Redirected Walking using Continuous Curvature Manipulation

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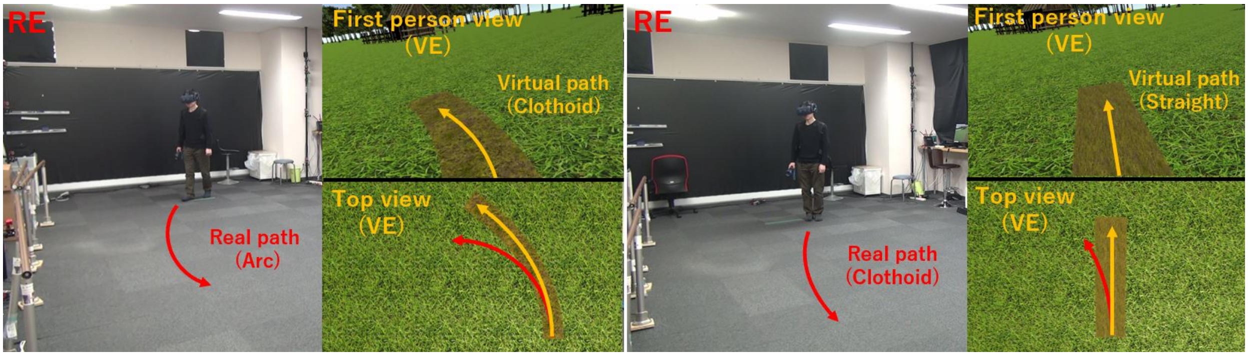

Fig. 1. Overview of the proposed RDW manipulation. The left image shows the user's trajectory of the real environment (RE) and the first person view and the top view in the virtual environment (VE) under the proposed manipulation method with a dynamic bending gain. In the case, users experience walking on a clothoid curve whose curvature continuously changes in the VE while walking on an arc path whose curvature is constant in the RE. The right image shows the user's trajectory of the RE and the first person view and the top view in the VE under the proposed manipulation method with a dynamic curvature gain. In the case, users experience walking on a straight path in the VE while walking on a clothoid curve whose curvature is continuously changing in the RE.

Abstract— In this paper, we propose a novel redirected walking (RDW) technique that applies dynamic bending and curvature gains so that users perceive less discomfort than existing techniques that apply constant gains. Humans are less likely to notice continuous changes than those that are sudden. Therefore, instead of applying constant bending or curvature gains to users, we propose a dynamic method that continuously changes the gains. We conduct experiments to investigate the effect of dynamic gains in bending and curvature manipulation with regards to discomfort. The experimental results show that the proposed method significantly suppresses discomfort by up to 16 and 9% for bending and curvature manipulations, respectively.

Index Terms—Redirected walking, continuous curvature change, dynamic gain, clothoid curve, virtual reality

1 Introduction

Because walking is one of the most basic human actions, it is quite important for a virtual environment (VE) to allow users to walk naturally as if they were walking in a real environment (RE). Allowing this leads to a higher level of immersion. One of the simplest methods for this is to allow users to walk in an RE while reflecting their positions and postures in the VE [38, 46]. This real walking method provides the same sensations as those felt in the RE, but it has a problem that the walking range is limited to the size of the system-confined RE. To solve this problem, redirected walking (RDW) [32] was proposed. RDW enables users to walk through a vast VE in a limited system-confined RE by controlling the spatial correspondences between the VE and the RE. This is achieved by manipulating users' walking trajectories through modified visual feedback of the virtual surroundings without users noticing this manipulation.

RDW manipulation methods are categorized into three types: translational, rotational, and curvature manipulations [20, 28, 39]. With the translational manipulation, scaled user movement in the RE can be reflected in their movement in the VE. The ratio of the RE vs. VE movement is defined as the translation gain [40]. With the rotational manipulation, the amplified user head rotation in the RE can be reflected in their head rotation in the VE. The ratio of RE vs. VE rotation is the rotation gain [40]. In this paper, we define a manipulation that modifies the curvature of the walking path as "curvature manipulation". There are two types. The first maps a circular arc in the RE to a straight line in the VE. The curvature of the path in the RE is the curvature gain [40]. The second maps a circular arc in the RE to one of a larger or smaller radius in the VE. The ratio of RE vs. VE path curvature is the bending gain [20].

Although these manipulations enable users to walk in a VE that is larger than the system-confined RE with natural walking sensations, some problems persist. For example, the RDW manipulation thresholds that can be applied without being noticed by users is limited. For translation gains, users are aware that the RDW is applied when the translation gain exceeds 1.24 [39]. Extending the applicable range of the gain is an important issue in RDW.

To address this, it has been shown that the use of dynamic gains instead of constant gains as in previous research can expand the applicable manipulation range. Congdon et al. [9] compared dynamic and constant gains via rotational manipulation to investigate user noticeability. The experimental results showed that the dynamic gain was less noticeable under rotational manipulation, even when a larger gain was given. This study suggests that dynamic gain may be beneficial in RDW. However, its effectiveness has only been confirmed for rotational manipulation, and it is not clear whether it is effective for other RDW types. Because curvature manipulations are more versatile than other RDW techniques, it is important to check whether their efficiency can

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be increased by dynamic gain.

Meanwhile, natural human motion can be approximated using a model that minimizes jerk [13]. In RDW, sudden gain changes can shift the user's trajectory, leading to an increase in the jerk. Therefore keeping the gain changes small will bring the user's motion closer to a natural one. Moreover, there is a habituation [45], in which the response to a stimulus decreases when a stimulus having small repetitive changes is presented. The curvature manipulations applied for the entire duration of the walk tend to have longer exposure times than those of rotational manipulations, which are typically applied only for a short period of (e.g., while looking back). Therefore, the effects of these perceptual characteristics are likely to occur. Considering this, it is expected that the effect of curvature manipulation can be enhanced by using dynamic gains. For this reason we clarify the extent to which the effectiveness of curvature manipulation is improved by introducing dynamic bending and curvature gains. In particular, we investigate the extent to which the use of dynamic gains can reduce discomfort compared with the use of conventional constant gain.

The main contributions of this paper include the proposal of a curvature manipulation method using dynamic bending and curvature gains and the demonstration that the use of these dynamic gains in curvature manipulations can reduce discomfort compared with conventional curvature manipulation with constant gain. Our experimental results show that the proposed method can significantly suppress discomfort, which leads to better spatial compression efficiency in curvature manipulations without being noticed by the user.

2 Related Work

There are three types of methods that enable a user to explore a VE [2]: those without actual walking, those with walking on a spot, and those with natural walking activities. The first method relies eye movement [41], hand movement [6, 7, 34], and center-of-gravity movement [11, 19], among others. Although this method has the advantage of no spatial constraints, it does not involve human ambulation and is therefore not sufficiently immersive. Because the experience of walking in the VE must provide a natural walking sensation similar to that of the RE, it is difficult to achieve this goal using this method. The second method uses treadmills [17, 37], locomotion devices [4, 18, 24], and walk-in-place technology [12, 50] and has the advantage of being spatially unconstrained. However, this method is not sufficiently immersive, because users are stationary relative to space. As with the first method, the walking experience by this method is not similar enough to reality. In addition to this, it is very expensive to utilize treadmills or locomotion devices. The third method overcomes many of these limitations. Doing so, a natural gait can be realized, but the range of movement is limited to the size of the constrained system space.

RDW was proposed to remove these limitations. It relies on the manipulation of VE structure and the hidden manipulation of the user's viewpoint to realize slightly different movements in the VE than those in the RE. For example, there are approaches that manipulate the positions of doors and corridors [42], and some that overlap rooms [8, 43, 47, 48]. These methods are applicable to a limited number of scenes (e.g. indoor). On the other hand, the viewpoint manipulation is widely applicable regardless of VE structure.

There are four main gains that often used to manipulate this viewpoint: translation gain (g_T), rotation gain (g_R), curvature gain (g_C), and bending gain (g_B). With translation gain, the user's movement in the RE is scaled up or down and the scaled user's movement is reflected in the VE movement. With rotation gain, the user's rotation on the spot in the RE is scaled up or down and the scaled user's rotation is reflected in the VE rotation. Another method that differs from RDW but uses intentional noticeable gains to perform large manipulations has also been proposed [1]. Rotation gain is also used for the reset manipulation to guide the user to the center of the RE after reaching the edge of the RE [30, 49]. To guide the user to the center of the RE, a method using distractors as guides was also proposed [10]. Curvature gain modifies the position and orientation of users who walk on a circular arc in the RE to those of a straight line in the VE. Bending gain modifies the position and orientation of users who walk on a circular arc in the RE to those on an arc having a larger or smaller radius in the VE. Other types of gains (e.g., turning [25], strafing [52], gradient [23]), and those related to jumping [16] have been used.

There are various detection thresholds for these gains, each indicating the range of manipulations that can be applied without being noticed by users. For example, a curvature manipulation is unnoticeable if the radius in the RE is 22.03 m or greater [39], and a bending manipulation can increase the radius in the VE to 10.88 m when the radius in a RE is 2.5 m [20]. In previous studies, various approaches have been adopted to extend the detection threshold. Grechkin et al. [15] investigated whether the combined application of translation and curvature gains improved the effectiveness of curvature manipulation but found no changes in the detection threshold. Neth et al. [26] showed that the slower the users' pace, the less likely it is that the curvature manipulation is noticed. Thus, when the user walks at a speed of 0.75 $m \cdot s^{-1}$, the radius of the RE path can be compressed to 10.57 m. Matsumoto et al. [22] found that the radius of the RE path could be compressed to 6 m by adding haptic information, such as when walking and touching a wall using curvature manipulation. An approach using auditory information has also been proposed [14, 29], showing an effective expansion of the detection threshold for curvature manipulation in situations where the reliability of visual information is low [14]. Sun et al. [44] demonstrated that by utilizing saccades, (i.e., quick, simultaneous movements of both eyes between two or more phases of fixation in the same direction), bigger rotation gains could be applied. Addtionally, Rietzler et al. [33] investigated the curvature gain, which is not based on the perceptual threshold but is based on the applicability of the RDW in terms of the naturalness of the motion and discomfort, showing that a larger gain was capable.

These approaches have mainly focused on the application of constant gains. On the other hand, it has been suggested that dynamic gains would be more effective in RDW. Congdon et al. [9] compared a method of gradually changing the rotation gain with suddenly changing the rotation gain like a step function, demonstrating that the former method makes it more difficult for users to notice the manipulation. It is thought that the jerk and the phenomenon of habituation exist in the background of such dynamic gain applications. In turn, it has been shown that natural human motion can be approximated by a model that minimizes jerk [13]. In RDW, a continuously changing gain can be used to suppress sudden changes in motion and keep the jerk small, which leads to a natural human motion with little discomfort. Habituation is a phenomenon in which the response to a stimulus decreases when the stimulus is presented continuously and is considered to be a part of non-associative learning [31, 45]. Although habituation occurs for a specific stimulus and recovers in a certain amount of time, it can be improved by repeated exposure. On the other hand, when another stimulus intervenes, the effect is reduced. A study examined the long-term effects of habituation in RDW [5], showing that the participants noticed the manipulation at a radius of 7.7 m in a RE before walking, but they did not notice the manipulation until a radius of 5.4 m was reached after 20-min walking with a constant curvature gain.

Based on these findings, we consider that a more effective RDW can be achieved by using dynamic gain not only for rotational but also for curvature manipulations. In the next section, we propose dynamic manipulations that change the curvature of a walking path continuously with bending and curvature gains.

3 Continuous Curvature Manipulation

In this section, we propose a method of dynamically increasing the amount of manipulation by continuously changing the curvature of user's walking path in order to achieve more effective manipulation in the RDW. We hypothesized that this would enable us to acclimate user perception of the RDW manipulation and apply a large gain while suppressing any increase of discomfort by minimizing the change in the stimulus when increasing the amount of RDW.

3.1 Path with Continuous Curvature Change

In the proposed method, the path curvature in either RE or VE changes continuously, and the arc with the constant curvature used in the conventional curvature manipulation is insufficient. In this study, we used a clothoid curve to realize the continuous curvature change of a path.

A clothoid curve is a one whose curvature varies in proportion to the length of the curve and is expressed by the following equation.

$$\begin{aligned} \mathbf{P} &= \mathbf{P_0} + \int_0^s e^{j\phi} ds \\ &= \mathbf{P_0} + \int_0^s (\cos\phi + j\sin\phi) ds \end{aligned} \tag{1}$$

$$\phi = c_0 + c_1 s + \frac{1}{2} c_2 s^2 \tag{2}$$

where $\mathbf{P}$ is the position vector on the curve, $\mathbf{P_0}$ is the starting point, s is the length from the starting point, and ϕ is the tangent direction, [rad], at any point on the curve. c_0, c_1, and c_2 are all constants.

In the above equation, if $s = 0$, then $\phi = c_0$, where c_0 is the tangential direction at the starting point. Similarly, when $s = 0$, $\frac{d}{ds}\phi = c_1$, where c_1 is the curvature, $[\mathrm{rad} \cdot \mathrm{m}^{-1}]$, at the starting point. Additionally, since $\frac{d^2}{ds^2}\phi = c_2$, c_2 represents contraction, which is the curvature change rate $[\mathrm{rad} \cdot \mathrm{m}^{-2}]$, the fact that this is constant indicates that the curvature change rate of a clothoid curve is constant regardless of its length.

Because the curvature of a clothoid curve always changes at a constant rate, the curve exhibits a smooth curvature change, which can mitigate sudden changes in centrifugal force and speed. For this reason, a clothoid curve is used in the RE for the curves of highways [3] and vertical loops of roller coasters.

3.2 Dynamic Bending Gain using Continuous Curvature Change

As mentioned, a walking path having a continuously changing curvature can be designed using a clothoid curve. Using such a path, we investigated the dynamic curvature manipulation method in the RDW including bending and curvature gains. First, we propose a dynamic bending gain.

The bending gain is defined as $g_B := \frac{r'}{r}$. Here where r is the radius of the path in the RE, and r' is the radius of the path in the VE. In the conventional manipulation method with bending gain, the path in both the RE and the VE is a circular arc, and its radius is constant. Therefore, the value of the bending gain, g_B, is also constant. However, in the case of dynamic bending gain, this value changes dynamically. Thus, the radius, r, in the RE or the radius, r', in the VE changes dynamically.

In this study, to simplify the situation, we assume that only one of r and r' changes dynamically. In particular, because r' is constant at infinity in the manipulation with curvature gain described later, we consider a situation in which only the radius, r', of the path in the VE changes dynamically. Therefore, the bending gain we propose is used to map from an arc path of constant curvature in the RE to a clothoid path in the VE. We explain this manipulation method using Fig. 2, which is based on the manipulation method of a previous study [20].

The user's position in the RE is p, the position of the user in the VE is p' , and r is the radius of the path in the RE. The purpose of this manipulation is to find the corresponding position, p', in the VE from the user's position, p, in the RE, and following manipulations are performed.

1. Move the user's position, $p(p_x, p_y)$, in RE to the position, $q(q_x, q_y)$, which is corrected by d from the default circular path.

$$q_x = p_x + d\cos(\theta) \tag{3}$$
$$q_y = p_y - d\sin(\theta) \tag{4}$$

2. Find the position, $q'(q'_x, q'_y)$, on the clothoid curve corresponding to the position, $q(q_x, q_y)$, on the arc. The length of the clothoid curve should be equal to that of the arc, such that the user's walking distance is the same between the RE and the VE. Note that ϕ appears in equation 2, where it corresponds to the angle between the tangent line at position q' and the positive direction of the x-axis.

$$q'_x = \int_0^{r\cdot\theta} \cos\phi\, ds \tag{5}$$
$$q'_y = \int_0^{r\cdot\theta} \sin\phi\, ds \tag{6}$$

3. Find the position, $p'(p'_x, p'_y)$, which is corrected from the position, q', by the displacement, d, in the VE.

$$p'_x = q'_x + d\cos(\phi + \frac{\pi}{2}) \tag{7}$$
$$p'_y = q'_y + d\sin(\phi + \frac{\pi}{2}) \tag{8}$$

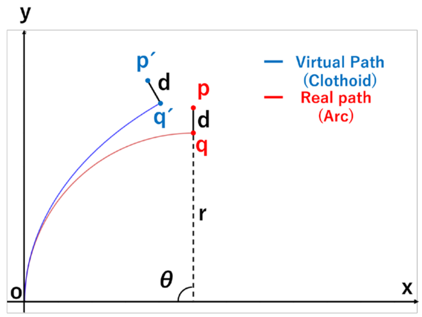


Fig. 2. An overview of manipulation with dynamic bending gain, showing a mapping from an arc path in the RE to a clothoid path in the VE. The user's position in the RE is p, and that in the VE is p' , and they are radially offset from the default path, q, in the RE and q' in the VE by d. r is the radius of the path in the RE, and θ is the angle corresponding to the user's movement in the RE.

By performing the above manipulations, users who walk on an arc path in the RE can be corrected to walk on a clothoid path in the VE, accounting for the deviation in the direction normal to the path. Additionally, the dynamic bending gain maintains a small difference in the shape of the path from the real path, making it difficult for the user to notice the manipulation.

3.3 Dynamic Curvature Gain using Continuous Curvature Change

Following the described bending gain, we describe the dynamic curvature gain using a continuous curvature change.

Curvature gain is defined as $g_C := \frac{1}{r}$. Here, r is the radius of the path in the RE. In conventional manipulations having constant curvature gains, the path in the RE is an arc with a constant curvature, the path in the VE is a straight line, and manipulation with a constant curvature gain, g_C, is applied. In contrast, the manipulation using the dynamic curvature gain proposed in this paper assumes a situation in which the curvature gain changes dynamically. Thus, the radius, r, of the path in the RE changes dynamically. Therefore, the curvature gain proposed in this study is used to map from a clothoid path in the RE to a straight path in the VE. We explain this manipulation method using Fig. 3.

The user's position in the RE is p, and the user's position in the VE is p'. The purpose of this manipulation is to find the corresponding position, p', in the VE from the user's position, p, in the RE, and the following manipulations are performed.

1. Find the arc length, l, and the distance, d, from the user's position, $p(p_x, p_y)$, in the RE to the position, $q(q_x, q_y)$, on the closest default path (clothoid curve). From equations 1 and 2, the coordinates of the points on the clothoid curve are a function of the arc

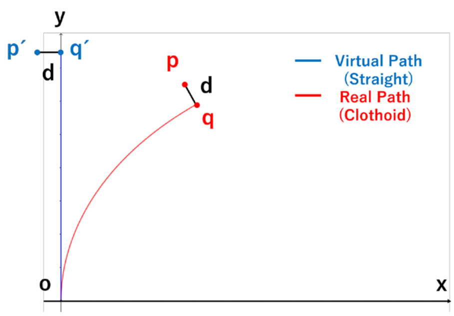


Fig. 3. An overview of the manipulation with dynamic curvature gain, showing a mapping from a clothoid path in the RE to a straight path in the VE. The user's position in RE is p, and that in VE is p' , and they are radially offset from the default path, q, in RE and q' in VE by d.

length, s, and are denoted as $x(s)$ and $y(s)$, respectively. s_{max} is defined as the maximum length of the default path.

$$l = \arg\min_{0\leq s\leq s_{max}} \{(p_x - x(s))^2 + (p_y - y(s))^2\} \quad (9)$$

$$d = \sqrt{(p_x - q_x)^2 + (p_y - q_y)^2} \quad (10)$$

2. Calculate the position, $q'(q'_x, q'_y)$, in the VE corresponding to the position, q, in the RE. The length of the clothoid curve and that of the straight line should be equal so that the user's walking distance is the same between the RE and the VE.

$$q'_x = 0 \quad (11)$$

$$q'_y = l \quad (12)$$

3. Find the position, $p'(p'_x, p'_y)$, which is corrected from the position, q' by the displacement, d, in the VE.

$$p'_x = -d \quad (13)$$

$$p'_y = l \quad (14)$$

By performing the above manipulations, the position of users who walk on a path with continuously changing curvature with a clothoid curve in the RE can be corrected to walk along a straight path in the VE while accounting for the shift in the direction normal to the path.

4 Experiments : Effect of the Curvature Change Rate of the Path on User Discomfort

In this section, we describe two experiments used to investigate the effect of the curvature change rate of the path on the user's perception of discomfort. One experiment was conducted for bending gain (Exp1), and the other was conducted for curvature gain (Exp2).

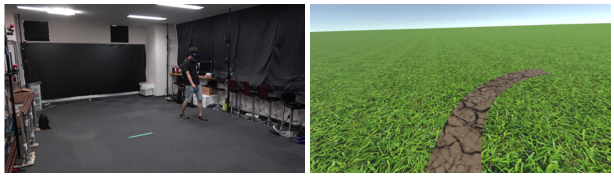
4.1 Experiment 1 (Exp1) : Dynamic Bending Gain

4.1.1 Experimental design

The VE, consisting grassland and a path, was implemented using Unity. Participants wore HTC Vive Pro head-mounted displays (HMDs) , their headphones, and a MSI VR ONE backpack personal computer (PC). They held HTC Vive controllers in their hands.

Five male participants (age 23–25 years, M = 23.6) participated. All had normal or corrected-to-normal vision: two wore contact lenses. Nobody reported any disorders of equilibrium or vision. All participants had used HMDs in the past.

The experiment was conducted using a within-subject design, and the total number of trials was 28. In each trial, the participants walked along a path presented in the VE. The path in the RE had a radius of 2.5 m. The path in the VE was a clothoid curve having a radius of 2.5 m at the starting point. We tested seven different conditions on the curvature change rate of the virtual path, $\in$ {-0.028, -0.024, -0.02, -0.016, 0.008, 0.02, 0.032}, based on preliminary considerations. For negative values, the radius of the path in the VE dynamically increased, and for positive values, the radius dynamically decreased. Both right and left directions were tested, and each condition was repeated twice.



(a) (b)

Fig. 4. Images of a scene during walking (a) Image of the RE(5×4 m tracked area). The participant walked along a circular path. The experiment was conducted in a larger RE (7×7 m tracked area) than this. (b) Image of the VE. A clothoid path was presented to the participant.

In this experiment, we measured the bending gain when the user perceived discomfort based on the method of the previous study [35] and used it as an index to evaluate the effect of the curvature change rate on the perception of discomfort. Because the method having dynamic gains required walking a certain distance to reach a specific gain, this measurement method was more appropriate than the conventional method of measuring the detection threshold by walking a short distance while applying a constant gain. Therefore, when a user felt discomfort during the walk, the controller trigger was pressed and a verbal report was made on the spot. The verbal report contained information about the discomfort perceived corresponding to any of the following three types. The first is about shaky screen, delayed image, or distorted image. The second is about the lack of realism. The last is about the similarity of the movement of the VE to RE walking. We randomly selected a trial to obtain Simulator Sickness Questionnaire (SSQ) results from four trials of each curvature change rate. Thus, seven trials were provided to answer an SSQ for seven curvature change rates.

After the experiment, they answered the Igroup Presence Questionnaire (IPQ) [36].

4.1.2 Procedure

It took about 60 min to complete the experiment per person. After receiving an explanation of the experiment, each participant answered a demographics questionnaire for age, gender, optical correction, vision disorder, and virtual reality (VR) game experience.

After answering the questionnaire, the participants wore HMDs, headphones, and backpack PCs. They held the controllers in their hands and began a practice trial followed by a real trial. In each trial, the participant continued walking on a curved virtual path presented by the HMD (Fig. 4) without resetting until perceiving discomfort about the movement. This was repeated for a total of 28 trials. After the trial, the participants answered the IPQ and verbally reported their impressions and findings, and the experiment ended.

4.1.3 Results

Fig. 5 shows the bending gain when the user perceived a sense of discomfort under the condition that the radius of the virtual path increased. The results were not found to be normally distributed according to the Shapiro–Wilk test at the 5% level. We analyzed the results with the Friedman test at the 5% significance level. As a result, no significant difference was found between the curvature change-rate conditions ($p = 0.472, \chi^2 = 2.52$).

Fig. 6 shows the box plot of bending gain when the user perceived a sense of discomfort under the condition that the radius of the virtual path decreased. The results were found to be normally distributed according to the Shapiro-Wilk test at the 5% level. We analyzed the results using a one-way repeated analysis of varience (ANOVA) test with multiple comparisons at the 5% significance level with the Shaffer correction. The ANOVA test revealed a significant difference between the curvature change rate conditions($F(2,8) = 9.651, p < 0.01, partial\ \eta^2 = 0.502$).

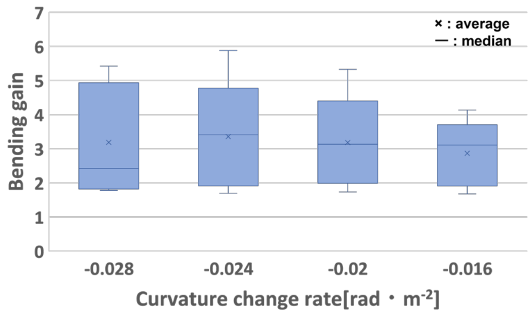


Fig. 5. Bending gain when perceiving discomfort under the condition that the radius of the virtual path increases. Error bars represent the standard error.

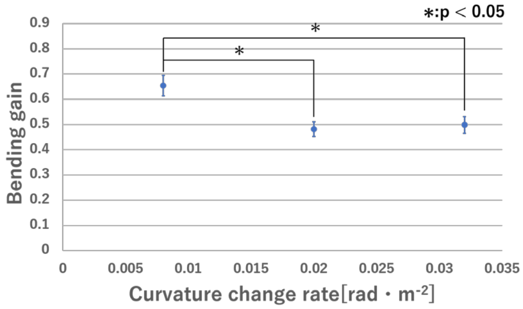


Fig. 6. Bending gain when perceiving discomfort under the condition that the radius of the virtual path decreases. Error bars represent the standard error.

The multiple comparison showed a significant differences in two pairs of curvature change rate: (0.008, 0.02) and (0.008, 0.032) $((0.008, 0.02): p = 0.025, r = 0.924; (0.008, 0.032): p = 0.046, r = 0.819; (0.02, 0.032): p = 0.6794, r = 0.217)$.

Regarding SSQ scores, a one-way repeated ANOVA test revealed no significant differences between the curvature change rate conditions $(F(6,24) = 0.4461, p = 0.8405, partial\ \eta^2 = 0.1)$. The IPQ scores after all trials are shown in Table 1.

4.1.4 Discussion

When the radius of the virtual path increases (curvature decreases), there is no significant difference in the bending gain at the time of perceived discomfort between the curvature change rate conditions. Therefore, we must reserve judgment on whether the rate of change of curvature of the virtual path from -0.028 to -0.016 affects the value of bending gain, which causes discomfort to the user. For practical purposes, a value closer to -0.028 is considered to be more effective, because it allows for faster application of larger manipulations.

When the radius of the virtual path decreases, there is a significant difference in the bending gain when the user perceives a sense of discomfort between the curvature change rates of between 0.008 and 0.02 and between 0.008 and 0.032. This indicates that the bending gain when the user perceives discomfort decreases as the curvature change rate increases from 0.008 to 0.032.

Additionally, some participants reported pulling the trigger after the discomfort became sufficiently large, indicating the need to separate the timing when they started to perceive the discomfort from the time when it became unacceptable.

Table 1. IPQ scores.

Items	Average	Standard Deviation
Sense of being there	4.6	0.8
Spatial presence	4.32	1.11
Involvement	3.15	1.55
Experienced realism	2.15	1.00

To improve the statistical reliability of this experiment, more attention should be paid to the numbers and gender biases of the participants. Previous research showed that female participants were more likely to feel cybersickness [21], and male participants were more sensitive to RDW manipulations [27]. In this experiment, there were only five participants and all of them were male, which made it difficult to get reliable results. Considering these, in following experiments, we need to gather more participants and eliminate the gender bias in order to analyze the perceptual characteristics of RDW more accurately.

We do not consider the condition of decreasing the radius of the virtual path in Exp3, because it is important to make the vast virtual space walkable in the RDW.

4.2 Experiment 2 (Exp2) : Dynamic Curvature Gain

4.2.1 Experimental design

The VE, consisting grassland and a path, was implemented using Unity. The participants wore HMDs (HTC Vive Pro Eye) for the stimulus presentation, their headphones, and backpack PCs (HP VR Backpack), holding HTC Vive controllers in their hands.

Six male and six female participants (age 22–36 years, M = 25.75) participated in our experiment. They are different participants from those in Exp1. All had normal or corrected-to-normal vision: nine wore contact lenses and two wore glasses. No one reported a disorder of equilibrium and vision disorder.

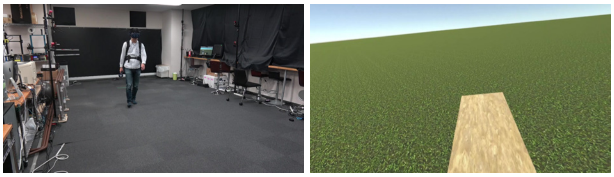
The experiment was conducted using a within-subject design, and the total number of trials was 18. In each trial, the participants walked along the path presented in the VE. The path in the RE was a clothoid curve having a radius of infinity at the starting point, and the path in the VE was a straight line. We tested five different conditions on the curvature change rate of the real path $\in \{0, 0.005, 0.01, 0.02, 0.04\}$. The condition in which the value of the curvature change rate was zero was the baseline condition in which no curvature manipulation was performed, and one trial each of the right and left directions was performed. In other conditions, the rightward and leftward directions were also tested, and each condition was repeated twice. Participants walked 80 m in the baseline condition. In other conditions, they walked until the curvature value reached 0.4 $rad \cdot m^{-1}$ in each trial. In other words, they walked 80 m when the value of curvature change rate was 0.005 $rad \cdot m^{-2}$, 40 m when 0.01 $rad \cdot m^{-2}$, 20 m when 0.02 $rad \cdot m^{-2}$, and 10 m for 0.04 $rad \cdot m^{-2}$.

In this experiment, participants reported when they began to perceive any discomfort in their walking sensation, and when the discomfort increased to an unacceptable level, they pressed the trigger of the controller. Additionally, a questionnaire asking about the magnitude of discomfort during walking using a seven-point Likert scale was presented in the VE for each participant to answer after every 10 m of walking. Additionally, the participants answered the SSQ once before and once after the experiment, and the IPQ after the experiment.

4.2.2 Procedure

It took about 60 min per person to complete the experiment. After receiving an explanation of the experiment, each participant answered a demographics questionnaire in advance in addtion to the SSQ.

Then, the participant donned an HMD, headphones, and the backpack PC and they held the controller in their hands. They then started a practice trial followed by a real trial. In each trial, during walking on a straight virtual path presented by the HMD (Fig. 7) participants changed direction every 5 m and answered questionnaires using a seven-point Likert scale regarding the magnitude of discomfort every 10 m until reaching the curvature value of 0.4 $rad \cdot m^{-1}$ on the real path. In the questionnaires, we asked the question, "How uncomfortable did you feel about the walking sensation?" and evaluated the user's discomfort level on a 7-point Likert scale ranging from 0 (not at all) to 6 (very strong). Each trial ended when the curvature value of the walking path in the RE reached 0.4 $rad \cdot m^{-1}$. This was repeated for a total of 16 trials. After the trial, the participants answered the IPQ and verbally reported their impressions and findings. Then, the experiment ended.



(a) (b)

Fig. 7. Images of a scene during walking (a) Image of the RE (5 m × 4 m tracked area). The participant walked on a clothoid path. (b) Image of the VE. A straight path was presented to the participant.

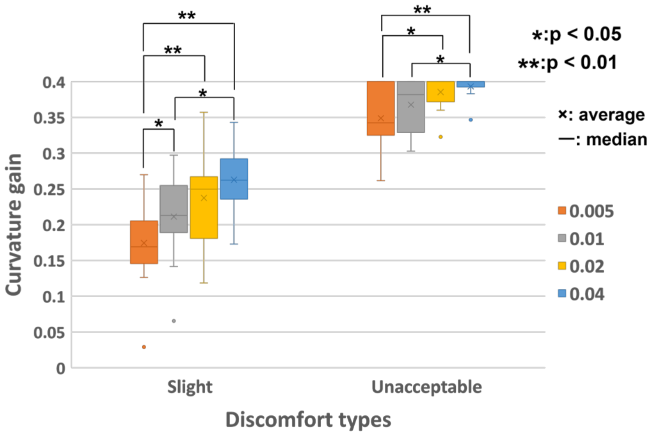


Fig. 8. Curvature gain at the time of discomfort perception for each curvature change rate condition reported by the participants when the trigger was pressed. Error bars represent the standard error.

4.2.3 Results

Fig. 8 shows the curvature gain when the participants perceive discomfort. The bar-chart group on the left-hand side of Fig. 8 shows the curvature gain when the participants begin to perceive any discomfort, and the bar chart group on the right in Fig. 8 shows the curvature gain when the discomfort increases to an unacceptable level. The discomfort types refer to two cases: when they start to perceive any discomfort and when the discomfort increases to an unacceptable level.

The results were not found to be normally distributed according to the Shapiro-Wilk test at the 5% level. We then analyzed the results with a two-way repeated ANOVA after transforming the data using the aligned rank transform [51]. The ANOVA revealed a significant main effect and large effect size of curvature change rates ($F(3,88) = 11.471, p < 0.001, partial\ \eta^2 = 0.280$), and a significant main effect and large effect size of discomfort types ($F(1,88) = 238.614, p < 0.001, partial\ \eta^2 = 0.731$), and no significant interaction effect ($F(3,88) = 1.546, p = 0.208, partial\ \eta^2 = 0.050$). Multiple comparisons of the curvature gain at the beginning of the perception of discomfort for each curvature change rate condition using Wilcoxon's signed rank test showed significant differences in four pairs of curvature change rates: (0.005, 0.01), (0.005, 0.02), (0.005, 0.04), and (0.01, 0.04) ($(0.005, 0.01) : p = 0.034, r = 0.432; (0.005, 0.02) : p = 0.003, r = 0.598; (0.005, 0.04) : p < 0.001, r = 0.712; (0.01, 0.02) : p = 0.204, r = 0.260; (0.01, 0.04) : p = 0.016, r = 0.491; (0.02, 0.04) : p = 0.092, r = 0.344$). Multiple comparisons of the curvature gain at the time of perceived unacceptable discomfort between each curvature change rate condition using Wilcoxon's signed rank test showed significant differences in three pairs of curvature change rates: (0.005, 0.02), (0.005, 0.04), and (0.01, 0.04) ($(0.005, 0.01) : p = 0.109, r = 0.327; (0.005, 0.02) : p = 0.020, r = 0.477; (0.005, 0.04) : p = 0.008, r = 0.543; (0.01, 0.02) : p = 0.195, r = 0.264; (0.01, 0.04) : p = 0.047, r = 0.406; (0.02, 0.04) : p = 0.438, r = 0.158$).

Fig. 9 summarizes the results of responses to the questionnaire on the magnitude of discomfort while walking, which were answered every 10 m, by the curvature of the path at the time of response.

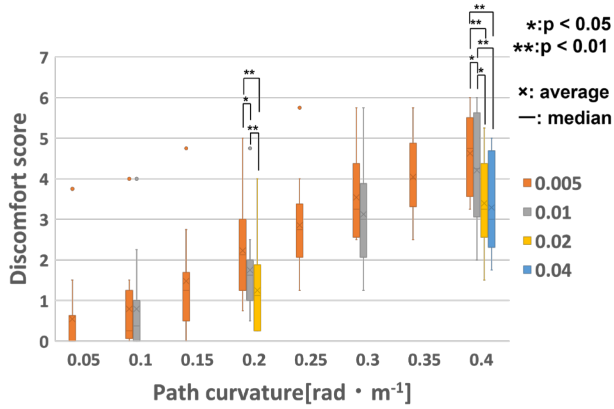


Fig. 9. Discomfort scores for each curvature. The error bars represent the standard error.

Table 2. IPQ scores.

Items	Average	Standard Deviation
Sense of being there	4.75	1.23
Spatial presence	4.43	1.02
Involvement	3.33	1.17
Experienced realism	2.27	0.68

When the value of curvature was 0.2 $rad \cdot m^{-1}$, the results were not found to be normally distributed according to the Shapiro-Wilk test at the 5% level. Therefore, the Friedman test was conducted, and a significant difference was found ($p < 0.001, \chi^2 = 17.73$). The Wilcoxon's signed rank test between the rate of change of curvature conditions showed a significant difference in all combinations ($(0.005, 0.01) : p = 0.049, r = 0.402; (0.005, 0.02) : p < 0.001, r = 0.712; (0.01, 0.02) : p < 0.001, r = 0.632$).

When the value of curvature was 0.4 $rad \cdot m^{-1}$, the results were found to be normally distributed according to the Shapiro-Wilk test at the 5% level. Therefore we analyzed the data with a one-way repeated ANOVA. The ANOVA results showed a significant difference and a large effect size ($F(3,33) = 18.556, p < 0.001, partial\ \eta^2 = 0.197$). Multiple comparisons using the Holm method with correction for p-values showed significant differences in all combinations except for the curvature change between 0.02 and 0.04 $rad \cdot m^{-2}$ ($(0.005, 0.01) : p = 0.027, r = 0.69; (0.005, 0.02) : p < 0.001, r = 0.861; (0.005, 0.04) : p < 0.001, r = 0.883; (0.01, 0.02) : p = 0.027, r = 0.684; (0.01, 0.04) : p = 0.008, r = 0.77; (0.02, 0.04) : p = 0.596, r = 0.162$).

Wilcoxon's signed rank test for the SSQ scores showed that the post-experimental score (mean: 32.41) was significantly higher than the pre-experimental score (mean: 11.22) ($p < 0.001, r = 0.607$). The IPQ scores after the experiment are shown in Table 2.

4.2.4 Discussion

The results suggested that the larger the rate of curvature change of the path during walking, the larger the curvature gain when the participants first felt discomfort. The same tendency was also observed for curvature gain when discomfort was unacceptable. On the other hand, there was no significant difference between the curvature change rates of 0.02 and 0.04 $rad \cdot m^{-2}$ for both discomfort types. This suggests that the curvature gain both when the participants first felt discomfort and when they felt unacceptable discomfort gradually increased in proportion to the curvature change rates, but it is not possible to determine whether user discomfort changes between the curvature change rates of 0.02 and 0.04 $rad \cdot m^{-2}$. Then, in the range studied in this experiment, the largest gain was obtained when the values of curvature change rate were 0.02 or 0.04 $rad \cdot m^{-2}$.

From the results of the discomfort scores for each curvature of the path, it can be seen that the perceived discomfort tends to increase as the curvature of the path increases. For the same curvature, the larger the curvature change rate, the smaller the discomfort score. The results under the curvature value of 0.4 $rad \cdot m^{-1}$ showed that there were significant differences in all combinations except for the curvature change rate between 0.02 and 0.04 $rad \cdot m^{-2}$. This suggests that for the same curvature, that is, the same value of curvature gain, the perceived discomfort is smallest when the curvature change rate is 0.02 or 0.04 $rad \cdot m^{-2}$.

Additionally, in this experiment, direction changes were made every 5 m, which may have created a temporary discontinuity of manipulation, increasing the users' discomfort. Furthermore, owing to the dynamic gain, the walking distance to the same curvature cannot be the same among the conditions. Therefore, it is possible that the larger the rate of change of curvature, the shorter the walking distance to reach the same curvature, and the less discomfort. Thus, it is necessary to consider the effect of walking distance when setting the conditions for dynamic gain application.

From the above, although there are some effects of walking distance, we can conclude that between 0.005 and 0.04 $rad \cdot m^{-2}$ of the curvature change rate, 0.02 or 0.04 $rad \cdot m^{-2}$ are the most effective in suppressing discomfort.

5 Experiments : Investigating the Effect of Dynamic Gains on Discomfort Suppression

In section 4, we examined the effect of the curvature change rate of the path on the user's perceived discomfort with dynamic bending and curvature gains. In this section, using the curvature change rate that was found to be effective in suppressing discomfort, we examine whether continuous curvature manipulations with dynamic gains can suppress discomfort.

5.1 Experiment 3 (Exp3) : Bending Gain

In this experiment, we verified the effect of applying dynamic bending gain to reduce perceived discomfort. We hypothesized that the use of dynamic bending gain would reduce discomfort compared to the use of a constant bending gain.

5.1.1 Experimental Design

The VEs comprising grassland, trees, huts, and a path used in this experiment were implemented using Unity. The participant wore an HMD (HTC Vive Pro Eye), its headphone, the backpack PC (MSI HP VR Backpack) and held an HTC Vive controller in their hand.

Nine male and nine female participants (age 19–35 years, M = 23.61) participated in our experiment. These are separate participants from those in Exp1 and Exp2. All had normal or corrected-to-normal vision: Ten wore contact lenses and five wore glasses. No one reported a disorder of equilibrium or a vision disorder.

The experiment was conducted using a within-subject design, and the total number of trials was 16. The experimental conditions included two forms of bending (i.e., continuous and abrupt) × two gains (i.e., 3.0 and 5.0) × two directions (i.e., left and right) × two reps. To counterbalance these conditions, the order of trials in the experiment was completely randomized. In each trial, the participants walked along the path presented in the VE.

The conditions for the two forms of bending (i.e., Continuous and Abrupt) were as follows: a condition in which the users walked 5 m with no gain, 10 m with dynamic bending gain, and 5 m with constant bending gain (Continuous), and a condition in which the users walked 10 m with no gain and 10 m with constant bending gain (Abrupt). The path in a RE is an arc path with a radius of 2.5 m in both conditions.

For the bending gain condition, we set two conditions for the magnitude of the bending gain (g_B) to be applied as constant bending gain: 3 and 5. The values of the curvature change rate with dynamic bending gain for each condition were -0.027 and -0.032 $rad \cdot m^{-2}$, respectively. The value of -0.032 $rad \cdot m^{-2}$ was not included in the range verified in Exp1, but it was close as the range of -0.028 to -0.016 $rad \cdot m^{-2}$, which did not significantly affect the perception of discomfort in Exp1. It was set as such, because it was necessary to verify the bending gain of five, which exceeds the perception threshold. Fig. 10 shows the change

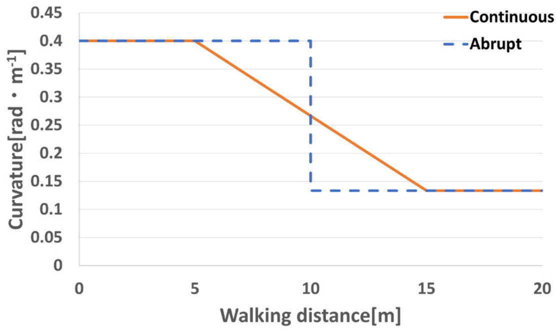


Fig. 10. Walking distance and curvature change for two forms of bending (i.e., Continuous and Abrupt) when the target gain was three. The detail for each condition is as follows: Continuous: Path condition with dynamic bending gain. 0–5 m is a no-gain section, 5–15 m is a dynamic bending gain section, and 15–20 m is a constant bending gain section and Abrupt: path condition without dynamic bending gain. 0–10 m is a no-gain section, and 10-20 m is a constant bending gain section.

(a) (b)

Fig. 11. Images of a scene during walking (a) Image of the RE. The participant walked on a circular path. (b) Image of the VE. The participant walked on a clothoid path.

in curvature of the path in the VE for each condition of bending form when the target bending gain was three. In the condition with dynamic bending gain, the curvature changed at a constant rate between 5 and 15 m like a ramp function, whereas in the condition with constant bending gain, the curvature changed abruptly at 10 m like a step function.

In this experiment, the participants answered discomfort during the trials with a numerical value from 0 (not at all) to 100 (very strong) by means of a questionnaire using a visual analog scale (VAS) at the end of each trial. They also answered the SSQ before and after the experiment and the IPQ after the experiment.

5.1.2 Procedure

It took about 40 min to complete the experiment per person. After receiving an explanation of the experiment, the participants answered a demographics questionnaire and the SSQ.

The participant then wore the HMD, headphones, and the backpack PC, and held the controller in their hand. The participants then started a practice trial followed by a real one. The participants walked on a curved virtual path presented by the HMD (Fig. 11) in each trial. Participants changed direction every 5 m. After walking 20 m, they answered a questionnaire about the magnitude of discomfort caused with the VAS, which was repeated for a total of 16 trials. After trial, they answered the SSQ and the IPQ and verbally reported their impressions and findings. Then the experiment ended.

5.1.3 Results

Fig. 12 shows the discomfort during walking as reported by the VAS.

The results were found to be normally distributed according to the Shapiro-Wilk test at the 5% level. Then we analyzed the results with a two-way repeated measures ANOVA. The ANOVA revealed a significant main effect and small effect size of path condition ($F(1,17) = 16.544, p < 0.01, partial\ \eta^2 = 0.034$), a significant main effect and small effect size of the gain condition ($F(1,17) =$

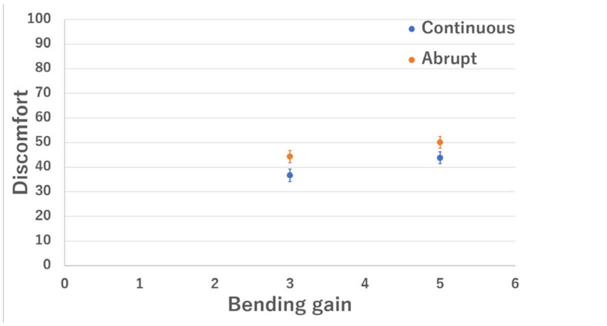


Fig. 12. Discomfort score by VAS. "Continuous" in the legend corresponds to the condition with dynamic bending gain, and "Abrupt" corresponds to the condition without dynamic bending gain. Error bars represent the standard error.

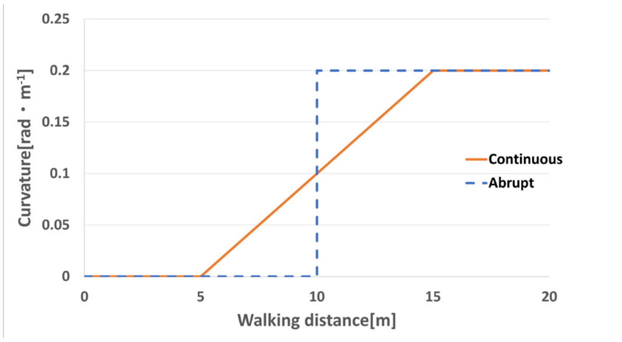


Fig. 13. Walking distance and curvature change for two forms of bending (i.e., Continuous and Abrupt) when the target gain was three. The detail for each condition is as follows: Continuous: Path condition with dynamic curvature gain. 0–5 m is a no-gain section, 5–15 m is a dynamic curvature gain section, and 15–20 m is a constant curvature gain section and Abrupt: Path condition without dynamic curvature gain. 0–10 m is a no-gain section, and 10-20 m is a constant curvature gain section.

Table 3. IPQ scores.

Items	Average	Standard Deviation
sense of being there	4.44	0.83
spatial presence	4.06	1.00
involvement	3.61	1.27
experienced realism	2.38	0.96

15.754, $p < 0.01$, *partial* $\eta^2 = 0.040$), and no significant interaction effect ($F(1,17) = 0.176, p = 0.68$, *partial* $\eta^2 = 0.000$).

Wilcoxon's signed rank test for the SSQ scores showed that the post-experimental score (mean: 20.99) was significantly higher than the pre-experimental score (mean: 4.57) ($p < 0.01, r = 0.607$). The IPQ scores after the experiment are shown in Table 3.

5.1.4 Discussion

Significant differences and small effect sizes were found for the main effect of the path condition on discomfort. This suggests that the discomfort can be kept significantly smaller with dynamic bending gain than with constant bending gain. This supports the hypothesis that the use of dynamic bending gain would reduce discomfort compared with the use of a constant bending gain. Specifically, by using dynamic bending gain, the discomfort was suppressed by approximately 16% when the value of the bending gain was three, and by approximately 12% when the value of the bending gain was five.

This discomfort suppression effect could be further improved. In this experiment, a large direction change of 90° or more was made every 5 meters, and some participants commented that this direction change amplified their discomfort. This was caused by the fact that the participants' habituation effect to the manipulation was reduced, because the motion was temporarily interrupted by the direction change in the condition with dynamic bending gain. Therefore, reducing the number of direction changes or decreasing the angle as much as possible may sustain the habituation effect and lead to a greater discomfort suppression effect.

Furthermore, the abrupt change in bending gain occurred when the participants were changing direction, which might have made the change more difficult to notice. Considering this, it is possible that if the abrupt change in bending gain occurs when they are walking along the path, the discomfort may increase.

5.2 Experiment 4 (Exp4) : Curvature Gain

In this experiment, we verified the effect of reducing discomfort by using dynamic curvature gain with a continuous curvature change in real path. We hypothesized that the use of dynamic curvature gain would reduce discomfort compared to the constant curvature gain.

5.2.1 Experimental Design

The VEs consisting of grassland, some trees, huts, and a path used in this experiment were implemented using Unity. The participant wore an HMD (HTC Vive Pro Eye), its headphone, a backpack PC (MSI HP VR Backpack) and held an HTC Vive controller in their hand.

Nine male and nine female participants (age 19–35 years, M = 23.61) participated in our experiment. All had normal or corrected-to-normal vision: Ten wore contact lenses and five wore glasses. Nobody reported a disorder of equilibrium or vision disorder. The participants in this experiment were the same as those in Exp3, and the experiment was conducted on a day differing from that of Exp3.

The experiment was conducted using a within-subject design, and the total number of trials was 16. The experimental conditions included two forms of bending (i.e., Continuous and Abrupt) × two gains (i.e., 0.2 and 0.4 $rad \cdot m^{-1}$) × two directions (i.e., left and right) × two reps. To counterbalance the conditions, the order of trials in the experiment was completely randomized. In each trial, the participants walked along the path presented in the VE.

The conditions for the two forms of bending (i.e., Continuous and Abrupt) were as follows: a condition in which the users walked 5 m with no gain, 10 m with a dynamic curvature gain, and 5 m with a constant curvature gain (Continuous), and a condition in which the users walked 10 m with no gain and 10 m with a constant curvature gain (Abrupt). The path in the VE was a straight line in both conditions.

For the curvature gain condition, we set two conditions for the magnitude of the curvature gain (g_C) to be applied as constant curvature gain: 0.2 and 0.4 $rad \cdot m^{-1}$. The values of the curvature change rate with dynamic curvature gain for each condition was 0.02 and 0.04 $rad \cdot m^{-2}$. These gain conditions were chosen based on the results of the experiments described in Exp2, which showed that between the values of 0.005 and 0.04 $rad \cdot m^{-2}$, the values of 0.02 and 0.04 $rad \cdot m^{-2}$ suppressed the sense of discomfort the most. Fig. 13 shows the change in curvature of the path in the VE for each path condition when the target curvature gain was 0.2 $rad \cdot m^{-1}$. In the condition with dynamic curvature gain, the curvature changed at a constant rate between 5 and 15 m in the form of a ramp function, whereas in the condition without dynamic curvature gain, the curvature changed abruptly at 10 m in the form of a step function.

In this experiment, the participants answered the perceived discomfort during the trials with a numerical value from 0 to 100 by means of a questionnaire using a VAS at the end of each trial. Additionally, the participants answered the SSQ before and after the experiment and the IPQ after the experiment.

5.2.2 Procedure

It took about 40 min to complete the experiment per person. After receiving an explanation of the experiment, the participants answered a demographics questionnaire in advance. They also answered the SSQ.

After answering the questionnaires, the participant wore the HMD, headphones, and the backpack PC, and held the controller in their hand.

(a) (b)

Fig. 14. Images of a scene during walking (a) Image of the RE (5 m × 4 m tracked area). The participant walked on a clothoid path. (b) Image of the VE. The participant walked on a straight path.

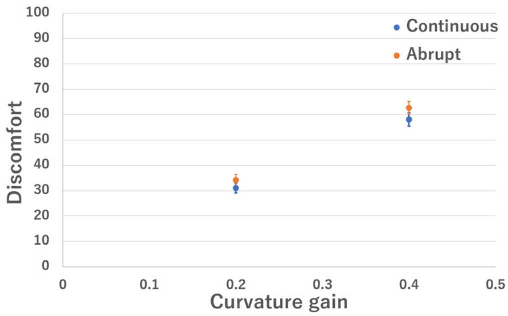


Fig. 15. Discomfort score by VAS. "Continuous" in the legend corresponds to the condition with dynamic curvature gain, and "Abrupt" corresponds to the condition without dynamic curvature gain. The error bars represent the standard error.

The participants then started a practice trial followed by a real one. The participants walked on a straight virtual path presented by the HMD (Fig. 14) in each trial. Participants changed direction every 5 m, and after walking 20 m, they answered a questionnaire about the discomfort by the VAS, which was repeated for a total of 16 trials. After the trial, the participants answered the SSQ and the IPQ and verbally reported their impressions and findings, and the experiment ended.

5.2.3 Results

Fig. 15 shows the discomfort during walking as reported by the VAS. The results were found to be normally distributed according to the Shapiro-Wilk test at the 5% level. Then, we analyzed the results with a two-way repeated measures using ANOVA. The ANOVA revealed a significant main effect and small effect size of path condition ($F(1,17) = 7.538, p < 0.05, partial\ \eta^2 = 0.012$), a significant main effect and small effect size of the gain condition ($F(1,17) = 54.71, p < 0.01, partial\ \eta^2 = 0.383$), and no significant interaction effect ($F(1,17) = 0.201, p = 0.66, partial\ \eta^2 = 0.000$).

Wilcoxon's signed rank test for the SSQ scores showed that the post-experimental score (mean: 25.56) was significantly higher than the pre-experimental score (mean: 6.03) ($p < 0.01, r = 0.58$). The IPQ scores after the experiment are shown in Table 4.

5.2.4 Discussion

Significant differences and small effect sizes were found for the main effect of the path condition on discomfort. This suggests that the perceived discomfort can be kept significantly smaller when dynamic curvature gain is applied than when a constant curvature gain is applied. This supports the hypothesis that the proposed method of dynamic curvature gain can suppress discomfort. Specifically, by using the dynamic curvature gain, the discomfort was suppressed by approximately 9% when the curvature gain was 0.2 $rad \cdot m^{-1}$, and by approximately 7% when the curvature gain was 0.4 $rad \cdot m^{-1}$.

This discomfort suppression could be further improved. In Exp4, similar to Exp3, a large direction change of 90° or more was made every 5 m, and some participants commented that this direction change amplified their discomfort. This was caused by the fact that the participants' habituation effect to the manipulation was reduced, because the motion was temporarily interrupted by the direction change in the condition with dynamic curvature gain. Therefore, reducing the number of direction changes or decreasing the angle as much as possible may sustain the habituation and lead to a greater discomfort suppression.

Additionally, the effect of the dynamic curvature gain on suppressing discomfort was smaller than that of the dynamic bending gain. In the proposed method, the curvature of the path in the RE was constant in the case of the bending gain. Thus, the stimulus to the vestibular sense was constant, while the curvature gain changed the curvature of the path in RE continuously, i.e., the stimulus to the vestibular sense changed. This suggests that a constant curvature of the real path, i.e., a constant stimulus to the vestibular sensation, may lead to a greater suppression of discomfort.

Table 4. IPQ scores.

Items	Average	Standard Deviation
Sense of being there	4.61	0.95
Spatial presence	4.18	0.76
Involvement	3.47	1.06
Experienced realism	2.53	1.00

6 Conclusion

In this paper, we proposed a novel curvature manipulation method with dynamic bending and curvature gains in an RDW. In Exp1 on bending gain and Exp2 on curvature gain, we investigated the effect of the curvature change rate of the path on the user's perception of discomfort. The results of Exp1 showed that when the radius of the virtual path increases gradually from 2.5 m, there is no significant difference in the bending gain when the participants perceived discomfort in the range of -0.028 to -0.016 $rad \cdot m^{-2}$ in the curvature change rate. The results of Exp2 showed that when the curvature of the path increases from 0, the values of the curvature change rate of 0.02 or 0.04 $rad \cdot m^{-2}$ were found to be more effective in suppressing discomfort than the others.

In Exp3 on bending gain and Exp4 on curvature gain, via the comparison with the constant gain, we examined whether it was possible to suppress the perceived discomfort during RDW by using the dynamic gain with a curvature change rate that was less likely to cause discomfort based on the results of Exp1 and Exp2. The results of Exp3 showed that the proposed method of dynamic bending gain significantly suppressed the discomfort by 16% compared with the case where only constant bending gain was applied. The results of Exp4 showed that the proposed method of dynamic curvature gain significantly reduced the discomfort by 9% compared with the case where only a constant curvature gain was applied.

These results indicate the possibility of extending the applicable manipulation range by dynamically changing the bending gain and curvature gain by continuously changing the curvature of the path. This could lead to an extension of the perceptual threshold of RDW by utilizing dynamic gains. Additionally, by applying the proposed method in the introductory part of the experience in various scenes, the effect of RDW in subsequent experiences can be improved.

On the other hand, there is a possible limitation in that the effect of the proposed method is reduced when there are many direction changes or path changes between left and right turns. This may be caused by the fact that the effect of habituation is reduced by changing the direction of the applied manipulation at the moment when the application of the continuously changing gain is temporarily interrupted by the change of direction and when the left and right directions of the path change.

In the future, it will be necessary to verify whether the proposed method can realize a more effective RDW with longer experience. Because the effect of habituation is enhanced by repeated presentation of stimuli, it can be expected to suppress discomfort more in contents requiring time such as training and exploration of a virtual museum.

Acknowledgments

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