Optical Marionette:
Graphical Manipulation of Human's Walking Direction

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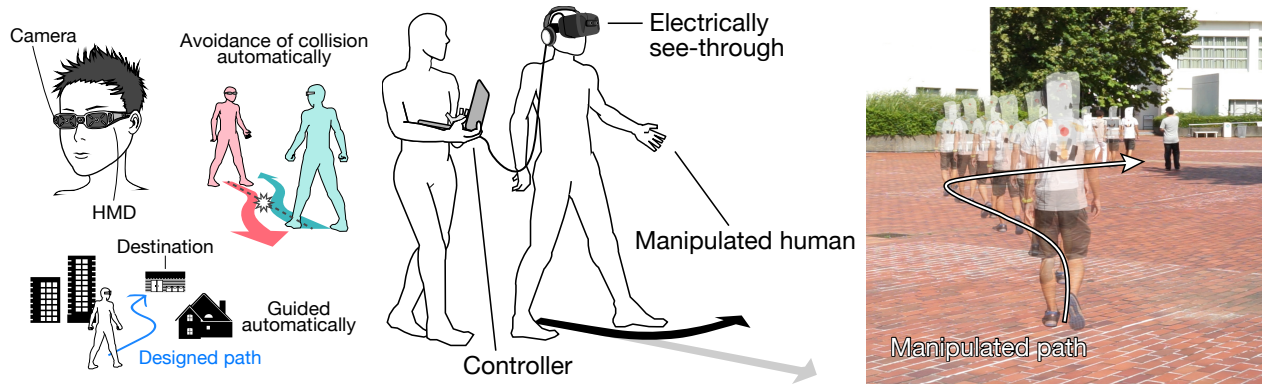ishii@iplab.cs.tsukuba.ac.jp

Figure 1. Introduction to this study, optical marionette: graphical manipulation of human's walking direction. In the future, we will wear an HMD while automatically avoiding any danger of collision with other persons or obstacles — all that is required is to walk straight ahead to get to the destination (left). Application example: remote-controlled human (middle). Result of the experiment under changing focal region method (right).

ABSTRACT

We present a novel manipulation method that subconsciously changes the walking direction of users via visual processing on a head mounted display (HMD). Unlike existing navigation systems that require users to recognize information and then follow directions as two separate, conscious processes, the proposed method guides users without them needing to pay attention to the information provided by the navigation system and also allows them to be graphically manipulated by controllers. In the proposed system, users perceive the real world by means of stereo images provided by a stereo camera and the HMD. Specifically, while walking, the navigation system provides users with real-time feedback by processing the images they have just perceived and giving them visual stimuli. This study examined two image-processing methods for manipulation of human's walking direction: moving stripe pattern and changing focal region. Experimental results indicate that the changing focal region method most effectively leads walkers as it changes their walking path by approximately 200 mm/m on average.

Author Keywords

Walker navigation; head mounted display (HMD); stereo camera; wearable devices; visual illusion; redirected walking; augmented reality (AR).

ACM Classification Keywords

H.5.1 Information interfaces and presentation (e.g., HCI): Multimedia Information Systems - Artificial, augmented, and virtual realities

INTRODUCTION

Navigation systems for walkers are now widespread and in commercial use. Conventional research on such navigation systems has explored methods of presenting information to users visually and aurally. However, existing navigation systems require users to recognize information and then follow directions as separate, conscious processes, which inevitably entails paying attention to the system.

Several studies have reported on how walkers can be guided without paying attention to their navigation systems. These studies have proposed methods that directly affect users' bodies so that the navigation systems can control them without requiring user recognition of the navigation processes. The advantage of employing such methods is that users have a light load in following directions. In addition, it does not occupy the visual attention of users.

These *subconscious* navigation methods require various hardware setups such as a wearable electronic muscle stimulator (EMS). Some systems also place a heavy burden on users

or hardware. To realize walker control methods with light loads on users, this study focused on visual control achievable by wearable equipment. In the virtual reality (VR) research field, the visual approach has achieved success in re-orienting users while walking [22, 28, 29], and visual optic flow techniques that affect self-motion have been evaluated in VR and augmented reality (AR) contexts [3, 4]. The optic flow technique, introduced by Bruder et al., focuses on making users perceive self-motion faster or slower than it actually is. However, they did not focus on reorienting user direction. Redirected walking has also been investigated for fully VR situations. Similarly, subconscious walking control in see-through AR/eSports contents, such as several people walking around in a limited space is a hot topic.

This paper proposes a method that enables walkers to be guided without paying attention to the information provided by the navigation system. The method combines a wide-viewing angle head mounted display (HMD) and a stereo camera for walker control. The resultant system displays images as if the HMD were transparent and controls the walking direction of users by superposing a visual illusion onto the raw images. This study was initiated with the hypothesis that walker movement can be controlled by appropriate visual programming that can facilitate a subconscious navigation system.

To investigate the above hypothesis, we built a prototype system and conducted a pilot study in which participants wore an HMD displaying various image-processing patterns. The pilot study found that there were two effective methods, namely, *moving stripe pattern* and *changing focal region*. Consequently, a user study was conducted with these two visual effects. The results of this study indicated that the changing focal region method was more effective for walker movement control and changed the walking path of users by approximately 200 mm/m on average. In addition, we formulated a model of our method based on the results. Insights gained regarding aligning and presenting visual stimuli within a user's field of view (FOV) can be beneficial for other domains such as cycling and automotive industries.

This study makes the following contributions: 1) effective image-processing methods for walker movement control with a see-through HMD in the real world, 2) investigation of the effects of these methods via a user study, 3) formulation of a model for these methods, and 4) discussion of the applications and limitations of the results.

BACKGROUND AND RELATED WORK

Electrical Stimulation Approach
Various methods to control walkers and enhance their VR experience via electrical stimulation have been proposed. Some of these approaches apply electrical stimulation to the vestibules of users [16, 17, 18, 27]. For example, parasitic humanoid [17] administers electrical stimuli to the vestibules of users that decreases the walker's sense of balance and enables changes in the walking direction. Research is also being conducted on galvanic vestibular stimulation for walkers and persons in wheelchairs [6].

Methods that use electrical stimulation to other organs include Affordance++ [15], which attempts to realize subconscious and strict affordance via EMS. Pfeiffer et al. [21] have also proposed an EMS-based walker navigation system that controls walkers' legs.

The advantage of electrical stimulation approaches such as these is that they cause no optical interference; however, the load on users is heavy. For example, exact placement of electrodes is essential.

Environmental Approach
Environmental approaches are visual approaches that control walker movement using a large display. Visual stimuli employing large displays evoke psychological effects on walkers, which can change their walking direction in accordance with the contents shown on the display. Vection field [7], on which researchers such as Sato et al. [25] and Trutoiu et al. [31] have conducted detailed studies, facilitates navigation and control of walkers using stripe patterns projected onto a floor display. Sato et al. showed that having the vection field on the ground is more effective than mid-air projection, whereas Trutoiu et al. conducted experiments using a large-screen virtual environment on the floor.

The vection field approach has the advantage of no installation load for users. Its disadvantage is that it necessitates a heavy load on the environmental side. In addition, vection fields employ psychological effects and their effectiveness depends on the personal characteristics of the user.

Wearable Approach
Wearable subconscious or passive navigation systems are being actively researched. These systems employ haptic stimuli to change user direction or a wearable vection field device to provide visual stimuli to walkers. Matsue et al. [19] and Nakamura et al. [20] conducted studies on hanger reflex — the reaction of the human body invoked by a wearable hanger that fits on the head and used to guide the user. Conversely, Kojima et al. developed a device that pulls on the ears of users to get them to change their directions [12].

Tanikawa et al. employed several vection field displays set around the user's head [30]. Using their system, they conducted a mental arithmetic test that created a situation in which participants walked while using a cellular phone. Their results showed that their vection field system can make changes in the direction of the participants that enabled them to avoid obstacles on the road.

The wearable approach is similar to the methods employed in our present study as our focus is on a wearable and effective visual approach to control walkers.

Audible or Tactile Approach
The audible or tactile approach is being studied with the aim of devising a minimal attention interface for navigation. Systems such as GpsTunes [26] give sound feedback with amplitude and panning variations that provide direction and distance information to users. AudioGPS [9] employs various musical instrument tones to indicate the direction in which to

|	Wearable	Environment
Visual	Reflex-based [30] **Our system**	Vection field navigation [7]
Other	GVS [16, 18, 27] EMS [21] Pull-Navi [12] Hanger reflex [19, 20]	—

Table 1. Position of this study in terms of related work.

Figure 2. Moving stripe pattern method: Real-world image (left). Stripe patterns are superimposed on the real-world image, and move (right).

move. SWAN [32] notifies users about the distance and direction to the goal via a beacon sound. Wöldecke et al. developed a custom-built haptic belt as part of a navigation system that employs haptic feedback [33].

The above approaches employ non-visual methods for navigation. The fundamental difference between our visual technique and these types of non-visual techniques is that in our technique users cannot notice that they are changing their walking direction. Clearly, non-visual techniques can control the walking direction of users with minimal effort. However, inevitably users will notice that they are changing walking direction because they see the real world via their naked eyes.

Position of This Study
Table 1 shows the position of this study in relation to other similar studies. Previous studies reported that visual sensation has more important effects than kinesthetic senses in human movement [8, 14]. This study was conducted based on similar user research. As stated above, the focus was on a device that is wearable and controls walkers subconsciously with processed images displayed on an HMD. This proposed method has several advantages: 1) Stimulus processing time is short compared to existing non-visual approaches because it employs a visual display with refresh rate 60 Hz. 2) In the VR research field, the visual approach has achieved success in reorienting users while walking [22, 28, 29]. 3) Users are not cognizant that they are changing walking direction.

IMPLEMENTATION
When humans maintain balance or move their bodies, they preferentially use visual information [8, 14]. As visual illusions affect the brain's perception process, the proposed method uses a combination of a stereo camera and a stereo HMD to create visual illusions for walker control. The system obtains real-world images from the camera, applies image processing, and then provides the user with real-time vi-

	Ovrvision
Stereo camera	640×480 px per camera 60 frames per second H 90° / V 75°
HMD	Oculus Rift Development Kit 2 960×1080 px per eye 100° field of view
OS	Mac OS X 10.10.5
Library	Oculus VR SDK 0.4.4 OpenCV 2.4.11

Table 2. Prototype specifications.
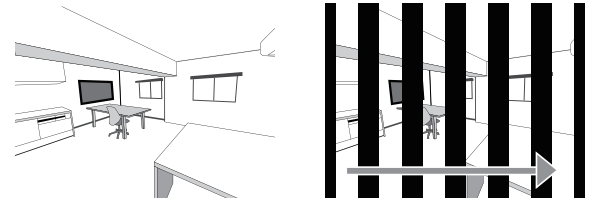
sual feedback to control his/her walking direction. This section discusses the prototype system and its image-processing method.

Prototype
The prototype system comprised an Ovrvision (Shinobiya.com Co., Ltd.) stereo camera and an Oculus Rift Development Kit 2 (Oculus VR, LLC) HMD (see Table 2).

Image Processing: Moving Stripe Pattern Method
Cognitive psychologists have discovered a variety of visual illusions, including vection field, which generates an illusory self-motion perception and is often applied in VR to improve user experience [1].

The proposed system employs an image-processing method that superimposes moving stripe patterns on real-world images to induce vection, as shown in Figure 2. Stripes are employed instead of random dot patterns to avoid the risk of causing carsickness [7]. Further, the stripe patterns remain on the real-world image and move to the right or to the left.

The width of the image provided by the stereo camera is 640 pixels (px). The width of each stripe is 40 px, and they are 100 px apart. In addition, there are slow-moving speed stripes that move at 1 px per frame (the frame rate of the stereo camera is 60 fps) and fast-moving speed stripes that move at 2 px per frame.

Image Processing: Changing Focal Region Method
The raw image provided by the stereo camera is cropped while maintaining the original aspect ratio and the HMD displays only the cropped image. Because the image is cropped around the center region of the raw image, the user sees an image with a narrower FOV than the original image, as shown in Figure 3 (left). Then, when the center position of the cropped area is shifted, the sight of the user is changed, as shown in Figure 3 (middle). Further, when the center position of the cropped area is moved horizontally, users feel that they have moved horizontally themselves, and they try to correct the movement. Consequently, the user's walking path is manipulated.

The focal region movement range is determined by the camera's magnification, resolution, and FOV. As shown in Figure 3 (right), the range, θ, can be calculated as follows:

$$\frac{\theta}{2} = \arccos \frac{2d^2 - \frac{w_1^2}{2} + w_1 w_2}{4\sqrt{d^2 + (\frac{w_1}{2})^2}\sqrt{d^2 + (\frac{w_1}{2} - w_2)}} \quad (1)$$
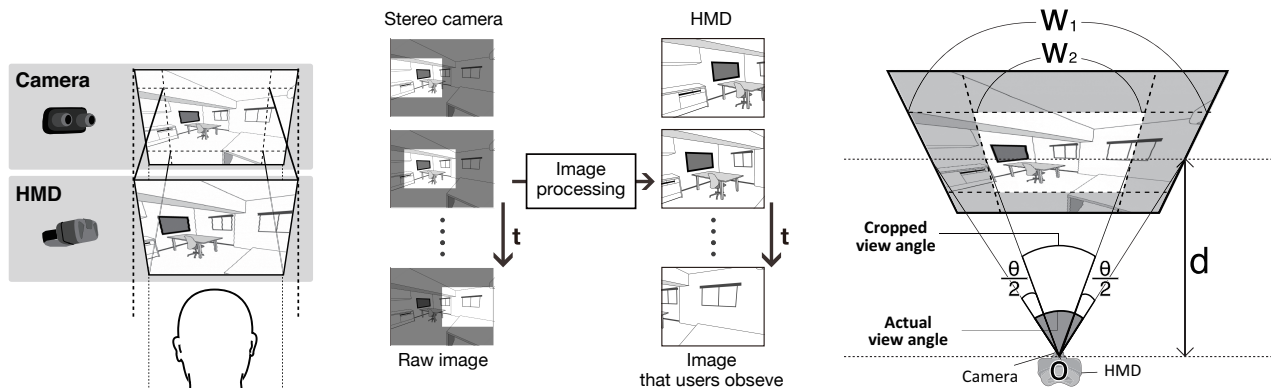$$\text{subject to } w_1 \geq w_2$$

Figure 3. Outline of the changing focal region method (left). Image process used by the changing focal region method (middle). Range of the focal region movement (right).

where w_1, w_2, and d are the horizontal resolutions of the camera, the cropped image that users view, and the distance between the camera and the focal plane respectively. The value of θ increases with w_1; thus, the higher the camera resolution or FOV, the wider the walker walking direction range the system creates.

In an experiment conducted, the raw image from the camera, with resolution 640×480 px, was magnified 1.5 times. The image was then cropped for manipulation, and the resultant cropped image had resolution 426×320 px. The image was cropped around the center region of the raw image, and the cropped area was moved horizontally left and right up to 107 px. The scroll speed of the cropped area in the slow condition was 0.5 px per frame and 1 px per frame in the fast condition. To guide users to the right, the cropped area is moved to the left, and vice versa.

PILOT STUDY
We conducted pilot study to determine which of the image-processing methods have the most effect on a human's walking direction. Five participants (1 female, 4 males) aged between 18 and 22 years (M = 20.2, SD = 1.83) participated. Each participant was briefed on the purpose of the study and was informed that s/he could abort the study or take a break at any time.

The participants each wore an HMD with a stereo camera attached and walked straight ahead in the hallway while viewing processed images on the HMD's screen. They were given the following guidelines: 1) try to walk at your usual speed, 2) do not turn your head while walking, 3) face straight forward while walking, and 4) be relaxed and focused while walking straight ahead. Six image-processing types were investigated: moving stripe pattern, rotating image, delayed image (only one side), magnifying (only one side), distorted image (only one side, trapezoid), and changing focal region. Each participant walked straight for 10 m 12 times (2 walks × 6 image-processing types). While the participants were walking, the experimenter operated a computer connected to the HMD, presented processed images to the participants, and observed their walking behavior. This study lasted approximately 20 minutes.

The study results indicated that the moving stripe pattern and changing focal region methods affect a person's walking direction more effectively than other image-processing methods.

EXPERIMENT
We also conducted an experiment to determine how to control the walking direction using the image-processing method. Participants each wore an HMD with a stereo camera attached and walked straight while viewing processed images on the screen of the HMD in the hallway and the square outside of the building.

Participants
Sixteen participants (3 females, 13 males) aged between 18 and 23 years (M = 21.4, SD = 2.0) participated in the experiment. All participants had normal or corrected vision; seven wore glasses and three wore contact lenses. The average height of the participants was 167.6 cm (SD = 9.0). We measured the participants' eye dominance using the Miles test [24], and found that 13 of them were right-eyed.

Experimental Design
The study was designed as a repeated measures experiment with two independent variables. The first variable was image-processing type: see-through image without processing, moving stripe pattern method (slow/fast), magnification, and changing focal region method (slow/fast). Magnification was added to the image-processing types for comparison because it is used in the changing focal region method. This enabled us to identify the effects of image magnification and to reveal the pure effects of changing the focal region. In addition, changing the FOV of an HMD has severe effects on spatial perception in VR and AR contexts [5, 13]. To reveal such effects, we added the magnification condition. The second independent variable was the place where the experiment was conducted: the hallway and the square outside of the building, as shown in Figures 4a and b. The hallway was narrow and had a width of 2.2 m. The participants could see several hints for spatial perception such as walls in the hallway. The square outside was large and had a width of more than 50 m. The participants could not find definite hints for spatial perception in the square.
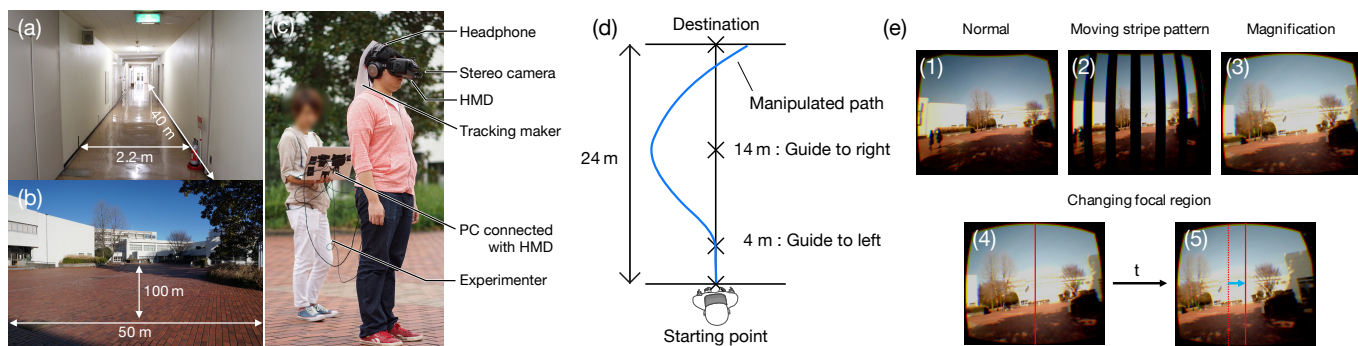
Figure 4. Locations where experiments were conducted. (a) Hallway. (b) Square outside of a building. (c) Experimental setup. (d) Points where the experimenter controlled the participants. (e) Presented image of each image-processing type, as seen by the participants. In the changing focal region, the position of the focal plane is initially at the center (e-4). Over time, the position of the focal plane is moved (e-5). The red line indicates the position of the focal plane.

Thus, there were 12 conditions (6 image-processing types × 2 places). The participants were exposed to different types of processed images at random to counterbalance any possible biases caused by the order of the conditions.

Procedure
Each participant was briefly informed of the purpose of the study and told that they could abort the study and take a break at any time. Further, they were provided with a consent form to sign and a demographics questionnaire to complete. To identify potential influences on the results, the participants also completed a Kennedy's Simulator Sickness Questionnaire (SSQ) [11] immediately before and after the experiment.

First, the participants wore the HMD with the stereo camera attached in the hallway. The experimenter calibrated the HMD position to center on the vanishing point at the end of the hallway. The participants also wore headphones to listen to the sounds of a metronome (set at 100 beats per minute), which was utilized to make users maintain the same walking speed (similar to the approach in [6]). A tracking marker was attached to each participant's head for the measurement. The experimental setup is shown in Figure 4c.

Before the actual evaluation began, the participants were asked to perform a practice task in which they walked straight for approximately 50 m. They were given the following rules: 1) walk to the sound of the metronome, 2) try to walk at your usual speed as much as possible, 3) do not turn your head while walking, 4) face straight ahead while walking, and 5) be relaxed and focus on walking straight.

In the actual evaluation, each participant walked straight for 24 m 12 times to examine each of the 12 different combinations (6 image-processing types × 2 places). They were instructed to stand at the starting point and an experimenter stood at a point 6 m away to ensure that they knew the direction even if there were no targets in the goal towards which they had to walk. While the participants were walking, the experimenter manually operated a computer connected to the HMD and controlled the participants' walking direction. At a point 4 m from the starting point (Figure 4d), the participants were guided to the left by the image-processing method: in

the moving stripe pattern method, the stripe pattern kept moving to the left; in the changing focal region method, the crop area was moved to the right horizontally. At a point 14 m from the starting point, the participants were guided to the right: in the moving stripe pattern method, the stripe pattern kept moving to the right; in the changing focal region method, the crop area was moved to the left horizontally.

After all 12 conditions were completed, the participants were asked to complete a questionnaire related to the image processing. This experiment took approximately 45 minutes and was recorded using a video camera.

Tracking System
We measured the distances in the images manually with 5 people. First, we recorded the experiment with a 1080p camera; our staff flashed an LED when a subject passed over distance markers placed every 2 m. Next, we captured the frames in which an LED flashed and manually measured the distance from the participant to a median line and the length of the objects in the environment in pixels. Finally, we calculated the actual distance (m) from the ratio of these values. In the experiment, theoretical error was estimated to within 1.5 cm, but even while accounting for human error, the variation was not expected to exceed 1 m.

RESULTS

Simulator Sickness Questionnaire (SSQ)
We analyzed the SSQ scores with t-test, and did not find any significant difference between pre-SSQ and post-SSQ scores. SSQ scores before the experiment averaged 4.7 (SD = 4.7), and the average post-experiment score was 6.7 (SD = 8.3). Furthermore, no participant reported feeling any motion sickness.

General Results and Statistical Analysis
The moving path of all participants under all conditions is shown in Figure 5. The mean value of the position change for each image-processing type is shown in Figure 6 and Table 3. Based on the results, the changing focal region method was most effective for walker movement control.
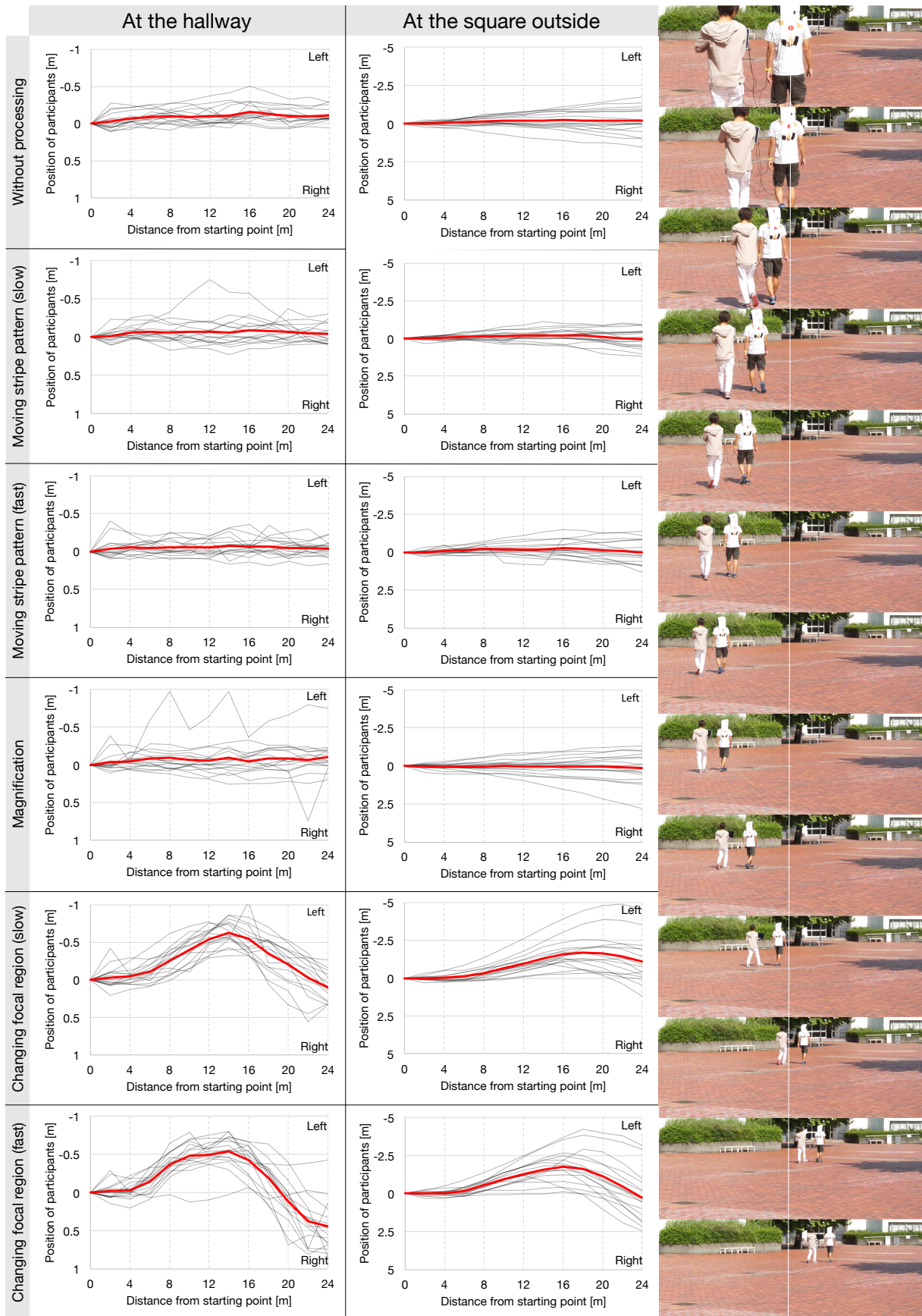
Figure 5. Movement path of all participants under all conditions (left). The path for each participant is shown as a gray line. The path that combines all the participants' paths is shown as a red line. Result of the experiment under the changing focal region method (right).
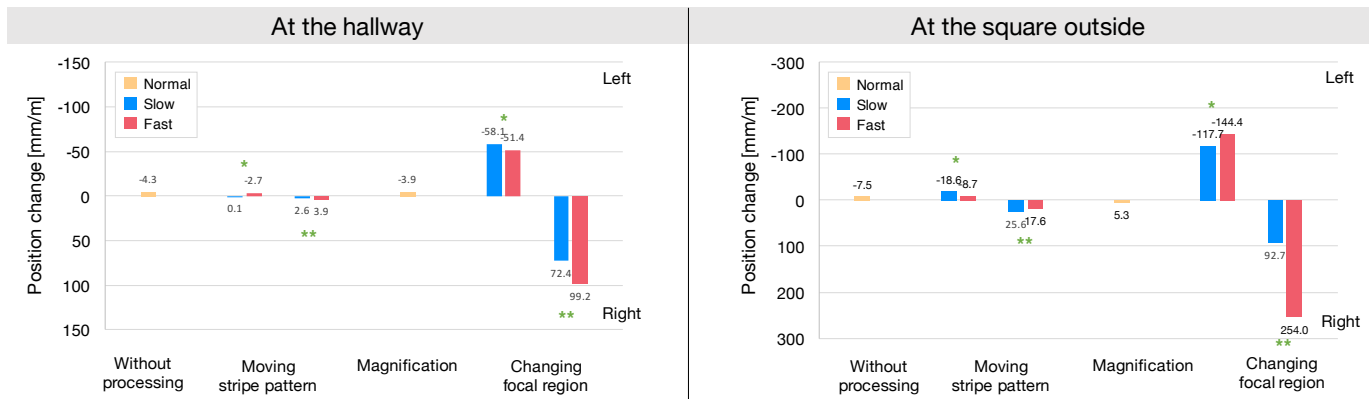
Figure 6. Mean value of the position change for each image-processing type. (*) Guide to the left. (**) Guide to the right.

Image processing type	Position change [mm/m]					
	At the hallway			At the square outside		
	Normal	Slow	Fast	Normal	Slow	Fast
Without processing	-4.3 (11.5)	–	–	-7.5 (17.0)	–	–
Moving stripe pattern (guide to left)	–	0.1 (5.4)	-2.7 (7.8)	–	-18.6 (17.0)	-8.7 (24.0)
Moving stripe pattern (guide to right)	–	2.6 (6.7)	3.9 (6.8)	–	25.6 (25.1)	17.6 (37.1)
Magnification	-3.9 (14.4)	–	–	5.3 (12.1)	–	–
Changing focal region (guide to left)	–	-58.1 (19.3)	-51.4 (20.6)	–	-117.7 (52.6)	-144.4 (70.3)
Changing focal region (guide to right)	–	72.4 (41.3)	99.2 (49.0)	–	92.7 (59.7)	254.0 (130.0)

Table 3. Mean position change value for each image-processing type. SDs are denoted in parentheses.

First, we analyzed the participants' walking paths with repeated measures ANOVA. The within-subject factors were image-processing type and the measured point of each participant's horizontal position (0–24 m, 2 m intervals). The sphericity assumption was supported by Mauchly's test of sphericity at the 5% level, or the degrees of freedom were corrected using the Greenhouse-Geisser estimates of sphericity. A comparison of without processing and the moving stripe pattern (slow/fast) showed no significant interaction effect. On the other hand, comparison of without processing with changing focal region (slow and fast) showed a significant interaction effect between image-processing type and the measured point in both the hallway (slow: $F_{2.47, 37.09} = 28.48$, $\eta^2 = 0.66$, p < 0.001; fast: $F_{2.73, 40.95} = 38.27$, $\eta^2 = 0.72$, p < 0.001) and outside (slow: $F_{1.55, 23.18} = 20.65$, $\eta^2 = 0.58$, p <0.001; fast: $F_{1.38, 20.72} = 14.04$, $\eta^2 = 0.48$, p < 0.001). Further, comparison of magnification and changing focal region (slow and fast) also showed a significant interaction effect in both the hallway (slow: $F_{2.37, 35.60} = 23.37$, $\eta^2 = 0.61$, p < 0.001; fast: $F_{3.02, 45.25} = 32.20$, $\eta^2 = 0.68$, p < 0.001) and outside (slow: $F_{1.56, 23.43} = 36.43$, $\eta^2 = 0.71$, p < 0.001; fast: $F_{1.37, 20.53} = 23.37$, $\eta^2 = 0.61$, p < 0.001). These results indicate that the participants' walking paths were strongly affected by this method. Comparison of without processing with magnification showed no significant interaction effect, neither in the hallway nor outside. This indicates that the cropped image by itself did not affect the participants' walking paths. Thus, it is clear that the participants' walking paths were affected by movement of the cropped area.

Second, we analyzed the position change amount for each image-processing type with repeated measures ANOVA and Tukey multiple comparisons at 5% significance level. The within-subject factors were image-processing type and place. We observed a significant major effect for image-processing type ($F_{5, 75} = 163.30$, $\eta^2 = 0.92$, p < 0.001) and also for place ($F_{1, 15} = 49.92$, $\eta^2 = 0.77$, p < 0.001). This means that the outside participants were affected more by the image-processing types. A significant interaction effect was also evident between steering method and place ($F_{5, 75} = 26.37$, $\eta^2 = 0.64$, p < 0.001). Post-hoc tests revealed the following: 1) significant difference was found between without processing and the changing focal region method (slow: p < 0.001, fast: p < 0.001), and 2) the changing focal region (fast) was significantly more effective in manipulating participant's walking path than the slow condition.

Changing Focal Region Method

We were able to change their walking path by approximately 200 mm/m on average under the fast condition in the square.

In the hallway, the participants could not move more than 1.1 m; thus, the mean value of the position change in the hallway was smaller than that in the square. Further, the value of the position changes in the hallway decreased sharply at the 24 m point, as shown in Figure 7, because some participants had reached the wall.

The value of the position change at each measurement point is shown in Figure 7. This shows the derivative value of the horizontal position change of the participants, and indicates the amount of change in the participants' movement. In this case, the fast condition more effectively affected the participants' walking direction than the slow condition. The mean value of the position change under the fast condition in the square
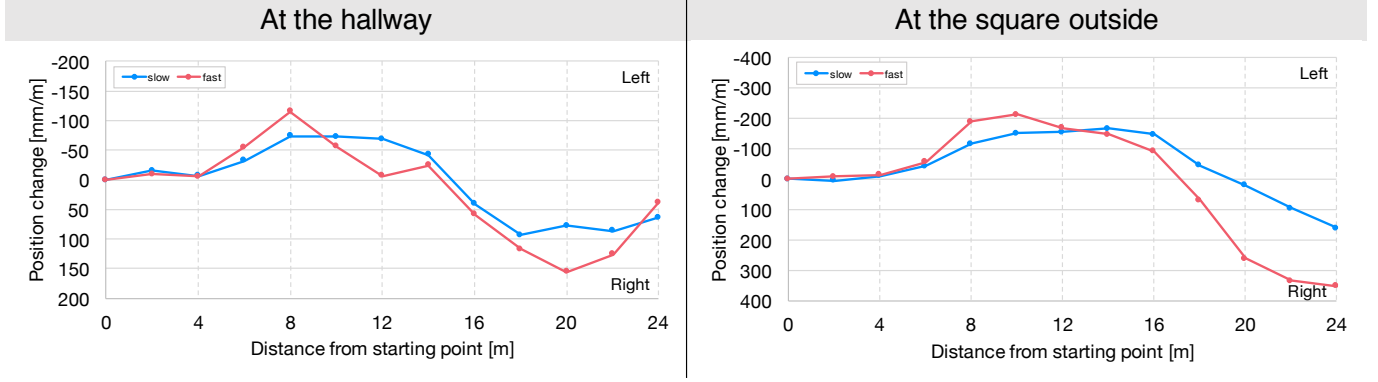
Figure 7. Value of the position change at each measurement point under changing focal region conditions.
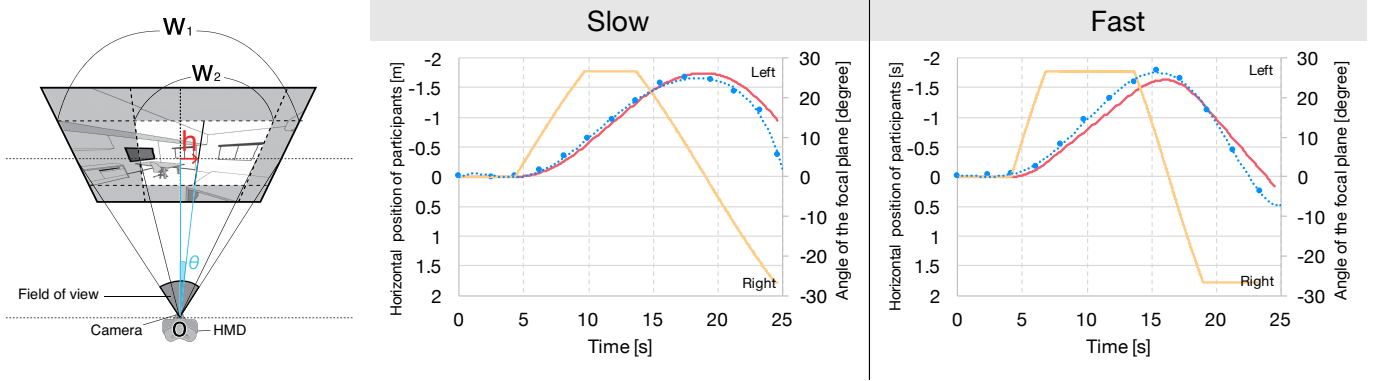

Figure 8. Relationship between scroll amount from origin and angle of the focal plane (left). Comparison between simulated path and measured path (right). The simulated path is shown as a red line, the measured path is shown as a blue line, and the angle of the focal plane is shown as a yellow line.

was twice as much as the slow condition (slow: 105.2 mm/m; fast: 199.2 mm/m).

Qualitative Results

Some participants noticed that they had been walking on a curved path, but they did not notice whether the image processing had started.

The answers given in the completed questionnaires indicated that the changing focal region method brought on much more visual discomfort than the moving stripe pattern method. Their average scores on a five-point Likert scale (1 = weak discomfort, 5 = strong discomfort) were 3.9 (SD = 1.26) and 2.6 (SD = 0.89), respectively. We analyzed this result with t-test, and there was a significant difference (t = -3.02, df = 15, p < 0.01).

Design Parameters and Formalization

We derived a relationship between scroll amount from origin and angle of the focal plane. As shown in Figure 8 (left), the angle, θ, of the focal plane to value of scroll h can be calculated as follows:

$$\theta = \arctan\left(\frac{1}{\frac{w_1}{2 \tan \frac{fov}{2}}} h\right) \quad (2)$$

subject to $w_1 \geq w_2, \frac{(w_1 - w_2)}{2} \geq h$

where w_1 and w_2 are the horizontal resolutions of the camera and cropped image that users see, respectively, and fov is the camera's FOV. Let v be walking speed, t elapsed time, and α amount of movement per degree. We can express the position of a user (x: distance from starting point, y: horizontal position) as

$$x = vt \quad (3)$$
$$y = \alpha x \theta \quad (4)$$

From Formulas (2) and (4), we obtain:

$$y = \alpha x \arctan\left(\frac{1}{\frac{w_1}{2 \tan \frac{fov}{2}}} h\right) \quad (5)$$

Using the experimental result, we obtained α:

$$\alpha = \begin{cases} -6.71 & (\theta \geq 0, \text{guide to left}) \\ -9.56 & (\theta < 0, \text{guide to right}) \end{cases} \quad (6)$$

We simulated the participants' walking path using the above formulas and α value. Further, we compared the simulated path with the measured path (Figure 8 (right)). Subsequently, we formulated a model for our method.

DISCUSSIONS

General Discussions

Our methods utilize an HMD and a camera for walker control. These components provide visual stimulus programmability and longer range control distance than that used in conventional studies. However, the combination of HMD and stereo camera is still heavy for users to carry, approximately 500 g – which is too heavy for everyday use. We expect that this problem will be solved by the development of lighter HMD devices. In addition, the resolution of the image is not very high and the FOV of the camera and display is not very wide. Consequently, the control direction angle is limited.

Although HMDs have been used for some time in entertainment, their use in the general public is not yet widespread. However, we envision that the combination of HMD and stereo camera will eventually gain widespread use in society. This study serves as a pilot study for future research studies. Furthermore, to determine the feasibility of this study, we demonstrated our system at SIGGRAPH 2016 Emerging Technologies, and approximately 800 people were successfully manipulated by the proposed method [10].

The answers in the completed questionnaires on visual discomfort indicate that the changing focal region method scored more than the moving stripe pattern method. We will investigate more comfortable methods with feedback control, such as changing visual angle depending on walking speed and timing of blink, in future studies. The answers also indicated that there was a little feeling of moving in the horizontal direction with the moving stripe pattern method; however, quantitative results revealed that this method did not fundamentally affect the participants' walking direction. Therefore, we conclude that this method can induce vection, but cannot change a person's walking direction.

Walkers' Safety and Ethical Issues

We assume that our method will mainly be applied to VR/AR situations and believe that in controlled spaces, safety can be established and users will agree to be manipulated by the method. Conversely, in everyday life, the high distortion of reality it entails and the fact that the user is not paying attention raises safety concerns that would make it difficult to employ our method.

Most of the participants expressed a positive reaction to our method, and there was no safety issue in the experiment itself as we followed the participants and prevented any possibly dangerous situations.

We believe this study also poses a question about the future safety of HMDs. As technology advances, it is likely that the entire reality a user sees will be brought via an HMD and a camera. If a hacker or malicious software exploited this method, users could be unwittingly manipulated and be exposed to danger. This study provides a starting point for considering such situations.

Spatial Perception

Several researchers [5, 13] reported that changing the FOV of an HMD has severe effects on spatial perception in VR and AR contexts. However, no significant difference was found between the see-through image without processing and the magnification condition. Therefore, there was no horizontal spatial perception effect on the experimental results. By contrast, we could not determine whether there was any depth perception effect. We will conduct further experiments to determine this in the future.

Cognitive Resource

Bruder et al. showed that a significant amount of cognitive resources is required for redirected walking [2]. Similarly, our technique might require some cognitive resources. In this study, we defined "subconscious" not as users not using cognitive resources but as users not noticing that they are changing their walking direction. However, investigation of cognitive resource is essential to reducing burden. Therefore, we have to investigate how much cognitive resources are really required by users to follow the manipulation.

Limitations and Scalability

The moveable range and movement speed resolution of the focal plane point are determined by the FOV and resolution of the camera, respectively. Therefore, we need to conduct a follow-up experiment using a camera with a higher resolution and a wider FOV.

In our current system, walkers cannot negotiate 90-degree corners. However, this limitation might be eliminated by using omnidirectional cameras [23] because of their wider FOV. We have already investigated using omnidirectional cameras and found that they did not work well because changing the focal region in an omnidirectional camera simply produces visual contradiction when walking. However, we believe that this issue may be rectified using SLAM.

APPLICATION SCENARIOS

AR/eSports

Our technique is valuable in VR/AR situations where users walk around, such as control methods in see-through VR/AR (e.g., AR city tours and museum guides and interactive media). Redirected walking has been investigated for fully VR situations. Similarly, subconscious walking control in see-through AR/eSports contents, such as several people walking around in a limited space is a hot topic. Furthermore, we believe that the portability of see-through HMD (camera + non-see-through HMD) will be significantly improved in the future.

Walker Navigation System

In the future, it may be possible to design an automatic navigation system using our technique. Because the system works subconsciously on users, they need not pay attention to the navigation feedback; thus, users need not worry about misunderstandings or information oversight.

We used the same formula derived from the experimental results (as stated in the Design Parameters and Formalization section), and implemented a prototype navigation system. Subsequently, we performed an experiment in a building to examine the operation of our navigation system in a real

Figure 9. Route used in the study (left). Participant using our navigation system (right). His walking direction was controlled by our navigation system, and he arrived at the destination.
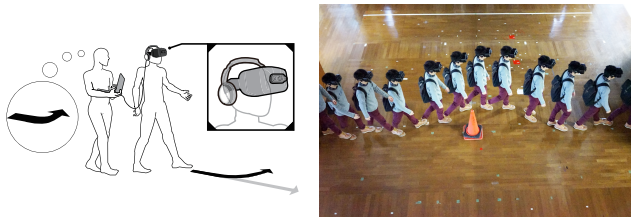

Figure 10. Remote-controlled human (left). Collision avoidance system (right). In this case, the user avoided the collision with the red pylon automatically.

environment. We invited four male participants (M = 21.5, SD = 1.7) and adopted the Wizard-of-Oz study. Thus, we could observe how participants are guided and be able to prevent accidents during the experiment. The experimenter followed the participants and manually operated the navigation system to guide them to the destination.

The route utilized is shown in Figure 9 (left). Note that the participants did not have any knowledge of the route.

The participants each wore an HMD with attached stereo camera, and was asked to walk casually and to reorient to the direction if they felt their course tilting. They were also asked to pay attention to any obstacles. The experimenter followed each participant and manually operated the navigation system to guide him to the destination. On completing the route, the participants were asked to report their thoughts. The whole experiment was recorded by a video camera.

One set of results is shown in Figure 9 (right). Three of the participants were guided to the destination successfully, and the overall feedback on the navigation system was positive, such as "*This system is enjoyable for me*" and "*I felt relaxed because I just walked casually.*" Some of the negative feedbacks obtained were as follows: "*This time I didn't get any motion sickness but I was afraid of getting it while using this system*" and "*It was hard to perceive space while using this system.*"

Remote-controlled Human

Our system can control walking direction; therefore, we can manipulate humans via remote control (Figure 10 (left)). This is applicable for entertainment. For example, by controlling many people wearing our system, the people can just simply walk facing forward, allowing mass games to be realized.

Collision Avoidance System

When a person is absorbed in something and is not aware of some obstacles, s/he may sometimes collide with obstacles. To address such issues, we can construct an automatic collision avoidance system that combines our system and a depth sensor. This system ensures the safety of walkers and does not interrupt users because it works subconsciously (Figure 10 (right)).

FUTURE WORK

From the experimental results, it is clear that participants were more affected when they were guided to the right than to the left. This could stem from the fact that the left/right manipulation was not balanced, the first manipulation was always towards the left. Therefore, we will conduct additional experiments with another procedure to further examine this issue.

In this user study, we showed that our walker control method works successfully. The user study, however, was performed with limited parameter variations, e.g., the scrolling speed and width of the stripe pattern, and the moving speed of the focal region. Moreover, the answers in the questionnaires indicate that the current image-processing design caused unpleasant feelings. We will investigate ideal image-processing parameters to avoid this issue.

CONCLUSION

This paper presented a proposed method that utilizes image-processing methods to induce vection and consequently subconsciously control the walking direction of walkers. We employed a combination of a wide-viewing angle stereo HMD and a stereo camera for walker control. In this scenario, users perceived the real world by means of stereo images provided by the stereo camera and the stereo HMD, attained real-time feedback to their sight from the processed images, and thus were controlled by the navigation system. This study also provided a proof-of-concept implementation that demonstrated the feasibility of the approach. The pilot study proved that the moving stripe pattern and changing focal region methods worked successfully. We also showed that the changing focal region method worked most effectively for walker movement control and changed users' walking path by approximately 200 mm/m on average. We believe that the methods explored in this study will facilitate new relationships between walkers and the computational environment in the real world.

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