International Conference on Artificial Reality and Telexistence
Eurographics Symposium on Virtual Environments (2018)
G. Bruder, S. Cobb, and S. Yoshimoto (Editors)

Error Correction in Redirection: Rotational Manipulation for Natural Walking and Control of Walking Paths

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Abstract

This study proposes a novel rotational manipulation method for redirection when users attempt to turn around a corner within a virtual environment. The basic manipulation of conventional redirection can be classified into translational, rotational, and curvature manipulations. In conventional rotational manipulation, users must stop and rotate. However, this behavior is not natural in everyday walking. In addition, because the manipulated rotation varies depending on the amount of the user's rotation, this manipulated rotation could differ from the assumed rotation if the user does not rotate by the assumed angle during this manipulation. Correspondingly, the actual walking path may deviate from the planned path. Misalignment of the walking path may cause a deviation in the interaction with an object in real space, thus resulting in collision with real-space objects and other users. We devised a basic manipulation of redirection and formulated a novel method for manipulating the amount of rotation when users rotate while moving. Using this method, we changed the axis of rotational manipulation for preventing mismatches between real and virtual environments, and set an area to correct the error in rotational manipulation. The results of our experiments demonstrated that it is possible to control the walking paths and manipulate the amount of rotation during movement without changing the amount of rotation perceived by users, and without increasing discomfort. The results demonstrated that our method is useful for manipulating the viewpoint when a user walks naturally.

CCS Concepts

• ***Human-centered computing*** → ***Virtual reality;***

1. Introduction

Virtual reality (VR) has been developed and applied to entertainment, but its applications have been extended to various other fields ranging from training to tourism. An important factor in the experience of the VR content is the sense of immersion.

To provide a strong immersive feeling to experiences in a virtual environment (VE), it is important to incorporate physicality into the VE. Hence, herein, a method is considered to identify the correspondence of the movements in real space and in VE when a user is moving within a VE [SUS95, UAW*99]. However, for the implementation of the transformation method for matching the virtual and real spaces with one-to-one correspondence, a vast real space is required to enable walking around an equally vast VE in an equivalent manner. Various locomotion interfaces have been proposed as possible solutions to this problem [IYFN05, MFW08]. Moreover, researchers and various companies have been developing systems that transform the amount of walking in real space to the amount of movement in a VE, such as the Virtuix Omni [omn]. Because users actually walk during the execution of these methods, a somatosensory feeling is induced that is close to that induced during actual walking. Therefore, they can walk within a limited real space, yet their movements can be mapped within a vast VE. However, these devices are expensive and do not provide the same sensation as that induced in actual walking.

Redirection has been proposed as an alternative solution. Redirection can modify our spatial perception and compresses a large VE into the space of a physical room with significantly smaller spatial extent than the VE [RKW01]. Redirection can help maintain a sense of real walking by displaying the virtual image of the space, which is slightly different from the image obtained during actual walking. The viewpoint manipulation of redirection can be classified into three basic types: translational, rotational, and curvature manipulations [SBJ*10]. Each type aims to manipulate the amount of translation and rotation, and the curvature of the walking path in the VE. Among them, translational manipulation linearly reduces the required real space, and curvature manipulation still requires a large radius of curvature. Therefore, it is difficult to compress a vast VE into a relatively narrow real space with these two manipulations. In contrast, rotational manipulation can compress a large VE into a narrow real space. Under rotational manipulation, the gain, which is the magnification of the rotation amount in the VE with respect to the rotation amount in real space, is applied to the amount of rotation with the center of the user's head defined as the axis of rotation. In accordance to this manipulation, and while the

DOI: 10.2312/egve.20181313

area is set to apply the required gain, the user has to stop and then rotate [KBMF05], which is not natural for normal walking. When the amount of rotation is manipulated while moving, the rotation axis of the walking path is shifted with respect to that of the rotational manipulation, thus leading to a misalignment. In addition, unless users rotate by a predetermined amount within the area for which the gain was applied, the amount of manipulation is unexpected and the walking path deviates considerably. Therefore, it is necessary to establish a redirection method for turning while moving as is accomplished during naturally walking.

In addition, it is becoming increasingly important to control the user's walking path. In a recent VR content, the interaction with the environment in real space with the use of technologies, such as passive haptics, has become important to enhance the immersive feeling [IMWB01]. Additionally, it is confirmed that the combination of visual manipulations and passive haptics enhances the effect of redirection [MBN*16b]. Unless the walking path is controlled, the positions of the objects in real space are shifted, and the risk of collision with objects also increases. Furthermore, with the multiplicity of the VR content [voi15], controlling the walking path is important from a safety perspective.

In this study, we propose a novel method that manipulates the amount of rotation when a user rotates while moving, that is, when changing direction in a natural manner. This method changes the axis of rotation to eliminate misalignment when turning. Additionally, it corrects the error of the rotational amount caused by the unexpected rotation in an area where the gain is applied so that the user does not notice the manipulation. With this method, it is possible to manipulate the amount of rotation when the direction is changed during motion without the need to stop and rotate, unlike the conventional rotational manipulation. In addition, to enhance the immersive feeling of the VR content, we can control the walking path and hence increase safety.

The contributions of this work are summarized as follows:

- Unlike conventional rotational manipulation, it is not necessary for a user to stop and rotate about their own axis by correcting the error of rotation; correspondingly, it becomes possible to walk more freely in the VE, and the immersive feeling is thus enhanced.
- The walking path can be controlled by correcting the error of rotation and by guiding a user to the assumed walking path. Even when the interaction of the real space with the environment is required, the position of the object in the real space does not shift from that in the VE.
- The walking path can be controlled, hence, the danger of collision with objects in real space or with other users is reduced.

2. Related Work

Many systems have been developed that make it possible to explore a vast VE within a limited real space. Virtusphere [MFW08] allows users to walk in a VE in accordance to walking within a human-sized basket that rotates in an arbitrary direction. CirculaFloor [IYFN05] consists of robots that move according to the user's path and create a virtual floor. In addition, various methods have been proposed that allow users to explore the VE by walking in a shuffle on a mortar-shaped pedestal with a very small coefficient of friction, such as the Virtuix Omni [omn]. Strider VR has also been proposed, which detects the rotation of the sphere spread on the pedestal and reflects the amount of walking on it while walking in the VE [str]. Because the users actually walk when all these devices are used, somatosensory feelings are induced that are close to those induced during actual walking and they can walk within a vast VE within a limited real space. However, these systems pose a risk of injury to users in addition to being complicated and expensive.

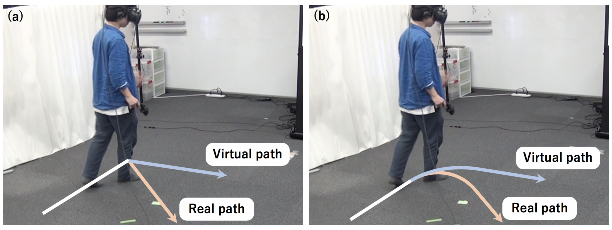


Figure 1: *Comparison between a conventional and the proposed method of rotational redirection during gait. (a) Gain is applied to the amount of rotation when a user stops and rotates in conventional rotational manipulation. However, stopping and turning on one's own axis is not natural in everyday walking. (b) Illustration of the implementation of the proposed method whereby the amount of rotation is manipulated by changing the axis of rotation and correcting the error of the amount of rotation during the user's natural walking pattern.*

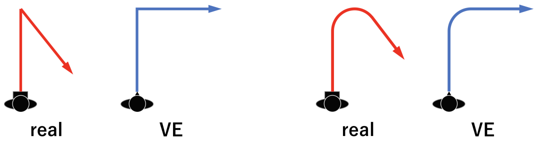
Redirection (redirected walking) [RKW01] is proposed as a method for walking in a vast VE with a natural walking sensation. By changing the mapping for both the real space and the VE, it is possible to express a vast VE in a limited real space. There are three types of basic manipulations of redirection: translational, rotational, and curvature. Each method manipulates the amount of movement in the VE by applying the gain associated with the user's walking pattern in real space to translation, rotation, and to the curvature of the walking path. In these cases, rotational manipulation multiplies the gain with the amount of rotation when the user stops and rotates. Furthermore, there are limits to the range of achievable viewpoint manipulations and the determined thresholds [SBJ*10]. A manipulation technique referred to as reset has been proposed for the application of rotational manipulation [WNR*07]. Reset is a method used to make a user stop and rotate in the vicinity of the spatial boundaries of the real space, manipulate the rotation amount at that time, and guide the user to the center of the real space available for walking [PFW09]. This makes it possible for the user to keep walking in the VE indefinitely within a limited real space. Additionally, as mentioned earlier, rotational manipulation multiplies the gain with the amount of rotation when the user stops and rotates. However, stopping and turning on one's own axis is unnatural in everyday walking. Therefore, this process results in the loss of immersion [NHK14].

Combining multiple basic manipulations of redirection has also been attempted previously [GTA*16]. This study attempts to improve the effect of curvature manipulation by combining translational and curvature manipulations. This study shows that the threshold of curvature manipulation does not change, even when two manipulations are combined. This is because the effects of the curvature manipulation and the translational manipulation are orthogonal to each other.

There are several types of redirection controllers [NPB*18]. One of these is a scripted controller [RKW01], which predetermines the real and the virtual paths. Apart from these, there is a generalized controller that guides users to a certain point regardless of their movement [Raz05], and a predicted controller that guides users to a certain point by predicting their movement and optimizing the route [ZWBH13]. These redirection controllers properly manipulate the gains of the basic manipulation according to the algorithm.

Controlling the walking path is important when the interaction with objects is considered in real space during redirection. It is known that by adding interaction, such as haptic cues in the VR experience, the immersiveness increases, and human spatial perception can be manipulated more effectively [BKN*12, MBN*16a, AHB*16, IMWB01]. Ban et al. revealed that it is possible to change the perception of the shape of an object by converting the position of the finger which touches the object so as to correspond to the shape of the visually presented object [BKN*12]. Matsumoto et al. revealed that by distorting a wall in real space as the user walks alongside it and touches it, the radius of curvature necessary to perceive traveling along a straight direction can be reduced from 22 m to 6 m [MBN*16a]. In this way, it is possible to provide a more intense immersive feeling or manipulate the spatial perception more efficiently by actually touching objects in the VR experience. However, when the walking path is shifted, the positional relationship between the object in real space and that in the VE shifts and the risk of collision with the object increases. Furthermore, in recent years, the demand for multiplayer VR has increased [voi15], and users wearing head-mounted displays (HMDs) in multiplayer VR cannot easily notice that other users are nearby [PK15]. Therefore, it is also important to control walking paths and prevent collisions between users during redirection [AGR17]. Numerous algorithms have been proposed for generalized and prediction controllers used for controlling the walking path so that collisions with real objects are avoided [CCR18]. However, in the case when scripted controllers are used, especially for rotational manipulation, there is a possibility that the walking path deviates from the preplanned path unless the user walks in accordance to the originally determined path. Therefore, establishing a method of controlling the walking path is necessary even with this manipulation.

Many ways of walking around the VE have been invented in this manner. Redirection has made it possible to walk through a vast VE while providing a sense of natural walking. However, there is a problem when one has to walk unnaturally using rotational manipulation of redirection. In addition, it has become important to control the walking path owing to the use of haptics for improving the effect of redirection and multiplayer VR. Based on the above, we propose a new method for controlling the walking path and for further manipulating the rotational amount while moving.



(a) *Conventional rotational manipulation.* **(b)** *Rotational manipulation during motion.*

Figure 2: *Conventional and proposed methods.*

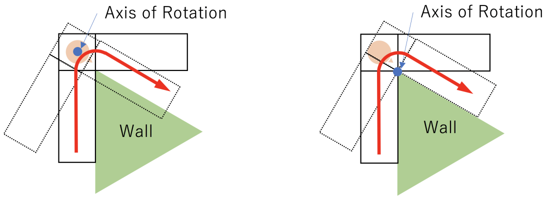
3. Method

3.1. Concept

The purposes of this method are to control the amount of rotation while moving and to regulate the walking path unlike conventional rotational manipulation which forces users to stop and rotate, as shown in Figure 2. As shown in Figure 2(b), during the natural turning maneuver, the moving object usually rotates without changing the radius of turning. Thus, the proposed method is different from curvature manipulation. Therefore, this manipulation cannot be performed with the existing basic manipulation so we considered a novel manipulation method. Given that multiple-turn situations, such as meandering, comprise multiple cases of single turns, we consider the act of a single rotation as the basic motion in natural walking. To create a situation in which users cannot avoid turning, we focus on the situation of walking around a corner. There are two ideas for this novel approach: changing the position of the rotational axis and setting the correction area.

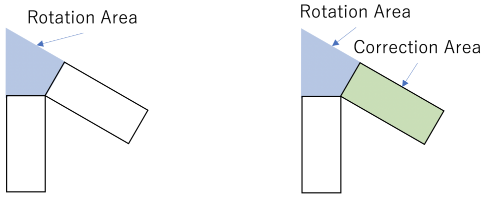
3.2. Axis of Rotation

The first proposed idea is to change the position of the rotational axis in rotational manipulation to the vertex of the corner, that is, to the center of the circular arc when turning direction. In conventional rotational manipulation, a gain is applied to the amount of rotation when the axis of rotation is centered on the user's head. However, considering the relative relationship between the user's body and the real environment when users turn around a corner for example, identifies a problem with consistency. In other words, a mismatch occurs in the interaction with an object in real space, such as the case when the object is walking while touching a wall or holding a handrail. Furthermore, the user's walking path deviates slightly from the assumed path. To solve these problems, the rotational axis in rotational manipulation must be the vertex of the corner around which the users turn, as shown in Figure 3. Herein, the solid line indicates the VE before the manipulation, the dotted line indicates the VE after the manipulation, the wall is set to the real space, and the red arrow represents the assumed walking path in real space. As a result, if the manipulated amount of rotation can be made equal to the assumed amount of rotation, the walking path can be controlled even if we manipulate the amount of user rotation during the movement.



(a) *Axis of rotation is the center of the user's head.* **(b)** *Axis of rotation is the corner vertex.*

Figure 3: *Position of the axis of rotation.*



(a) *Rotation area in the conventional rotational manipulation.* **(b)** *Rotation area and correction area.*

Figure 4: *Illustration of the setup of the correction area.*

3.3. Correction Area

The second idea proposed herein is to set the correction area to correct the error of the rotation to equalize the manipulated to the assumed amount of rotation.

In accordance to the conventional technique for rotational manipulation, an area is set such that a gain is applied to the amount of rotation, and users stop and rotate. This area is referred herein as the rotation area. Considering the situation in which users turn around a corner, the rotation area occupies an area like that shown in Figure 4(a). The reason for this is attributed to the fact that when a gain is applied to another area, even if the user is walking along a straight line, an unnatural gain will be applied to the rotation of the user's head, and the walking path will thus be bent. However, with this conventional method, there is a possibility that users do not rotate by the assumed amount within the rotation area. If users rotate in an area outside the rotation area, and the rotation amount in the rotation area is insufficient, the assumed amount of rotational manipulation is not performed, and there is a possibility that users do not trace the assumed walking path.

Therefore, we propose a method to set an area for correcting the error between the assumed and actual amounts of rotation the rotation area, as shown in Figure 4(b). This area is referred to as the correction area in this study. We manipulate the curvature so that users feel like they are moving along straight paths within the correction area, and correct the error according to the walking amount in the correction area. Correspondingly, we manipulate the viewpoint so that the correction is completed when they finish walking in the correction area.

$$\phi = R_c * \frac{d}{d_0} \tag{1}$$

Herein, ϕ [°] is the manipulated amount in the correction area, R_c [°] is the amount of rotation to be corrected in the correction area, d is the distance the user has moved, and d_0 is the distance necessary to be covered to complete the correction. In this study, we set $d_0 = 2$ m so that users feel as though they are moving along straight paths within the correction area. This numerical value was set based on the finding that a radius of 6.4 m is sufficient for a user to perceive that he or she is moving along a straight path within the VE [GTA*16].

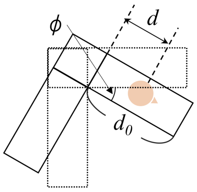


Figure 5: *Manipulation in correction area.*

4. Experiment

To verify whether the method for changing the axis of rotation and setting the correction area is useful as a rotational manipulation method when turning a corner, an experiment was conducted. We compared the proposed "*correction*" method, with the conventional "*baseline*" method whereby a gain was applied to the amount of rotation around the center of the head in the rotation area.

4.1. Hardware Setup

The experiment was performed in a 4 m × 4 m laboratory room. As shown in Figure 6, the participants wore an HTC Vive HMD and headphones, and had an HTC Vive controller. The HMD had a resolution of 1080 × 1200 pixels per eye, a refresh rate of 90 Hz, and an approximate diagonal field-of-view of 110°. The HMD and the controller can grasp the user movements in an area of up to 4.6 m × 4.6 m with submillimeter accuracy with the LightHouse system using infrared rays, and with a gyro sensor. We used this VR system to display images that matched the position of the head. In addition, by feeding white noise signals in the headphones, it was made impossible for the participants to estimate their own position based on the surrounding environmental sounds. For the rendering of the VEs displayed to the participants, system management, and data recording, we used an Intel computer with a 3.4 GHz Core i7 processor, 16 GB memory, and an Nvidia GeForce GTX1080 graphics card. The VEs presented to the participants were rendered with a simple VE that consisted of walls, a floor, and a ceiling according to the position of the eyes of the participants, as shown in Figure 7. The VEs were rendered with the Unity3D Engine 2017, and a path with a 90° bend was displayed.

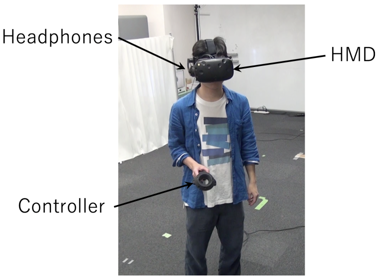
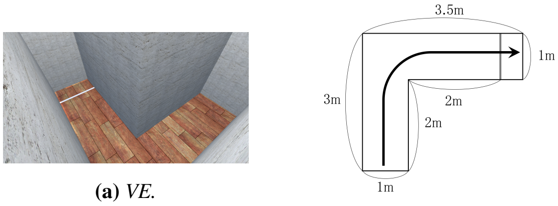


Figure 6: *Equipment used by the participants.*



(a) *VE.*

(b) *Overhead view of VE.*

Figure 7: *VEs presented to the participants.*

4.2. Participants

Twenty-four participants (19–26 years, mean age: 22.2 years, eight females) participated in our experiment. All participants had normal or corrected-to-normal vision. Four participants were left-handed. Seventeen participants had previously used an HMD. None of the participants had any prior knowledge regarding this experiment.

4.3. Evaluation

To evaluate whether the walking path can be controlled, we measured the distance between the position in real space at the end of the walking path, and the assumed arrival point at each rotational gain. We also measured the difference between the final amount of rotation in the real space of the participant and the assumed amount of rotation for each rotational gain. To evaluate the amount of rotation perceived by each of the participants and the discomfort when walking, we used the questionnaire that is described below.

questionnaire

To evaluate the perceived rotation amount when they turned the corner, the participants illustrated how they walked, as shown in Figure 8. They moved the red line with reference to the blue line and in accordance to the perceived amount of rotation. The angle between the upward direction of the blue and red lines was considered as the perceived amount of rotation. In addition, we used a visual analog scale method (0: not uncomfortable at all, 100: extremely uncomfortable) to evaluate the degree of discomfort when the participants walked through the aisle.

4.4. Experimental Design

We used a 2 × 5 within-subject experimental design. We tested two viewpoint manipulation methods, i.e., *correction* and *baseline*, and five gains for the rotation areas, such that $g \in \{0.6, 0.8, 1.0, 1.2, 1.4\}$. We tested both the right and left directions, and repeated each condition two times. In total, the participants completed $2 \times 5 \times 2 \times 2 = 40$ trials in which the order of conditions was randomized.

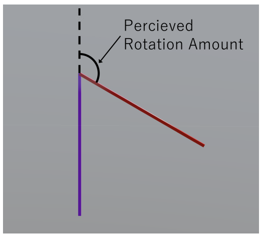


Figure 8: *Example of perceived amount of rotation.*

4.5. Procedure

The experiment lasted one hour for each participant, including the explanations of the experiment, training, experimental trials, breaks, and answering questionnaires. Before the experiment, all participants signed an informed consent form and the experiment was explained to them. They then completed a background survey (age, sex, handedness, visual acuity, and experience of wearing HMDs). They also filled out a simulator sickness questionnaire (SSQ) with 16 items [KLBL93] before and after the experiment. After the background survey, participants were equipped with an HMD and headphones, and practiced in a trial session that consisted of walking in the aisle subject to the condition of avoiding viewpoint manipulation. Subsequently, and before the experiment began, they responded to the questionnaire. In the trial session, the participants wore an HMD and were guided to the initial position presented via the HMD, and then walked down the aisle. After the end of their walking, they answered the questionnaire, which was displayed through the HMD they wore using the controller. They took three-minute breaks every 10 trials.

4.6. Result

A Wilcoxon signed-rank test was conducted on the SSQ score before and after the experiment, and their comparison elicited a significant difference ($p < 0.01$, $r = 0.896$).

Distance between Arrival Points

Figure 9 shows a box-and-whisker plot of the distances between the position in real space at the end of the walking path and the assumed arrival point in each condition. We ran the Shapiro–Wilk normality test to check the assumption of normality and found a violation in the assumption ($W = 0.721$, $p < 0.01$). Given that the purpose of this experiment was to compare the indices of two viewpoint manipulation methods, a Wilcoxon signed-rank test was conducted for each rotation gain with Holm correction. The result revealed that the distances between the position in real space and the assumed arrival point for *correction* were significantly lower than those for *baseline* for all the gain conditions except the case where the gain was unity (0.6: $p < 0.01$; $r = 1.08$, 0.8: $p < 0.01$; $r = 1.08$, 1.0: $p = 0.143$; $r = 0.299$, 1.2: $p < 0.01$; $r = 1.08$, and 1.4: $p < 0.01$; $r = 1.08$).

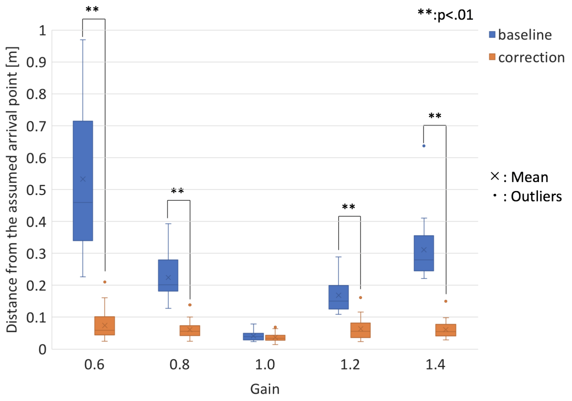


Figure 9: *Distance between the position in real space at the end of the walking path and the assumed arrival point.*

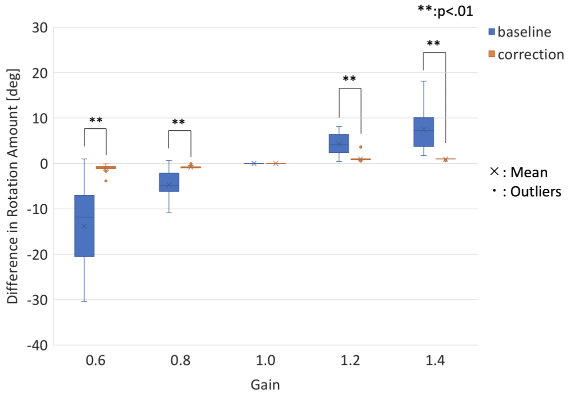


Figure 10: *Difference between the final, actual and assumed amounts of rotation in the real space of the participant.*

Differences in the Amount of Rotation

Figure 10 shows a box-and-whisker plot of the results of the differences between the final amount of rotation in the real space of the participant and the assumed rotation amount for each condition. Positive values indicate that the actual amount of rotation is larger than the assumed amount of rotation. We ran the Shapiro–Wilk normality test ($W = 0.782$, $p < 0.01$) and the Wilcoxon signed-rank test for each rotation gain with Holm correction. The results revealed that the differences between the final amount of rotation in real space and the assumed amount of rotation for *correction* significantly approached the value of zero in a larger number of tested cases compared to *baseline* for all other conditions except that for which the gain was unity (0.6: $p < 0.01$; $r = 1.05$, 0.8: $p < 0.01$; $r = 0.942$, 1.0: $p = 1.00$; $r = 0.00$, 1.2: $p < 0.01$; $r = 1.04$, and 1.4: $p < 0.01$; $r = 1.08$).

Perceived Rotation Amount

Figure 11 shows a box-and-whisker plot of the results of the amount of rotation perceived by the participants in each condition. The broken line identifies the angle of 90°, which is the angle of the corner presented in the VE. We ran the Shapiro–Wilk normality test ($W = 0.920$, $p < 0.01$) and Wilcoxon signed-rank test under each rotational gain with Holm correction in the same way. The results revealed that there were no significant differences between the perceived amounts of rotation for *correction* and those for *baseline* for each gain condition (0.6: $p = 0.0315$; $r = 0.439$, 0.8: $p = 0.540$; $r = 0.125$, 1.0: $p = 0.207$; $r = 0.258$, 1.2: $p = 0.121$; $r = 0.317$, 1.4: $p = 0.870$; $r = 0.0335$).

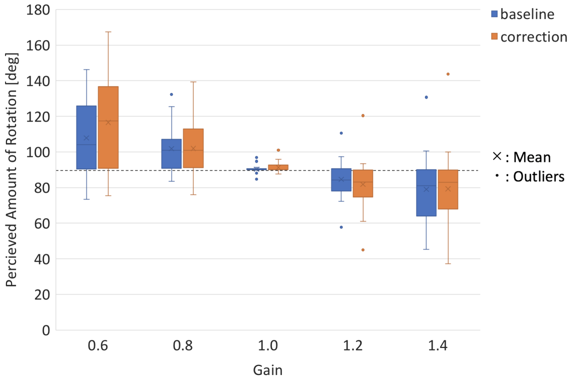


Figure 11: *Amount of rotations perceived by the participants.*

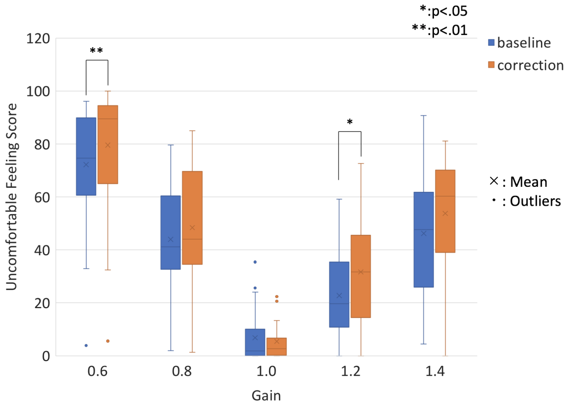


Figure 12: *Uncomfortable feeling scores.*

Uncomfortable Feeling

Figure 12 shows a box-and-whisker plot of the results of uncomfortable feeling scores for each condition. We ran the Shapiro–Wilk normality test ($W = 0.935$, $p < 0.01$) and Wilcoxon signed-rank test for each rotation gain with Holm correction. The results revealed that the uncomfortable feeling scores for *correction* were significantly higher than those for *baseline* for gains of 0.6 and 1.2 (0.6: $p < 0.05$; $r = 0.582$, 0.8: $p = 0.0207$; $r = 0.452$, 1.0: $p = 0.288$; $r = 0.217$, 1.2: $p < 0.01$; $r = 0.659$, 1.4: $p = 0.0269$; $r = 0.452$).

5. Discussion

As shown in Figure 9, the *correction* method suppressed the errors between the position in real space at the end of walking and the assumed arrival point for all tested conditions except that for which the gain was unity. Because we did not manipulate the viewpoint in the case the gain was unity, the conditions of *correction* and *baseline* were practically the same. Therefore, the results demonstrated that *correction* could make users walk to the assumed arrival point. In the same way, as the *correction* method suppresses the errors between the amount of rotation in real space and the assumed amount of rotation or all the tested conditions other than that associated with a gain of unity, the results demonstrated that *correction* could make users rotate by the assumed amount, as shown in Figure 10. The two results listed above indicate that *correction* could control the walking paths of users.

As shown in Figure 11, the amounts of rotation perceived by the participants were constant for *correction* and *baseline*. The result demonstrated that *correction* could present almost the same perception in reference to the amount of rotation as the conventional method, despite the large amount of rotation manipulation due to the manipulation of the correction area. Conversely, all the angles of the existed corners in the VEs were 90°, and as the gain deviated from the value of unity, the perceived amount of rotation also deviated from 90°. Similar to a previous study [SBJ*10], there was a range for which users could not notice the viewpoint manipulation even when the users' paths were bent, similar to the case of turning a corner, as assumed in this experiment.

As shown in Figure 12, the *correction* method induced uncomfortable feelings for the conditions at which the gain settings were 0.6 and 1.2. We manipulated the viewpoint in the correction area so that the participants felt as though they were moving along straight paths. However, for the gain of 0.6, the manipulations were extensive, and there was a possibility that the participants noticed the manipulation and felt uncomfortable. For the gain of 1.2, the overall feelings of discomfort were smaller than those elicited for all the other values of gain settings. Although the feelings of incompatibility were considerable in the rotation area for other gains, the discomfort in the rotation area was small when the gain was 1.2. Therefore, the feeling of strangeness that occurred in the correction area occupied much of the overall discomfort, and it seemed that the uncomfortable feelings of *correction* had become more pronounced.

In the conditions used for *correction*, the rotational axis of the viewpoint manipulation was not set at the center of the user's head as implemented in conventional manipulation. Instead, it was set at the corner vertex. *Correction* conditions raised both the average and the median values of uncomfortable feeling scores for all tested conditions other than the condition associated with a gain of unity. This may have been caused by a change of the rotational axis.

In this experiment, the viewpoint manipulation in the correction area was set to be completed when the participant walked 2 m. However, depending on the magnitude of the rotational gain and the method of walking, the viewpoint manipulation amount in the correction area might have exceeded the threshold of manipulation. Given that this manipulation may affect discomfort, it is necessary to verify the method again by changing the distance at which the viewpoint manipulation in the correction area is completed.

In addition, because there was a significant difference in the SSQ scores before and after the experiment, there was a possibility that simulator sickness in the VEs affected the spatial perception of the participants as the experiment progressed.

6. Conclusions

In this study, we proposed a novel viewpoint manipulation method that aimed to the control of the walking path and the manipulation of the amount of rotation while a user was moving, unlike in conventional rotational manipulation in which users stopped and rotated. In this method, the walking path was controlled by changing the axis of rotation and by setting the correction area in the redirection of the rotational manipulation.

In the experiment, we compared the distances between the arrival points, the differences between the amounts of rotation, the perceived rotation amounts, and the uncomfortable feelings between the conventional method, whereby the amount of rotation was multiplied by the gain, and the proposed method, whereby a correction area was set. The proposed method significantly reduced the differences of the distances between the two arrival points and the amount of rotation closer to zero. Furthermore, there were no significant differences with regard to the perceived rotational amount under any tested condition. Regarding the elicited uncomfortable feelings, the results revealed that the scores were significantly increased for the gains of 0.6 and 1.2. For the gain of 0.6, it was considered that the distance of the correction area was insufficient. For the gain setting of 1.2, the uncomfortable feeling scores increased but were small compared to those for other gains. Based on the results of this experiment, if the distance of the correction area was sufficient, the proposed method controlled the walking path without a change in the perceived amount of rotation, and without an increase in uncomfortable feelings, as compared to the conventional method. It is suggested that this method was useful as a viewpoint manipulation method for natural walking.

The proposed method made it unnecessary to stop and rotate during the rotational manipulation, unlike the conventional redirection approach, and made it possible to maintain natural walking and to manipulate the amount of rotation without departing from the walking path. In contrast, it was shown that changing the rotation axis may be a cause of increased discomfort. In addition, when we manipulated the viewpoint, if the curvature manipulation in the correction area exceeded a limit, the uncomfortable feeling scores increased. It is conceivable that the setting of the distance of the correction area was insufficient. The curvature manipulation gain of the correction area must also be considered in the future.

In addition, because the viewpoint manipulation in this experiment is different from the basic manipulation method whose detection threshold has been examined, it is necessary to newly examine the detection threshold of this manipulation.

It is also conceivable to use haptics for the interactions with the real environment. As known, haptic cues improve the effect of spatial modification in curvature manipulation [MBN*16a]. Thus, it is expected that the effect will be further improved when haptics are used in the viewpoint manipulation method proposed in this experiment. In addition, a method of deforming the shape perception of objects by combining the viewpoint manipulation and the transformation of the hand has been proposed [MHM*17]. We believe that it is possible to change the shape perception more effectively by applying the proposed method in this study to achieve viewpoint manipulation. By preparing multiple, simple-shape objects, and changing the angles of the corners of the object to change the perceived shapes of the object, it is possible for a user to walk around, while he/she actually touches objects which have various shapes. This paradigm may be applied to showrooms and to other similar applications. Furthermore, by devising the shape of the aisle, we consider that it will be possible to continue walking indefinitely in the aisle while turning corners.

In this study, we assumed a scene in which users turned around a corner, and constructed a novel viewpoint manipulation method that enabled natural walking for users. However, in the future, we aim to build a system that will enable the user to walk naturally in a more flexible situation, and to continue walking indefinitely and freely in the VE without feeling uncomfortable.

Acknowledgements

This work was partially supported by the MEXT, Grant-in-Aid for Young Scientists (A)(16H05866) and JST PREST JPMJPR17J6(17939529).

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