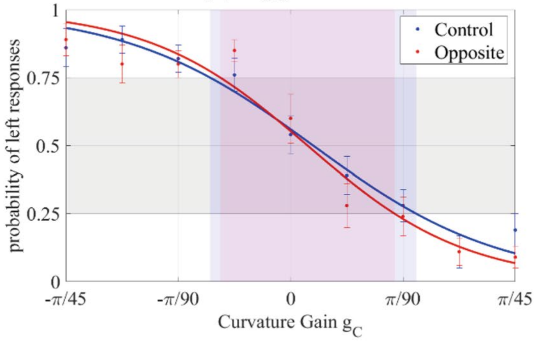
4.1.1 Influence of direction on curvature DT range

Figure 3 shows a graph detailing the probability of answering "left" to the 2AFC question (Is the physical path bent left or right?) according to the curvature gain (g_c). The skewness and kurtosis of the DT range were between − 2 to + 2 and − 7 to + 7, respectively, indicating that the data are considered to be normally distributed (Abd-El-Fattah 2010; Hair 2009). Sphericity was met as indicated by Mauchly's test ($\chi^2(5) = 10.727, p = 0.058$). We performed a repeated measures ANOVA to compare the effect of OF conditions on

(a) Same



(b) Opposite



(c) Distributed

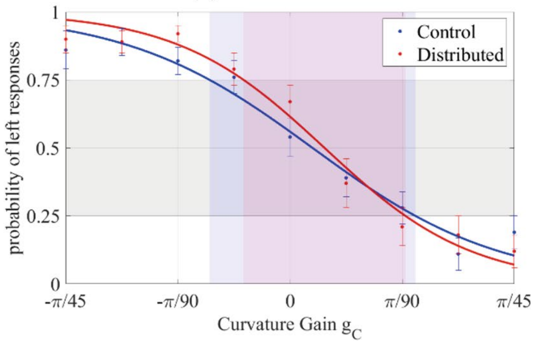


Fig. 3 Average probability of responding "left" under conditions of **a** Same, **b** Opposite, and **c** Distributed compared with the Control

the DT range. The average DT range was not significantly affected by the OF condition, ($F(3, 36) = 1.076$, $p = 0.372$, $\eta_p^2 = 0.082$). η_p^2 represents the partial eta-squared to measure the effect size. We compared the average DT range of each OF condition.

The average DT range for each OF condition (the Same, Opposite, and Distributed conditions) was narrower than that of the Control condition, which indicated that participants perceived redirecting manipulation easily when walking in the virtual environment with IMO-generated OF (see Fig. 3a–c). In particular, among the OF direction conditions, the Distributed conditions reduced the threshold of the curvature gain value that can be used for the walking direction change more than the Same and the Opposite conditions (see difference (%) column in Table 1). The 'Difference' column of Table 1 shows the percentage change in the DT range for each OF condition compared to that of the Control condition. Our result indicated that applying OF created by IMO and the various directions OF influenced the change in the user's perception of redirecting manipulation. Prior investigations have explored the impact of altering OF patterns on DT.

through adjustments in textures and lighting within virtual spaces or by the introduction of objects (Paludan et al. 2016; Waldow et al. 2018). These studies, however, have reported a lack of significant link between OF manipulation and changes in the DT range. Remarkably, our study yielded findings that contrast those of previous research. Irrespective of the participants' level of familiarity with VR, the application of dynamic OF resulted in a reduction of the DT range. One notable distinction lies in the dynamic nature of our virtual environments OF, generated by the movements of IMOs. This dynamic OF was in stark contrast to the static OF patterns used in earlier studies. Participants in our study were more likely to perceive the occurrence of OF, as IMOs were prominently present within their field of view, actively generating dynamic OF patterns. Hence, despite its propensity to decrease the DT range, our study reveals that dynamic OF exerts an influence on the DT range. In the experimental environment of previous studies, which did not allow almost any movement other than walking a given path in virtual space only for DT estimation (Bruder et al. 2009b; Steinicke et al. 2008a; Steinicke et al. 2009), the RDW performance was the highest in the Control condition. A narrower DT range means that the user's walking path can be slightly manipulated. Thus situations that demand avoiding an obstacle or escaping a confined space require more frequent intervention of the RDW technique, which reduces the effectiveness of the redirection performance. However, when the RDW technique using a narrow DT range is applied, the visual-vestibular discrepancy does not increase, and the user's physical walking path does not change significantly; thus, the user can feel less discomfort while moving in the VR environment, and the VR system can accurately trace the user's location. Although the range of DT is reduced when OF is additionally provided, the RDW technique with predictable RDW performance can be applied by further analyzing the cause of DT narrowing in this virtual environment and by estimating the effect of OF on RDW performance. In this context, the RDW technique can meet the needs of practical application without limiting VR content (Nilsson et al. 2018a). Examples include environments in which motion exists around the user (i.e., a situation in which the user crosses a crosswalk with many vehicles passing, a planet with independent motion in the space background moves, and a Tinkerbell flies around the user).

Table 1 DT analysis according to OF condition

OF condition	UDT	PSE	LDT	DT range	Difference (%)
Control	– 0.0250	0.0070	0.0390	0.0641	
Same	– 0.0169	0.0104	0.0377	0.0546	– 14.80
Opposite	– 0.0218	0.0052	0.0323	0.0542	– 15.46
Distributed	– 0.0144	0.0107	0.0359	0.0504	– 21.38

4.1.2 Influence of VR familiarity on curvature DT range

The curvature DT estimated by participants based on VR familiarity was analyzed across all OF conditions. A repeated measures ANOVA with Greenhouse–Geisser correction ($\varepsilon = 0.616$) and post hoc tests using Bonferroni adjustment was conducted to compare the DT ranges across all OF conditions and user's VR familiarity, ($F(3,33) = 0.764$, $p = 0.522$, $\eta_p^2 = 0.065$). The results showed that there is no significant effect on the DT range between the VRUF and VRF groups according to different OF conditions. As presented in Fig. 4 and Table 2, compared to the DT range for all participants, the average DT range for the VRF group was 25.22% wider, while the DT range for the VRUF group was 27.76% narrower (see Difference compared to the same condition (CsC) (%) column in Table 2). The 'Difference CsC (%)' column of Table 2 shows the percentage change of DT ranges of VRUF and VRF groups compared to the DT ranges of all groups in the same condition. Similar to a previous study showing that action video game players experienced more vection and limited discomfort than non-action video gamers (Freitag et al. 2016; Sargunam et al. 2017), the VRF group could strongly feel the illusion of self-motion induced by the OF of IMO. We inferred that the VRF group would not have noticed redirecting manipulation even when a greater curvature gain occurred.

In each of the OF conditions, the DT range of the VRF group was always wider than the case of the VRUF group (see Table 2). The DT ranges of the VRF and the VRUF groups were compared in each OF condition as follows.

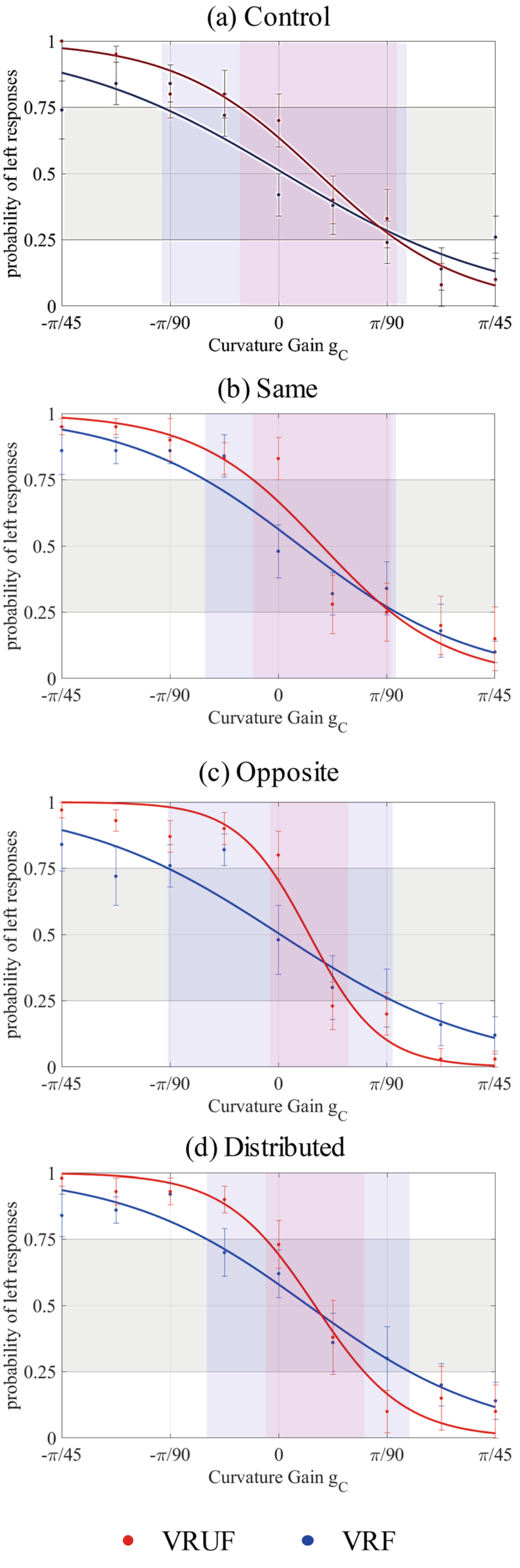


Fig. 4 Average probability of responding "left" considering the VR familiarity in each condition of **a** Control, **b** Same, **c** Opposite, and **d** Distributed

Table 2 DT analysis according to the VR familiarity in each OF condition

	UDT	PSE	LDT	DT range	*Difference CsC (%)
All condition					
All	– 0.0192	0.0085	0.0362	0.0554	
VRUF	– 0.0080	0.0120	0.0321	0.0400	– 27.76
VRF	– 0.0295	0.0052	0.0399	0.0693	25.22
Control condition					
All	– 0.0250	0.0070	0.0390	0.0641	
VRUF	– 0.0125	0.0128	0.0380	0.0505	– 21.16
VRF	– 0.0376	0.0018	0.0412	0.0788	22.95
Same condition					
All	– 0.0169	0.0104	0.0377	0.0546	
VRUF	– 0.0081	0.0141	0.0364	0.0445	– 18.53
VRF	– 0.0236	0.0072	0.0380	0.0616	12.80
Opposite condition					
All	– 0.0218	0.0052	0.0323	0.0542	
VRUF	– 0.0026	0.0100	0.0226	0.0252	– 53.43
VRF	– 0.0356	0.0007	0.0369	0.0725	33.77
Distributed condition					
All	– 0.0144	0.0107	0.0359	0.0504	
VRUF	– 0.0041	0.0117	0.0275	0.0317	– 37.15
VRF	– 0.0231	0.0095	0.0422	0.0653	29.54

*Difference CsC = Difference compared to same condition

Regarding the VRUF group, the DT range was the widest in the condition without the IMO, but the DT range was narrower than the DT range of the VRF group regardless of the direction conditions (see Fig. 4). Unexpectedly, the DT range narrowed in the order of the Same, Distributed, and Opposite conditions, which revealed the reverse order to the difference pattern of the DT range of the VRF group (see Difference CsC (%) column in Table 2). The OF did not induce the illusion of self-motion but helped the participants to recognize redirecting manipulation. Therefore, the participants might have experienced redirecting manipulation even with a smaller curvature gain.

The gaze behavior of individuals with prior experiences or domain knowledge differed from those without such experiences. Experienced individuals tend to exhibit efficient and purposeful gaze patterns due to their deeper understanding of the relevance of visual cues, whereas novices may display less efficient gaze movements (Kasarskis et al. 2001; Yorkston et al. 2000). We collected feedback from participants after the experiment involving IMO to evaluate IMO's impact on their experience. Interestingly, over 60% of the VR-unfamiliar participants reported that IMO did not significantly affect them, and they paid little attention to it. Considering our findings that VR-unfamiliar participants had a reduced presence compared to the VR-familiar group, they may have been less accustomed to the virtual environment and therefore possibly less responsive to IMO. We categorized our VRF group as possessing prior experiences; they might exhibit distinct gaze behaviors when exploring the virtual environment with OF, which likely contributed to differing tendencies in DT range changes compared to the VRUF group. For example, participants in the VRUF group likely concentrated on the walking path to complete the task rather than observing IMO. Conversely, participants in the VRF group may have paid relatively more attention to IMO. In essence, due to varying gaze patterns in each group when exploring the virtual space, we hypothesize that the DT range assessed by the VRUF group under different OF conditions would exhibit trends opposing those of the VRF group. To explore this possibility, it is imperative to collect and compare data related to participants' gaze patterns (e.g., objects fixated upon, gaze fixation time, gaze frequency, etc.) or head rotation data.

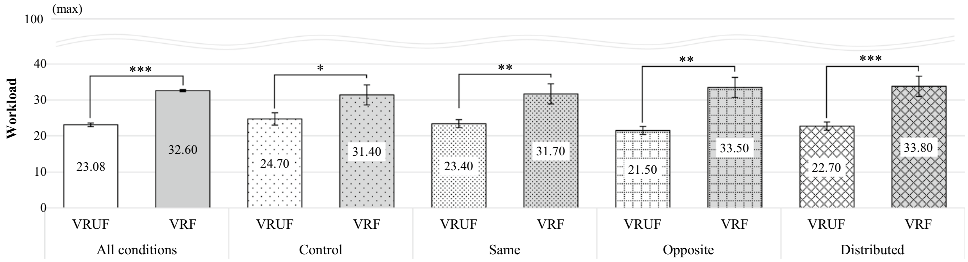
Regarding the VRF group, the DT range in the absence of IMO was the widest (see Fig. 4a), but it changed according to the direction of the OF of the IMO, which rotated in various directions. The DT range increased in the order of the Opposite, Distributed, and Same conditions (see Table 2). As the OF by IMO increased the amount of the OF in the direction of curvature redirecting (the Same condition), the participants would have strongly felt the discrepancy between visual and vestibular signals (see Fig. 4b). In the Opposite condition, the OF caused by curvature redirection and the OF generated by IMO canceled each other out, and the amount of OF perceived by the participants was reduced. In this regard, we assumed that the participants were not aware of redirection manipulation (see Fig. 4c). In the Distributed condition, two drones rotated in the same direction as the redirecting manipulation direction, and the other two drones rotated in the opposite direction to the redirecting manipulation direction. The OF value was approximately half the value of each DT range under the Same and Opposite conditions (see Fig. 4d and the Difference CsC (%) column in Table 2). In that case, an OF in the Distributed condition has a similar effect on the participants to that when there is a simultaneous influence of the OF in the Same and Opposite conditions.

Given the relatively narrow average DT range of the VRUF group, the user's walking path should be manipulated less than that of the VR-familiar group. In particular, in a virtual environment where OF is added, the user's walking path needs to be manipulated even less. As described, an RDW strategy that can achieve the highest RDW performance according to the conditions of OF and VR familiarity should be established. Under the Same condition, the difference between the DT ranges of the VRUF and VRF groups was the smallest; therefore, when VR familiarity is ambiguous, robust RDW performance can be expected under these OF conditions regardless of VR familiarity. By contrast, in an environment with IMO rotating opposite from RDW manipulation direction, the difference between the DT ranges was the largest according to the VR familiarity. According to our results, for users who are familiar with VR technology, if an OF in the opposite direction from RDW is applied, the users may be unaware that a large value of RDW gain is applied. Consequently, RDW performance can increase.

4.2 Influence of IMO on perceived user experience

4.2.1 Workload

The workload of the VRF group was higher than that of the VRUF group. Because the skewness of the workload did not exceed an absolute value of two and the kurtosis of the workload did not exceed an absolute value of seven, the data was considered normally distributed. We performed a repeated measures ANOVA with a Greenhouse–Geisser correction ($\varepsilon = 0.683$), which indicated that there was no interaction between the OF condition and VR familiarity, ($F(2.048, 36.864) = 2.470$, $p = 0.097$, $\eta_p^2 = 0.121$). We conducted a post hoc test with Bonferroni adjustment to compare the workload of VRUF and VRF groups in each OF condition. In particular, VRF participants experienced a considerably higher workload in Control ($p = 0.026$), Same ($p = 0.003$), Opposite ($p = 0.001$), and Distributed ($p < 0.001$) conditions than those of the VRUF group, as displayed in Fig. 5. In a previous study, participants did not easily observe a redirecting manipulation when walking



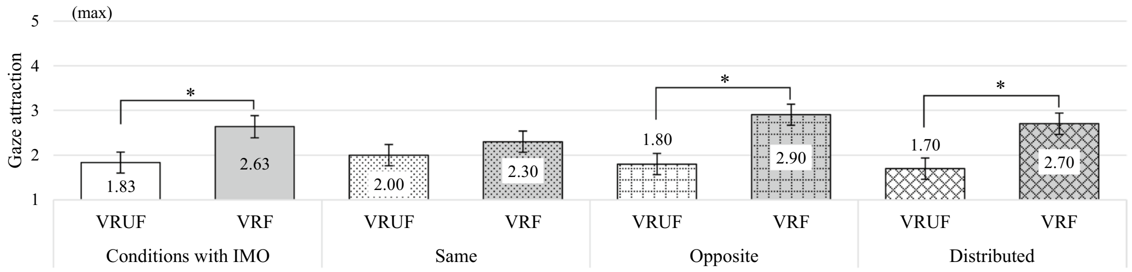
*Significant at p-value < 0.05, **Significant at p-value < 0.005, ***Significant at p-value < 0.001

Fig. 5 Workload according to the VR familiarity in each optical flow condition while performing a task that required a higher cognitive load (e.g., a dual task) than walking while performing a single task (Nguyen et al. 2020). The result of another study showed that the higher the interaction complexity, the lower the perception of the RDW technique (Ciumedean et al. 2020; Cools and Simeone 2019), indicating a similar trend to our experimental results in which the VRF group, which felt a high workload, was estimated with a wider DT range. In a previous study, participants with similar prior experiences tended to strongly feel vection (Pöhlmann et al. 2022). We inferred that the VRF group strongly experienced self-motion illusion caused by the OF of IMO. The OF may have increased the workload because it was difficult for the VRF group to distinguish whether their walking trajectories changed to the left or the right in the 2AFC questions they answered for DT estimation. The VRUF group did not feel the illusion of self-motion as strongly as the VRF group did. Answering the 2AFC question also was easy; hence, the workload would not have increased. For this reason, familiarity with VR technology works similarly to making interactions with VR environments more challenging, and modulation of visual cue patterns can increase the workload. Additionally, the walking direction of the user can be changed with a large curvature gain value.

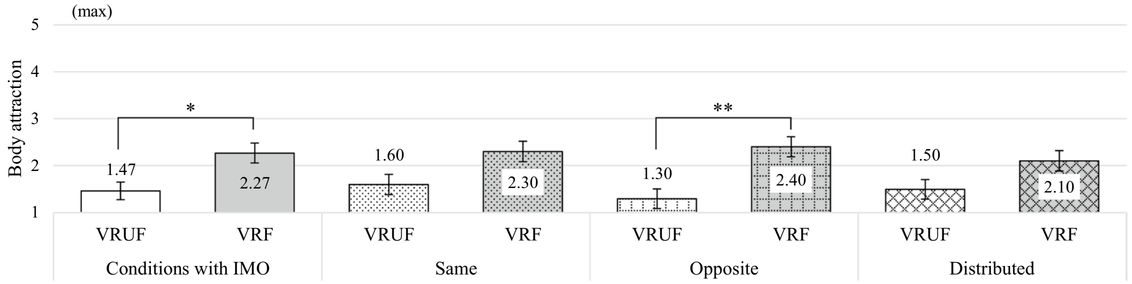
4.2.2 Attraction of IMO

In the condition with IMO rotational movement, the VRF group's gaze attraction (questionnaire: "As I walked, my gaze followed the moving object (drone).") and body attraction (questionnaire: "While walking, my body tried to follow a moving object (drone).") scores were higher than those of the VRUF group. The gaze and body attraction scores were considered normally distributed based on the fact that the skewness and kurtosis of each data did not exceed an absolute value of two, and the kurtosis did not exceed an absolute value of seven. Repeated measures ANOVA was performed with Greenhouse–Geisser correction ($\varepsilon = 0.603$ for gaze attraction and $\varepsilon = 0.532$ for body attraction). In gaze attraction, there was no significant interaction between OF condition and VR familiarity, $F(1.891, 34.032) = 1.299$, $p = 0.285$, $\eta_p^2 = 0.067$. Likewise, in the case of body attraction, the VR familiarity and OF conditions did not significantly interact, $F(1.595, 28.719) = 0.875$, $p = 0.406$, $\eta_p^2 = 0.046$. Given that post hoc test with Bonferroni correction, VR familiarity significantly influenced the gaze ($p = 0.038$) and body ($p = 0.027$) attraction scores in the condition with IMO, as shown in Fig. 6a and b). According to the attraction scores, the VRF group exhibited a tendency to significantly see the rotating IMO more than the VRUF group in Opposite ($p = 0.041$) and Distributed ($p = 0.039$) conditions and

(a) Question: As I walked, my gaze followed the moving object (drone).



(b) Question: While walking, my body tried to follow the moving object (drone).



*Significant at p-value < 0.05, **Significant at p-value < 0.005

Fig. 6 Scores of **a** IMO's gaze attraction and **b** IMO's body attraction according to the VR familiarity in each optical flow condition significantly follow the IMO more than the VRUF group in the Opposite condition ($p = 0.002$) (see Fig. 6a and b). Based on previous studies that suggest that users who had no similar VR experiences felt strange when using VR and had difficulty feeling unmediated experience (Lombard and Ditton 1997; Sagnier et al. 2019). The group unfamiliar with wearing the VR HMD and being in a virtual space tends to focus more on their walking rather than focusing on IMO, which results in a low attraction score of IMO. Although we did not instruct participants to focus on the flying drone, the VRF group, which gazed at the drone more frequently and whose body was willing to follow it, may have considered the IMO as a distractor that attracts the user's visual attention and hinders the user's awareness of the reorientation manipulation (Williams and Peck 2019).

Additionally, as a result of the shorter vection onset time when visually perceiving and focusing on an independent target instead of focusing on the visual effect that induces vection (Trutoiu et al. 2008), we can interpret that the VRF group that gave a high gaze and body attraction score perceives vection faster. According to our results, VRF participants physically focused on the IMO and perceived the OF provided by the IMO, and experienced the illusion of self-motion strongly, resulting in wider DT ranges than those of VRUF. Thus, the attraction of the IMO to participants could be related to whether or not they experienced vection by the OF and the change in the DT range of curvature redirection. To analyze the effect of the OF in more depth, using sensors—such as an eye tracker or GSR, that can check gaze patterns and workloads of a user when various curvature gains are applied—the perception of the user of redirection manipulation depending on the OF can be measured in real-time.

4.2.3 Presence and VR sickness

According to the skewness and kurtosis of the presence and VR sickness, our data was considered normally distributed. Repeated measures ANOVA was performed with Mauchly's test for presence ($\chi^2(5) = 4.664$, $p = 0.459$) and for VR sickness ($\chi^2(5) = 9.656$, $p = 0.086$) and did not indicate any violation of sphericity. There was no significant interaction between OF condition and VR familiarity in the presence ($F(3, 54) = 0.290$, $p = 0.833$, $\eta_p^2 = 0.016$) and VR sickness ($F(3, 54) = 1.488$, $p = 0.228$, $\eta_p^2 = 0.076$). We conducted a post hoc test with Bonferroni adjustment, which showed that the presence and VR sickness of VRUF and VRF groups were not significantly affected by the OF condition. Although not statistically significant, the VRF group felt a higher presence, on average, than the VRUF group in all conditions (see Fig. 7a). The presence score of the VRUF group would have been lower than that of the VRF group because the VRUF group could recognize redirecting manipulation accurately even when the curvature gain value was small. Given this point, our results indicated that the influence of the participants' VR familiarity may affect their sense of presence. VRF and VRUF groups experienced a similar level of VR sickness (see Fig. 7b). All participants

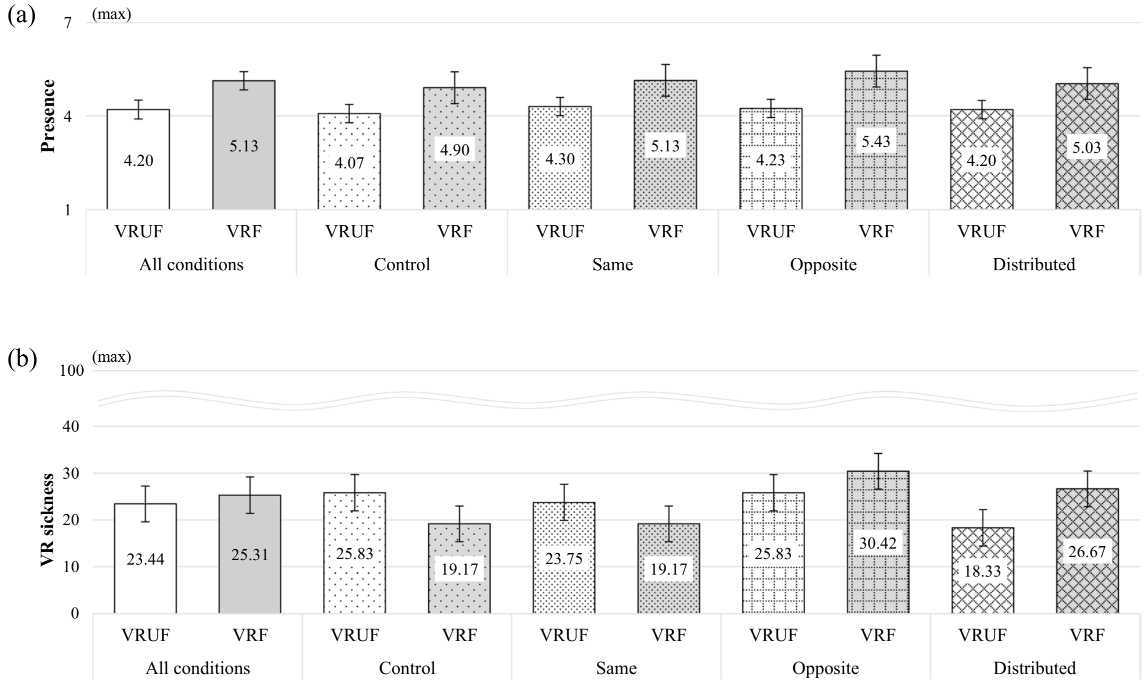


Fig. 7 Scores of **a** presence and **b** VR sickness according to the VR familiarity in each optical flow condition

rated their VR sickness level as low. Additionally, the effect of VR familiarity was negligible. The results support the previous study that prior experience with VR increases the presence felt by participants in the virtual environment but has no significant effect on motion sickness (Sagnier et al. 2019).

5 Conclusion

In this study, our approach applies an IMO-generated OF visual cue to a moving user in a virtual environment, making the user less aware of redirecting manipulations because of the illusion of self-motion feeling. IMO was designed to generate OF patterns in the direction coincident with, opposite to, and of dispersion from the direction of curvature redirecting manipulation, and we estimated the DT based on nine curvature gains.

Our experimental results show that when the OF with directionality was inserted in the virtual space, the participants tended to experience redirecting manipulation more easily than when no OF was present. In contrast, under the conditions that the OF is provided, the DT range increased more for the VRF group than for the VRUF group. This implies that because the user with VR familiarity is more immersed in the VR scene and IMOs, the user felt a strong illusion of self-motion caused by the OF. The results confirmed that the user's VR familiarity affects the RDW performance and can also change the RDW performance in the virtual environment in which the directional OF exists. Thus, a higher RDW performance can be expected from a user with a high VR familiarity. Furthermore, if the user's VR familiarity is ambiguous, the modulated OF can expect robust RDW performance regardless of VR familiarity.

The results indicated that while the introduction of OF may reduce a user's DT range, intriguingly, it also has the potential to extend the DT range, particularly among VR-familiar users. In the future, we aim to extend this study by considering the level of VR familiarity and rendering IMOs with different velocities and types to understand the factors that affect DT change. In addition, the OF generator for manipulating the user's walking trajectory or the OF information extractor of the user's VR scene during redirection will help understand the OF effect that the user perceives for redirecting manipulation. The user's level of VR familiarity can evolve in response to their exposure to VR experiences, and the DT range may also alter under varying levels of VR familiarity. Therefore, it is necessary to examine the nature of the DT range extension according to the user's VR familiarity, such as whether the DT range undergoes a proportional extension or stabilizes at a specific level depending on the user's VR familiarity. To extend the application of the RDW technique to VR contents from a static environment to a dynamic environment and establish an RDW technique design strategy to increase RDW performance according to the user and situation, it is important to investigate whether the OF and user's VR familiarity change the thresholds of rotation and translation gains in RDW.

Acknowledgements This research was supported in part by the National Research Foundation of Korea (NRF) funded by the MSIT(2021R1A4A1030075) and Institute of Information & communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (No.2019-0-01842, Artificial Intelligence Graduate School Program (GIST)).

Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

Ethical approval The research was approved by the Institutional Review Board (IRB No. 20210806-HR-62–01-02).

Informed consent We informed and obtained consent from each participant prior to research engagement.

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