VMotion: Designing a Seamless Walking Experience in VR

Misha Sra
MIT Media Lab
Cambridge, MA USA
sra@media.mit.edu

Xuhai Xu
Tsinghua University
Beijing, China
xxh14@mails.tsinghua.edu.cn

Aske Mottelson
University of Copenhagen
Copenhagen, Denmark
amot@di.ku.dk

Pattie Maes
MIT Media Lab
Cambridge, MA USA
pattie@media.mit.edu

ABSTRACT

Physically walking in virtual reality can provide a satisfying sense of presence. However, natural locomotion in virtual worlds larger than the tracked space remains a practical challenge. Numerous redirected walking techniques have been proposed to overcome space limitations but they often require rapid head rotation, sometimes induced by distractors, to keep the scene rotation imperceptible. We propose a design methodology of seamlessly integrating redirection into the virtual experience that takes advantage of the perceptual phenomenon of *inattentional blindness*. Additionally, we present four novel visibility control techniques that work with our design methodology to minimize disruption to the user experience commonly found in existing redirection techniques. A user study ($N = 16$) shows that our techniques are imperceptible and users report significantly less dizziness when using our methods. The illusion of unconstrained walking in a large area ($16 \times 8m$) is maintained even though users are limited to a smaller ($3.5 \times 3.5m$) physical space.

ACM Classification Keywords

H.5.1. Information Interfaces and Presentation (e.g. HCI): Artificial, augmented, and virtual realities

Author Keywords

Virtual Reality; Reorientation; Seamless Experience; Context-Sensitive Design; Visibility Control; Locomotion;

INTRODUCTION

The ability to move is a fundamental requirement for exploration in both real and virtual worlds (VWs). Natural exploration is desirable for many practical virtual reality (VR) applications in areas of education, tourism, rehabilitation, and entertainment. Mapping physical space to a virtual space of the same size can support walking for navigation and interaction and provide a compelling experience [27, 34]. However, a major limitation is that physical dimensions of the tracked space constrain the size of the VWs that can be explored on foot. While navigation techniques, both design and device based like teleportation [1], magic carpets [15], miniaturization [35], or 360° treadmills [26] allow for experiencing VWs that are much larger than the tracked physical space, the sensation of walking is still not satisfactorily addressed. If the user cannot naturally move and engage with the virtual environment as if it were real, presence or the sense of 'being there' may break [24]. Research suggests that users navigate best with locomotion techniques that provide vestibular and proprioceptive feedback such as real walking [21]. Additionally, locomotion techniques that stimulate the vestibular and proprioceptive systems are less likely to cause VR sickness than locomotion interfaces that do not stimulate them [2, 21].

Redirected walking, a technique for continuous manipulation of mapping between physical and virtual rotations to steer the user away from the tracked space boundaries [20], has been shown to be effective for allowing natural and unconstrained walking in VWs. Other real walking locomotion interfaces include scaled translation gain [6, 39] or motion compression [14]. Both these interfaces either rotate the VW or scale the user's motion. While numerous redirection studies have demonstrated promising results, redirection techniques are still somewhat limited in their practical applicability for the typical consumer [33]. The techniques typically require a large physical space [18, 28], have difficulty changing a user's direction when the user gets close to tracked space boundaries [31], need frequent and rapid head rotations to keep the VW rotation imperceptible [20], and can cause virtual reality sickness [10].

Resetting, also known as reorientation, is a class of techniques used to steer the user away from physical boundaries. While redirection techniques are applied continuously as the user walks around, resetting techniques stop and reorient the user only at the boundary of the tracked physical space. Reorientation techniques rotate the VW around the user's current position. The user must also reorient their body by physically turning to be able to follow their desired path in the rotated VW. Williams et al. [40] proposed a reset technique that di-

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rects the user to walk backwards or to physically turn around while the VW remains frozen. A notable disadvantage of resetting is that it interrupts the experience and can thereby decrease presence and immersion. To address the need for rapid head rotation for redirection, Peck et al. [17] introduce a fast moving object called a distractor, which encourages users to rapidly turn their head back and forth for tracking its movements. However, the usefulness of the distractor is weakened as it can disrupt the user's experience and it requires users to be trained to follow it whenever it appears [3, 18]. General purpose distractors that effectively serve their purpose but intrude upon the scenario context, interrupt the flow of the narrative and can break the user's sense of presence.

In this paper, we present a design methodology and four visibility control techniques that work together to overcome previous limitations by integrating distractors into the narrative and making them part of the user's main activity in the VW. In our design, the distractors are what make the experience interactive and engaging and hence, in the rest of this work we refer to them as attractors. We leverage human perception, specifically, *inattentional blindness* [11] and some aspects of how the human visual system [37] functions to design interaction which allows us the opportunity to imperceptibly rotate the VW when needed. Unlike previous distractor-based methods that manipulate a user's physical trajectory by combining reorientation with redirection techniques [17], our methods do not use redirection (continuous VW rotation). We hypothesize that our embedded or context-sensitive design methodology along with visibility control techniques can help minimize breaks in presence from disruptions to the user's main activity, preclude the need for frequent and rapid user head rotation, reduce physical space requirements, successfully steer users away from boundaries, lessen virtual reality sickness, and maintain high presence in the virtual experience.

Our methodology of embedded or context-sensitive reorientation is based on the perceptual phenomenon of *inattentional blindness*, which suggests that a user does not perceive items that are in plain view [11] when they are intently focused on a different task. The methodology entails creating experiences that embed scene-relevant and task-relevant attractors into the narrative and the user's main activity in VR. The attractors spawn in appropriate spatio-temporal positions and fully engage users, allowing for organically integrating reorientation into the experience of, and interaction with the VW.

For designing interactions with the embedded attractors, we introduce the idea of using elements of visual and motion perception [37]. Specifically, we propose four general visibility control techniques: *reduced field of view*, *limited viewing distance*, *tilted viewing angle* and *shallow depth of field*. To demonstrate how the visibility control techniques and the embedded attractors work together, we present a fully working VR experience. Our study results show that VW rotation using our techniques is less noticeable than VW rotation without these techniques and has minimal impact on the experience even when users do notice the associated scene rotation. Reported dizziness using our techniques is significantly lower due to using real-walking for locomotion and imperceptibility of VR rotation, leading to a more comfortable and seamless VR experience. Because users are simply performing their intended activities, and the attractors are not disruptors, the users' sense of immersion and presence is maintained.

The key contributions of our work are:

- Design of visibility control techniques based on elements of visual perception to make reorientation imperceptible.
- A design methodology to seamlessly integrate reorientation into the user's main activity through *attractors*.
- Four design strategies based on the perceptual phenomenon of inattentional blindness for VR designers who want to create seamless real-walking experiences in VR.

RELATED WORK

This paper presents a design methodology and visibility control techniques that together enable walking through an immersive VW that is considerably larger than the available tracked space. We summarize below a few of the most directly related works.

Real Walking in Virtual Reality

The benefits of supporting natural body movement in VWs have been extensively studied. Real walking has been shown to provide a greater sense of presence than walking-in-place or flying [35], better performance on search tasks [21], and benefits for memory and cognition [41]. Redirected walking or redirection has been shown to successfully support real walking in VR [20]. Two common approaches to redirection are: introducing a VW rotational gain in order to imperceptibly rotate the scene such that the user stays away from the boundaries of the tracked space [20], and (2) scaling linear movement to enable travel over larger distances in the VW [6]. Other techniques for supporting walking in virtual environments like estimating walkable areas automatically from a 3D scan of the physical space [27] or by using simultaneous localization and mapping (SLAM) [13] have also been explored. A study on redirected walking shows that users can be physically turned approximately 49% more or 20% less than the perceived virtual rotation without visibly noticing [28]. A walking arc with a radius of at least 22m is necessary for scene rotation or curvature gains to be imperceptible to the user though most users do not have this much tracked space [28]. As both redirection approaches introduce a visual-vestibular conflict, they can cause dizziness or virtual reality sickness [4]. In contrast to redirection techniques, our method does not continuously manipulate the mapping between physical and virtual motions. Instead, we rotate the scene only when the user is engaged in interacting with the VW, thereby making any rotation largely imperceptible.

Reorientation

While redirection techniques are applied continuously as the user walks around, reorientation or resetting techniques stop and reorient the user only at the boundary of the tracked physical space [40]. A notable disadvantage of resetting is that it interrupts the user and depending on the frequency of interruption, it can negatively impact the immersive experience. To mitigate potential breaks in presence, Peck et al. [17] combined distractors with redirection. The distractors were preferred over visual or audio reset instructions. However, the out of place distractors and the user training required to look at the distractors impeded the flow of narrative by distracting from the user's main goal in the virtual experience. Our method integrates the reorientation techniques into the user's primary activity. We use interactions with attractors in the VW to advance the narrative and manipulate a user's physical path. We rotate the scene, only when the user is engaged in a task, towards the direction that can lead them away from the boundary.

Perception

Magicians have been exploiting the limits of perception and attention for centuries. Redirection and reorientation techniques work because visual perception dominates proprioception in VR if the magnitude of the conflict is within tolerable limits [20, 28]. In Infinite Walking [30], the VR scenario instructs users to explore the environment while stopping at specific points to take panoramic photos in the virtual world. To take a panoramic photo, the user needs to turn 360° and while they are turning, the virtual world is rotated such that when they stop, they are correctly aligned to walk forward in both the virtual and physical spaces [30]. Visual motion perception serves many roles, including perception of depth, the separation of objects, and the estimation of the motion of objects in the world [38]. Everyday visual experience shows that humans can see things move and can judge how fast and in what direction they move, with some accuracy. Research indicates that three dimensional perception of position and orientation is largely affected by reference objects in the field of view [37, 38]. Hence, the fewer reference elements in the scene, the less a user will be aware of the self body scale information [37], and thus, be less sensitive to any changes of the background. In order to make movement unnoticeable, we exploit the underlying process of motion perception in our visibility control techniques.

Change blindness [23], a perceptual phenomenon when a person fails to detect an obvious change to an object or scene, has been successfully used as a redirection technique [32]. Another type of phenomenon is inattentional blindness, where a user does not perceive items that are plainly in view [11]. The famous Invisible Gorilla Test shows that when humans keep their attention on the main task, they fail to notice other unexpected changes [22]. The difference between change blindness and inattentional blindness lies in the fact that the former is the failure to notice an obvious change in the scene from before while the latter is the failure to notice something incongruent in plain view [7]. The design of our visibility control techniques is based on the perceptual phenomenon of inattentional blindness.

DESIGN METHODOLOGY

Embedded Context-Sensitive Distractors

An attractor is presented when the user approaches the boundary of the safe area. We define the term embedded context-sensitive attractor to encompass the general notion of attractors

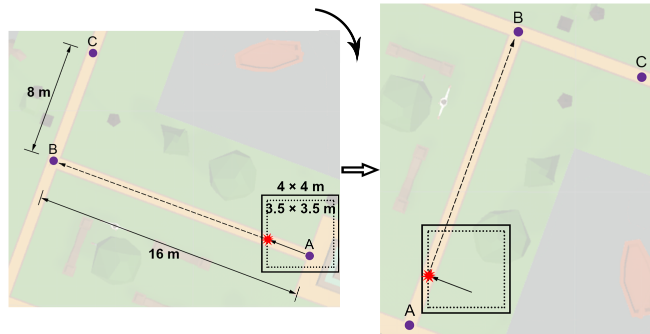


Figure 1: Virtual world rotation. Black square is the tracked space. Left: At the boundary of the safe area (red dot), one of our reorientation techniques is triggered randomly to engage the user in an interactive activity relevant to their goal. During the interaction, the VW is rotated by 90 ° to lead the user away from the safe area boundary. Right: The user (red dot) position shows newly available walking space inside the tracked area after virtual world rotation.

that are coherent with the narrative, related user interactions, and the virtual environment. For example, in games modeled after real world places, attractors like a bird in a park or an enemy in a battle scene would not feel out of place and any interaction with them could be seamlessly integrated into the user's activity and goals in that VR experience. Blending reorientation events into the narrative, such that interaction with them feels natural and organic, requires designing the experience with reorientation in mind instead of layering the techniques *post-factum*. Seamless integration allows the scene to be rotated while the user interacts with the attractor (see Figure 1) thereby reorienting their physical trajectory while maintaining the virtual one. The result is reduced interruption of primary activity and enhanced presence that comes from natural, non-disrupted real-walking based movement, and the VR experience.

Visibility Control Techniques

We propose a new type of reorientation method with four visibility control techniques: *reduced field of view*, *limited viewing distance*, *tilted viewing angle* and *shallow depth of field*, designed to manipulate elements of human visual and motion perception. According to Gibson [5], everyday living depends on direct perception that guides action intuitively and automatically. Our visibility control techniques work with embedded attractors to engage the user in scene and activity relevant tasks. This provides us the "opportunity" to furtively rotate the virtual scene when the user is performing a task as part of their VR experience.

Reduced Field of View

This technique requires users to look through devices or small openings that are appropriate for the task they need to perform. Doing so effectively limits a user's field of view (FoV) which in turn can make it difficult for them to notice VW rotation. Examples of devices include looking through a pair of binoculars, a telescope or microscope, a camera viewfinder or any other type of reticle. Examples of openings include holes, cracks, slits, or other similar apertures. The narrative needs to provide a reason (embedded attractor) for the user to look through the device or opening. Binoculars or microscopes can additionally magnify the view seen through them, changing a user's perception of size and motion relative to self-body scale, and adding another component that can make scene rotation less noticeable.

Limited Viewing Distance

This technique involves using elements of the virtual environment to limit the user's ability to see in the distance. Examples include dust, fog, blowing leaves, garden sprinklers, heavy snow or rain which reduce the distance that users can see to a few meters. Reducing distance visibility removes visual reference points from the viewable scene which can make VW rotation imperceptible. Mixed with nearby attractors to allow the user to focus on or interact with something instead of feeling lost, this technique can provide another opportunity to rotate the VW.

Tilted Viewing Angle

This technique requires users to look towards the clear sky or any background that has a limited number of objects which can act as visual reference points for indicating motion. The user can be made to look up or down by using an attractor. The attractor needs to be designed such that it fills the user's field of view, when held or looked at against a partially empty background. Doing so provides an opportunity to subtly rotate the VW. Examples include reading a book up close or inspecting an insect or other object closely against a plain background.

Shallow Depth of Field

Depth of field (DoF) is the distance between the nearest and farthest objects in a scene where objects appear acceptably sharp in an image. In cinema, manipulating DoF is used as a method to guide the viewer's attention by selectively bringing objects into focus while blurring others. For example, changing the center of attention in a scene by having a foreground object in focus, with the background out of focus. VR hardware uses fixed-focus displays, making it difficult to attain a natural depth of field as the user's eyes shift focus from objects in background to those in the foreground. Like the storytelling mechanic from cinema, this technique simulates DoF by blurring the background and keeping the foreground in focus thereby indirectly guiding the user's attention. The foreground object is the distractor while the blurred background and inattentional blindness allow for imperceptibly rotating the VW.

In both *Limited Viewing Distance* and *Shallow Depth of Field*, visibility of background reference points is masked to reduce noticeability of scene rotation. The difference lies in the design of the interaction. The former involves passively tracking moving objects in the scene while the latter involves active interaction through dialog or other means with one or more characters in the scene.

Implementation Criteria

The two main implementation criteria in our design are, 1) having tasks or attractors along a path that are coherent with the scene or experience, and 2) having elements in the scene that can affect the user's visibility temporarily such as reducing their field of view or limiting the viewing distance. Both design elements serve to create opportunities for interaction and visibility control which in turn allow us to imperceptibly rotate the virtual world, leading to a seamless walking experience. While several linear narrative based experiences could take advantage of our design, what constitutes the *attractors* and which scene objects can aid the design of visibility control may not be readily obvious for all scenarios. Sandbox experiences that support open-ended exploration over task completion for making progress through the experience, may also be able to use our design if suitable attractors and other objects exist in the scene.

Below are three exemplary scenarios that meet our implementation criteria that show that within the stated scope, there are a variety of VR experiences where our design is suitable.

Treasure hunt

Users follow a map to the treasure which would require them to stay on a predetermined path. The attractors would be objects that provide clues to the location of the treasure like small puzzles or tasks. Scene elements affecting visibility would be things such as a pirate's spyglass or a large wind blown pirate flag or the ship's sail. Looking through the spyglass would *reduce field of view* while a flag or sail billowing in the wind would temporarily *limit viewing distance*.

Job Simulator extension

Job Simulator is one of the most popular VR games currently available [*]. In our version of the game, that allows users to walk around naturally, the chef would walk to and from the kitchen along a specified path that goes between the restaurant tables. Cooking and cleaning interactions, talking with customers, and dropped objects would serve as attractors. Visibility would be affected by things like waiters walking by with platters of food (*limited viewing distance*) or the user peering into the fridge for food (*reduced field of view*).

Pokemon like game

Here the main task would be to walk along a fixed path through the forest collecting things or monsters, interacting with them, and battling them. Trees or insect swarms would serve to affect visibility by blocking the user's *field of view* or *reducing viewing distance*.

We believe the designed visibility control techniques can significantly impact a user's visual and motion perception in VR. When used with appropriate embedded attractors, they can make users less aware of VW rotation.

IMPLEMENTATION

To investigate the capabilities of the embedded design methodology and the visibility control techniques, we created a virtual experience set in park (see Figure 1). In the game, we ask the user to walk from point A to B and then to C where the points are located on three corners of a $16 \times 8m$ rectangle. The rectangle defines the paved walking paths in the virtual park.

[*] https://owlchemylabs.com/job-simulator-sales-milestone/

Figure 2: View of the park looking at the starting point A in the foreground and the first destination point B marked by a yellow star at the end of the $16m$ **long straight path.**

Background Story

In order to seamlessly integrate reorientation into the experience, we designed tasks that a user needs to accomplish as part of the game experience. Our user is a young naturalist, who goes to an small park for collecting data on exotic birds and bugs. The naturalist begins their quest near the fountain in the center of the park (point A). They are told that successfully arriving at point B in the distance will give them new tools to help analyze their gathered data (see Figures 1 and 2). After arriving at point B, they are asked to walk to the next checkpoint C, which holds information about secret locations teeming with even more exotic flora and fauna. As the naturalist walks towards points B and C, they are presented with opportunities to collect data. Gathering data involves careful observation of birds or insects, whether it is viewing through binoculars or through unveiling treasures hidden in amber. On occasion, the naturalist interacts with other people in the park, who are fellow naturalists or park visitors, looking for help or information.

Reorientation Techniques

The physical tracking area is a $4 \times 4m$ square and the "safe area" is set to a $3.5 \times 3.5m$ inner square. Whenever the user is about to walk out of the safe area, a reorientation event is triggered, i.e., a task-relevant attractor is spawned causing the user to stop and interact. The reorientation rotates the VW by 90°, which reorients the user away from the boundary that they originally approached. Our $3.5 \times 3.5m$ space is about half the size of the tracking space used by Peck et al. [17] for moving in a comparably sized virtual space. While still larger than the tracking space that most consumers may have at home, we believe in our future work we can design a system that can support a seamless walking experience for most home VR users.

The current design can support branching paths (though not tested in the user study) by presenting appropriate attractors as incentives for decision making. For example, showing participants an attractor some distance away from a T-junction or a crossroads to encourage them to take one of the many path options. The current setup can also support slightly curved paths in the virtual world while allowing the user to walk on curved paths in the tracked space. However, given the small tracking space, the experience is not very different from users walking on a straight path. Prior work shows that truly walking on a curved path while thinking you are walking in a straight line in the virtual world requires a path of radius 22m [28].

Before we describe each technique's implementation in the game in detail, we first introduce *directionally constant* need-based rotation in contrast to directionally variable continuous rotation [17], as our scene rotation method. When the user approaches the boundary, the desired direction of the scene after reorientation has already been determined based on the user's position, approach angle, and future direction. For instance, in Figure 1 when the user starting at point A reaches the red dot at the inner square's boundary, we know that we need to rotate the scene clockwise by 90°. If the user approaches a boundary by walking straight at it, then either a clockwise or a counterclockwise rotation works. We define *directionally constant* rotation as – a method to insert desired rotation that does not change direction once the scene starts rotating. This is different from directionally variable and continuous rotation where the VW rotation direction is based on the user's head rotation direction [17] and changes continuously.

We set the *directionally constant* rotation gain rate to 0.5 but this rate can be adjusted as needed depending on the size of the physical space. When the user turns in the desired direction while interacting with the environment, the VW rotates half as fast. However when the user turns in the opposite direction, instead of rotating the scene 1.5 times faster, we temporarily set the world's rotation speed to be the same as the user's turning speed. This is because prior research shows that users are more sensitive to scene motion if the scene moves against head rotation than if the scene moves with head rotation [8, 28]. Compared to the distractors in Peck's work that always move in one direction [16], the *directionally constant* rotation method introduces asymmetric rotations that allow both the user and the attractors to move in any direction, hence enlarging the design space of attractors.

$$Gain = \frac{rotation_{virtual}}{rotation_{user}} = \begin{cases} 0.5 & \text{user rotates in the desired direction} \\ 1.0 & \text{user rotates in the opposite direction} \end{cases}$$

Note that our methods do not continuously manipulate the mapping between the physical and virtual motions, thereby avoiding a visual-vestibular conflict and accompanied dizziness. We only rotate the scene when the user is interacting with the attractors. Since our physical space is much smaller than spaces used previously to demonstrate redirection techniques [17, 33], the effectiveness of slow, continuous redirection is limited. Our pilot study found that continuous rotation in a small space is very noticeable and can cause nausea. An added benefit of rotating the scene only when the user is busily engaged is the level of control it allows designers. For example, if the path in the virtual world is long and straight, then the physical path will consist of a number of short relatively straight line segments. Compared to a set of unpredictable curves that arise due to continuous rotation, the straight line segments can be more easily controlled and designed.

Because we only use reorientation events and not continuous redirection, we can easily calculate the minimum number of reorientation events needed for a space of known size. For instance, if the safe area is a square (as is the case in our space) with width d and the user needs to walk a straight path with length l, then the ideal number of reorientation events c can be calculated as:

$$c = \max\{\frac{l}{d} - 1, 0\}$$

This number can be used as a reference by designers and developers for planning and creating the requisite number of attractors and visibility control methods.

(a) Viewing through Device **(b) Change in Environment**

Figure 3: (a): The bird is 3m above the ground, 5m horizontally away from the user. It flies in a 180° arc with the user as the center of the circle (radius 5m). The user holds the 'binoculars' close to their eyes to look at the bird through them. (b): The insects are 1.5m above the ground, 1m horizontally away from the user. They fly in a circle of radius 1m with the user as the center. The user can reach out with their hand to 'touch' the dragonflies.

Viewing through Device

This technique uses the *Reduced Field of View* visibility control method. It is implemented as an exotic bird that appears in the distance as our naturalist walks down the path towards points B or C. When the bird appears, the user receives a notification (both text and audio) asking them to pick up binoculars from the ground to observe the bird (see Figure 3a). The bird, acting as an attractor, flies around the user in a pre-determined path in the sky. To keep the bird inside the binoculars' reduced FoV, the user needs to turn their head and body. As the user follows the movement of the bird through the binoculars, the *directionally constant* rotation gain is injected into the VW. If the user stops looking through the binoculars, the rotation is halted. The bird leaves once the VW is rotated 90°. A notification informs the user that enough data on the bird has been collected and they can put down the binoculars. The user adjusts their body orientation (if any) to allow them to continue walking along the path.

Change in Environment

We implement this technique using the *Limited Viewing Distance* method. Generating fog around the user obscures the background. Several insects swarm when the fog rises and fly around the user a circle with random directions and speeds (see Figure 3b). The radius of the circle is set small enough for the user to see the attractors (insects) but not much else beyond the fog is visible. A notification asks the user to observe the insects and to keep at least one of them in focus, which causes the user to turn their head and rotate as the insect leads them. When the fog is thick enough to cover the background, the VW is rotated. Similar to the first technique, once the world rotates 90°, the insects leave and the fog gradually dissipates. Another notification pops up indicating the end of data collection and asking the user to continue walking to their destination.

Interaction with Object

This technique is based on the *Tilted Viewing Angle* visibility control method. It is triggered when the naturalist walks by a tree. An opaque piece of amber drops close to them and a notification directs their attention to the fallen amber. They are asked to pick it and hold it up high against the sky. While doing so, they are also directed to spin their body until they find the correct light and viewing angle to see the insect trapped inside. *Tilt angle* or viewing angle is defined as the head pitch angle, positive for looking up and negative for looking down. When the *tilt angle* reaches a threshold (empirically set at 45° in our example), the user needs to rotate their body to find the right light and viewing angle conditions for the amber to become transparent (see Figure 4a). They need to spin 180° (either clockwise or counter-clockwise, depending on the desired direction of the scene after reorientation) in the physical world to accomplish this task. The amber becomes clearer as the user spins until becoming completely transparent when the user is fully turned to reveal the insect inside. The *directionally constant* rotation gain is added to the VW when the user is spinning while looking up. A message saying "collecting data" shows up for three seconds after the user's body is fully turned to allow time for rotating the VW. The user is then asked to put the amber back on the ground and continue walking to their destination.

Interaction with Character

This technique is instantiated by a human character approaching our naturalist to ask about other locations for collecting data or to ask if the naturalist happened to come across a set of lost keys. It is based on the *Shallow Depth of Field* method. As the user turns to locate the source of the sound (the character), the background is blurred to mimic shallow DoF but the character in the foreground stays in focus (see Figure 4b). The character paces back and forth in a predetermined circle around the user, which induces the user to turn back and forth as they listen to and engage with the character. A conversation is made possible by the user responding to questions asked by the character. The VW is rotated when the character

(a) Interaction with Object (b) Interaction with Character

Figure 4: (a): The green slider indicates the head tilt, with 45° as the maximum. The blue slider indicates how much the user has rotated the body, with 180° as the maximum. The user holds a piece of amber up high against the sky. (b): The virtual character is 1.5m away from the user and depth of field is set as 2m. The character walks back and forth in a 180° arc with the user as the center (radius 1.5m). The user waves to the character.

paces. Even though the world rotation ends fairly quickly, the character continues talking for a few more seconds to end the conversation in a natural manner.

EVALUATION

Participants and Apparatus

We invited 16 participants (6 females) to evaluate our techniques, with an average age of 21.9 ($SD = 5.1$). We used an HTC Vive headset during the study, as it gave us a room-scale tracked space without requiring any third party position tracking systems. Our tracked area was set as $4 \times 4m$, and the user was required to walk along the edge of a $16 \times 8m$ rectangle in the virtual scene.

Design

We investigated the effect of our visibility control techniques on the participants' sense of presence, level of dizziness, and reported discernibility of virtual world rotation in a within-subjects study. Each participant experienced two sessions, one with our visibility techniques, hereon referred to as *with* session and the other without the techniques, hereon referred to as *without* session. Half of the participants began with the *with* condition and the other half experienced the *without* condition first.

In the *with* session, when reorientation was triggered, i.e., the participant got near the boundary of the inner square, the system automatically and randomly selected one of the four methods described above and displayed relevant instructions to the participant for accomplishing the task. In contrast, during the *without* session, the four visibility manipulation techniques were removed but the attractors appeared and the scene was rotated like the originally proposed redirection technique [20]. For the reduced *Reduced Field of View* technique, binoculars

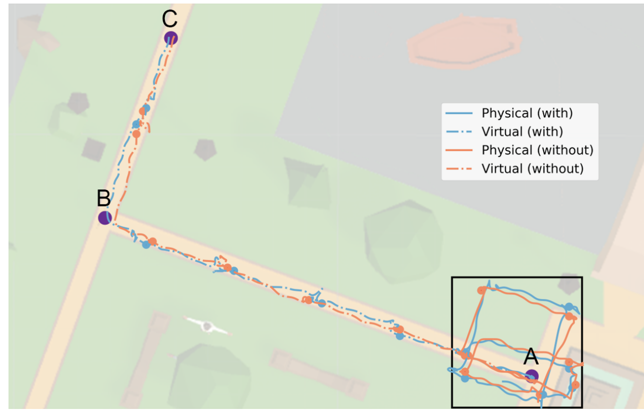


Figure 5: Physical and virtual paths of one participant in the park as seen from a top-down view. Dots represent the points where reorientation was triggered.

were removed but the bird attractor still appeared. Instructions were modified to remove any reference to binoculars and participants were asked to simply look at the bird. In the case of *Limited Viewing Distance*, no fog was generated and the user was asked to look at the nearby flying insects. In the *Tilted Viewing Angle*, the *tilt angle* threshold was removed and participants could spin their body without needing to hold the amber up against the sky for viewing. Finally, in the *Shallow Depth of Field* technique, the background was not blurred during the interaction with the virtual character. All other factors (e.g., tasks, attractors, environment) remained unchanged in the *without* session.

After each session, the participant completed a questionnaire, hereon referred to as Q1, which consisted of the following parts:

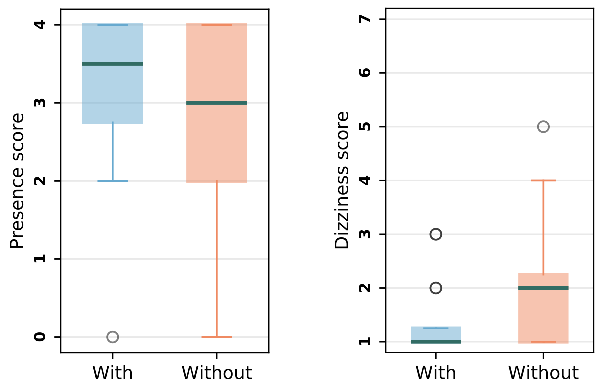
1. Demographic questions and a previous VR experience question (1-7 point Likert Scale, Never before – A great deal)

2. Four questions from the Slater-Usoh-Steed (SUS) presence questionnaire [36] (7-point Likert Scale, Not at all - A lot)

3. One experience of dizziness question from the Kennedy Simulator Sickness questionnaire [9] modified from a 4-point scale to a 7-point Likert scale (Not at all – A lot)

4. An open ended question about anything the participant found unusual during the experience.

In order to eliminate the carry-over effect between questions about presence, the demographic questions were interspersed with the other questions, as suggested by [25]. Since participants needed to fill the questionnaire after each session, they ended up answering the demographic questions twice. After a participant finished both sessions, we asked them to fill another questionnaire, hereon referred to as Q2, which was composed of five questions. Four questions asked participants to compare noticeability of VW rotation between *with* and *without* conditions for each visibility technique. The fifth question asked them to compare overall noticeability of scene rotation in both conditions.



(a) Presence Score **(b) Dizziness Score**

Figure 6: Presence and dizziness scores in the *with* session and *without* sessions. Overall, participants reported high presence and low dizziness in both conditions.

Procedure

Before starting the first session, participants were asked to sign a consent form and read the background story. They were provided with a list of tasks to accomplish in the park. They were also shown how to use the Vive hand controller for picking up objects. We helped them put on the HMD and headphones before getting started with the first session. Each session took about 7-8 minutes, following which the participants answered Q1. A researcher held the Vive cables to prevent the participant from accidentally tripping. After completing both sessions, we told the participants that they had walked in a virtual park which was 8 times larger than the physical area they were in. We explained how scene rotation worked when they interacted with birds, insects and virtual characters in the park. When the participants indicated understanding the reorientation concept, we asked them to complete Q2 for comparing how obvious was the VW rotation in either session.

RESULTS

Participants walked to the final destination with an average of 6.8 reorientation events ($SD = 1.0$). A paired t-test did not show any significant difference between the two sessions on the number of reorientation events (6.7 ± 1.3 for *with* vs 6.9 ± 0.8 for *without*, $p = 0.41$) or on the average duration (18.2 ± 5.5 for *with* vs 16.9 ± 3.0 for *without*, $p = 0.14$) of reorientation. Figure 5 shows four walking paths of one participant, two for each session (virtual and physical). Note the similarity between the sessions, both in the paths and in the positions where the reorientation events happened. This indicates that users behaved very similarly in both sessions and removes the effect of behavior difference on the results of our questionnaires.

Presence and Dizziness

In Q1, four questions are related to presence. The presence score is the count of questions answered with 5 or higher [12, 17], and can range from 0 to 4. Figure 6a shows the scores of the *with* (3.8 ± 1.1) and the *without* (3.3 ± 1.3) sessions. Treating the presence score as binomially distributed for logistic regression on session, as intended by the SUS approach [25], there is no significant difference between the two sessions ($\chi_1^2 = 0.5, p = 0.49$). Participants in both sessions were able to maintain high presence during the study.

The results for the question about the experience of dizziness are shown in Figure 6b, which indicate that overall participants experienced low dizziness in both sessions (1.4 ± 0.7 for *with* and 2.1 ± 1.2 for *without*). However, there still exists a difference between the two conditions: 75% of the participants rated the lowest score in the *with* session while only 37.5% rated 1 in the *without* session. According to whether a player rated dizziness 1 or not, the chi-square test shows a significant difference in dizziness between the two conditions ($\chi_1^2 = 4.6, p = 0.03$). Players in the *without* condition experienced higher dizziness than those in the *with* condition.

Reorientation Noticeability

We discovered interesting results from the last question in Q1, which asked participants if they noticed anything unusual during the experience. Note that when the user answered this question after each session, they had not yet been informed about the rotation of the virtual world. In *with* session, 14 out of 16 users did not notice the reorientation at all. While in *without* session, seven reported feeling the virtual world rotation. Chi-square test shows significant difference between the two sessions ($\chi_1^2 = 3.9, p = 0.05$). This means our techniques decreased the obviousness of rotation effectively.

Among the 10 users who rated their previous VR experience below four, four users explicitly mentioned noticing rotation of the world in the *without* session. *"I was able to realize that the scene shifted directions when I was performing a task."* (P1). *"When rotating my head the direction of the path changed while looking away. Sometimes rotating and walking felt like they were happening more quickly than if I was doing those actions in real life."* (P2). However, none of the 10 participants mentioned the rotation of the world in the *with* session. Among the remaining six participants who reported being familiar with VR, three of them noticed the rotation of the scene in the *without* session. Two of these three participants also noticed the rotation in the *with* session. One user explicitly expressed their preference for the techniques in the *with* session. *"I liked the obscure mist and vignette binoculars. It helped reduce nausea."* (P15). Splitting participants into two groups based on VR experience (answer above 4 or not), chi-square test was applied on two sessions respectively. The results (*with* session: $\chi^2_{1,with} = 3.8, p_{with} = 0.05$, *without* session: $\chi^2_{1,without} = 1.6, p_{without} = 0.21$) indicate that unexperienced VR users were less aware of the reorientation, especially in *with* session.

We arrive at a similar conclusion from the results of Q2. Fifteen participants responded to Q2. 11 of them agreed that the rotation with our methods was less obvious (see Figure 7). Among the four techniques, *Limited Viewing Distance* had the best performance, with 12 out of 16 users saying rotation with

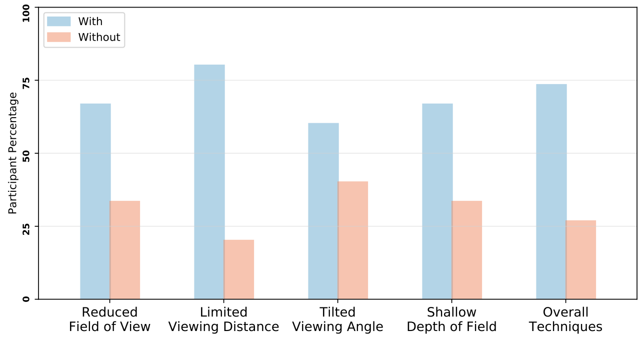


Figure 7: Number of participants who found VW rotation imperceptible for each visibility control technique when asked to compare between the *with* and *without* conditions.

fog is less obvious. *Tilted Viewing Angle* comparatively performed the worst, with only 9 users supporting that technique.

Discussion

According to the context-sensitive design method, attractors were embedded into the narrative in both sessions of the user study, and the only difference was the presence or absence of visibility control methods. User interaction with the attractors (bird, amber, character and insects) was part of the participants' main activity of data collection as a naturalist. Embedding attractors into the main activity reduced disruptions and did not require experimenter intervention to keep users within the tracked space bounds, likely leading to a high presence score.

The results from our user study are very promising. Presence was high in both conditions ($\text{Median}_{with} = 3.5$, $\text{Median}_{without} = 3$, with 4 as the maximum) likely because the participants could walk to navigate the VW and there was visuo-motor synchrony in their hand-head movements [24, 35]. The visibility control methods decreased reported dizziness significantly. Moreover, a majority of the participants reported that the rotation in the *with* session was less obvious than in the *without* session. Both these results support the effectiveness of our techniques and can be explained by the workings of the human motion perception system [38].

Ratings on the noticeability questions indicated that inattentional blindness is quite effective in virtual environments. Only two participants out of 16 (both experienced 3D gamers) noticed the world rotate in the *with* condition when asked to identify any unusual events in the qualitative questionnaire. All other participants stated they did not notice anything unusual about rotation of the VW.

Given the difference in dizziness for each condition, we believe our reorientation techniques proved quite effective and thus desirable for inclusion in VR design. Inattentional blindness when paired with an appropriate attractor can successfully create a natural walking experience in a small space.

Another interesting finding from the study is that participants with experience playing video games reported higher sensitivity to the reorientation. We speculate that because playing video games improves spatial skills [29], participants were able to discern changes in the virtual environment, though specific reasons for this difference are not evident in our data.

STRATEGIES FOR EMBEDDING ATTRACTORS

The main goal is for designers to think about and plan for reorientation through interaction with *attractors* as part of the narrative design process. By attracting a user's attention away from the horizon to objects up close or up above, designers can remove or mask reference objects in the scene, that can otherwise make scene rotation obvious. Designers should think about *attractors* as the moving elements in the scene while static objects or objects used to interact with the *attractors* form the essence of visibility control. For e.g., the bird in the presented implementation is the *attractor* while the binoculars represent one type of visibility control technique, namely *Reduced Field of View*.

Design of Attractors

For the design of attractors, Peck et al. [17] answered the question of *when* should the attractors appear and disappear. We answer the question of *what* should appear during the reorientation. Our design focuses on mechanisms for integrating attractors into the narrative and the user's main activity, which can reduce disruption of the immersive experience caused by non-integrated attractors [16]. In our work, we embed the attractors into the biological data collection task that the naturalist needs to accomplish. Not only are attractors seamlessly embedded into the experience serving to forward the narrative, they are also the primary interactive elements in the VW. Designers and developers need to identify potential attractors in their scenarios and distinguish the moving and interactive attractors that can be incorporated into a task the user may need to do for progressing through the experience.

Designing Visibility Controls

The design of visibility control methods serves to reduce the noticeability of the reorientation while the user is engaged in interaction with the distractor. Developers can use any visibility manipulation method that is appropriate for their scenario, for e.g., a microscope in a virtual classroom or an ash filled volcanic eruption. The design of visibility control approaches should stay separated from the design of attractors for lending more flexibility and variety in the creation of interaction mechanics.

Attractors and Space Size

Traditional redirection methods that involve continuous scene rotation can become annoying if the tracking space is very small, which is the case for a large number of consumer room-scale setups [19]. The small space causes reorientation events to be triggered frequently in order to keep users in the tracked area and continuous and fast scene rotation can cause dizziness and nausea. Our pilot study showed that on average users got bored after the same reorientation technique was repeated more than 5 times (e.g., a mocking bird frequently appearing and disappearing) thereby reducing their sense of presence. However, our methodology allows for the design of diverse attractor and visual control technique combinations given that most VR experiences have moving objects and interactivity, the two main constituents of an attractor. For added variety, in our virtual data collection task, we implemented more than 20 types of birds and insects. Using 3D models with high detail and adding stats for discovered items can make each reorientation event seem novel, even though the interaction or reorientation mechanic is repeated. This is related to item collection games like the incredibly popular Pokémon[†], where the Pokémon capturing mechanism is repeated but individual Pokémon look different and have different stats and fighting capabilities. The combination of attractors and visibility control techniques can thus generate a large number of possible reorientation mechanics that can be used frequently, based on space size, without immediately and negatively impacting the user's experience.

Rotation as Gameplay

Our reorientation methods embed rotation of the virtual world into the users' interactive experience. Previous research suggests that a 0.5 rotation gain rate is very noticeable by 80% when used by itself [4, 28]. However, in our study, less than 40% of the participants perceived the rotation in the *without* session. The percentage was even lower (less than 20%) in the *with* session. This indicates that our embedded techniques may have a positive effect on reducing the obviousness of world rotation which can lead to improved satisfaction with the VR experience and reduced VR sickness.

When attractors are part of the experience, users may be less aware of the secondary function of the attractors, which is to allow us to rotate the VW imperceptibly. Together, functional and interactive attractors with visibility manipulation techniques can more easily elicit *inattentional blindness*, leading users to overlook the rotation of the virtual world. This gives designers and developers an interesting arsenal of tools at their disposal to integrate real walking in their VR applications.

LIMITATIONS AND FUTURE WORK

There are some limitations of our work. First, there is the cost of integrating reorientation into the VR experience. Designing integrated techniques, compared to using hard reset methods [40], out of context distractors [17] or adding non-walking navigation mechanisms like teleportation, takes time and effort. Second, there is a possibility that users may disregard the attractor, either unconsciously or consciously, and exit the tracked area. This can be partially resolved by providing a warning system like the chaperone on the HTC Vive (a blue grid that appears at the boundary of the tracked area when the user gets close). Adding a warning system may prevent the user from leaving the tracked space but it can disrupt presence. Lastly, users may walk too fast in a space that is too small, and not fully interact with the presented distractors, leading them to quickly step outside the safe and tracked areas. A possible solution to this may be implement a mechanism that asks users to step back into the safe area by marking its position in the virtual world and modifying the experience accordingly.

The current design focuses on scenarios where a user needs to move along a specified path. In the future, we plan on expanding our design methodology and implemented techniques to allow for walking on curved paths or walking freely in open spaces as well as exploring movement in indoor places. An interesting possibility may be to combine real-walking with artificial navigation techniques that fit the narrative like walking around the entirety of Star Trek's USS Enterprise and using teleportation to travel to different planets and then walking again to interact with life forms on the planets.

[†] http://www.pokemon.com/us/

CONCLUSION

In this paper, we introduced a design methodology that integrates reorientation into the user's primary activity in the VR environment. We showed how our embedded context-sensitive reorientation can improve the VR experience, resulting in a high sense of presence, significantly reduced dizziness and reduced noticeability of virtual scene rotation. We showed an example implementation of four novel visibility manipulation techniques, which work with attractors and are integrated in the narrative, tasks, and the virtual environment to further reduce users' sensitivity towards rotational changes of the virtual world. We believe that our methodology is an important step towards making natural walking a more effective and practical navigation mechanism for consumer virtual reality and can successfully provide a seamless experience with high presence.

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