The Magic Barrier Tape: a Novel Metaphor for Infinite Navigation in Virtual Worlds with a Restricted Walking Workspace

Gabriel Cirio
INRIA Rennes*

Maud Marchal
INSA/INRIA Rennes*

Tony Regia-Corte
INRIA Rennes*

Anatole Lécuyer
INRIA Rennes*

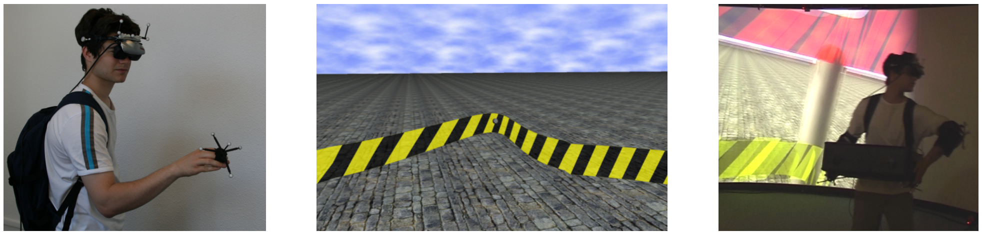

Figure 1: *The Magic Barrier Tape displays the boundaries of the real workspace as a virtual barrier tape, and uses a hybrid position/rate control to travel in the scene. The user (left) "pushes" on the Magic Barrier Tape (center) to move inside the scene when he reaches the workspace boundaries. Any tracked body part can be used to trigger the Magic Barrier Tape (right).*

Abstract

In most virtual reality simulations the virtual world is larger than the real walking workspace. The workspace is often bounded by the tracking area or the display devices. This paper describes a novel interaction metaphor called the Magic Barrier Tape, which allows a user to navigate in a potentially infinite virtual scene while confined to a restricted walking workspace. The technique relies on the barrier tape metaphor and its "do not cross" implicit message by surrounding the walking workspace with a virtual barrier tape in the scene. Therefore, the technique informs the user about the boundaries of his walking workspace, providing an environment safe from collisions and tracking problems. It uses a hybrid position/rate control mechanism to enable real walking inside the workspace and rate control navigation to move beyond the boundaries by "pushing" on the virtual barrier tape. It provides an easy, intuitive and safe way of navigating in a virtual scene, without break of immersion. Two experiments were conducted in order to evaluate the Magic Barrier Tape by comparing it to two state-of-the-art navigation techniques. Results showed that the Magic Barrier Tape was faster and more appreciated than the compared techniques, while being more natural and less tiring. Considering it can be used in many different virtual reality systems, it is an interaction metaphor suitable for many different applications, from the entertainment field to training simulations scenarios.

CR Categories: H.5.2 [Information Interfaces and Presentation]: User Interfaces—evaluation/methodology, input devices and strategies, interaction styles, user-centered design; H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—artificial, augmented, and virtual realities;

Keywords: 3D interaction, Interaction metaphor, Navigation, Walking workspace, Hybrid position/rate control

1 Introduction

The ability to get from one place to another is a fundamental requirement in both real and virtual environments. In many cases, navigation is not a goal, but rather a mean to reach a location in order to perform a task [Bowman et al. 2004]. In virtual reality, real walking is often the most appropriate navigation interface. It provides the most natural, intuitive and direct way of controlling one's position, matching vestibular and proprioceptive cues from the real movement with the visual feedback from the virtual movement, therefore producing an accurate multi-sensory perception of self-motion. It has been shown that real walking provides benefits over other locomotion techniques [Ruddle and Lessels 2009]. Besides, real walking is, after all, the locomotion interface that we use in our everyday life.

However, in most simulations the virtual world is larger than the real workspace. Navigation techniques become, paradoxically, both a strength and a weakness of current virtual reality systems. They allow individuals to easily and instantly travel long distances and to follow impossible virtual paths. However, they are unable to fully reproduce real life infinite walking capabilities since the user can quickly reach the boundaries of his real workspace. Hence, since real walking alone is not possible, the illusion of a virtual world is lost through the use of unnatural techniques usually coming from the 2D realm.

There are hardware and software-based approaches to overcome the problem of a restricted size workspace. Locomotion interfaces [Hollerbach 2002] such as treadmills often have major limitations that restrict their widespread use (huge size and weight, high cost, lack of accuracy). Navigation techniques based on input devices [Bowman et al. 2004] often fail at providing a simple, intuitive and immersive interaction.

In this paper, we propose a natural metaphor for locomotion in restricted size workspaces, using real walking in position control when inside the workspace, and an interaction technique in rate control at the limits of the workspace. The main idea is to use a well-known real world object, the barrier tape, and its well-known association to the "do not cross" message. The technique visually and clearly defines the workspace where the user can freely walk by surrounding it with virtual barrier tape. When the user reaches the virtual barrier tape, he can move farther in the scene by "pushing"

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*e-mail: {gcirio,mmarchal,tregiaco,alecuyer}@irisa.fr on the virtual barrier tape. Hence, the technique allows the navigation in an unlimited virtual space, allowing real walking when inside the workspace boundaries, providing an environment safe from collisions with the displays or tracking data loss, and this in a natural and efficient way, without break of immersion.

This paper starts with an overview of related work focusing on locomotion interfaces and, mainly, 3D navigation techniques. It is followed by a description of the design and implementation of the virtual barrier tape. Then, after describing extensions made to existing techniques to be able to compare our contribution with the current art, we report on the experiments conducted for the evaluation of the Magic Barrier Tape. The paper ends with a general discussion on the results of the experiments, some perspectives and a conclusion on this study.

2 Previous Work

There has been a large amount of previous work in the field of locomotion interfaces [Hollerbach 2002]. These devices allow users to be self-propulsed through a repetitive gait while staying in place by canceling the user's motion. Thus, they can provide kinesthetic feedback to the user. Some locomotion interfaces provide linear walking capabilities, such as treadmills and pedaling devices. Although the proprioceptive feedback matches real world movements, they are limited to a 1 degree of freedom (DOF) motion. Omnidirectional walking is possible with 3DOF treadmills and foot platforms [Hollerbach 2002], together with some foot-wearable devices [Iwata et al. 2007]. For the reasons mentioned in the introduction, namely their size and weight, their cost or their accuracy, they have not yet been widely adopted outside the laboratory.

Passive locomotion techniques were surveyed by Bowman et al. [Bowman et al. 2004]. These travel techniques allow the user to navigate inside a virtual world without moving from his real-world position. Among rate control techniques, the most common and widely used technique is the flying vehicle metaphor [Ware and Osborne 1990], often coupled to an input device such as a wand through which the user controls his speed and orientation inside the virtual world. Using position control, the eyeball-in-hand and the scene-in-hand [Bowman et al. 2004] techniques map the camera and the scene respectively to the user's hand. A clutching mechanism is required to navigate beyond one's arm length. The World-in-Miniature technique [Pausch et al. 1995] provides a hand-held miniature of the scene, through which the user can select the location he wants to navigate to, and then be taken to that location in the real size virtual environment. Although usually intuitive and efficient, these navigation techniques are often inadequate for real world simulation scenarios, since their metaphors do not match real world navigation.

Active locomotion techniques, oriented towards real walking, provide natural metaphors by adapting real walking to restricted size workspaces. Moreover, the vestibular and proprioceptive feedbacks produced by self-propulsion increase the realism of the techniques and therefore the degree of immersion of the simulation. The most basic example is the Walking-in-Place technique [Slater et al. 1995], where the user simulates the physical act of walking by stepping in place but without forward motion of the body, making a gesture that is interpreted as a virtual forward, backward or side-step motion. However, although the technique has the advantage of not having to deal with workspace limits, it falls short regarding kinesthetic feedback. By scaling the user's speed along his intended direction of travel, the Seven League Boots [Interrante et al. 2007] technique implements a scaling technique for real walking in order to reach virtual places beyond the real world workspace. The technique does not solve the limited workspace problem, and precise navigation can become very difficult. The Step WIM [LaViola et al. 2001] takes a different approach on scaling by adapting the World-In-Miniature technique to real walking. The miniature world is drawn on the floor, and the user walks to the new destination on the miniature, instead of using his hands. Although the technique involves real walking, the metaphor might not be considered as natural. Resetting techniques such as the Freeze-backup [Williams et al. 2007] use a clutching approach by freezing the scene while the user recenters his position in the real world once he has reached the limits of the workspace. Other resetting techniques such as the 2:1-Turn [Williams et al. 2007] map a 360° virtual rotation to a 180° real rotation to keep walking on the same direction in the virtual world while taking the opposite direction in the real one. These resetting techniques are performed consciously by the user following a warning signal, which implies a break of immersion. Moreover, the resetting itself might feel unnatural: there is a sudden change in locomotion direction and orientation that does not correspond to the natural movement.

Redirected Walking [Razzaque et al. 2001] and Motion Compression [Nitzsche et al. 2004] techniques solve many of the aforementioned problems by forcing the user into walking in a curved path in the real world when walking in a straight line in the virtual world through the progressive rotation of the scene around him. In a sufficiently large workspace, and with a straight virtual path, the user can walk endlessly without reaching the limits of the real workspace. These techniques are natural and in some cases imperceptible. However, they require large workspaces, can be confusing when doing unpredictable or quick changes of direction, and may require distracting events. In practice, they are more suited for Head Mounted Displays and wide area tracking systems.

3 The Magic Barrier Tape

We propose a novel interaction metaphor, the Magic Barrier Tape, that brings a solution to immersive infinite walking in a restricted workspace through a natural and efficient metaphor.

Walking workspaces of virtual reality systems are often bounded by the tracking area, the display devices or by the walls of the immersive room. Hence, the Magic Barrier Tape has two fundamental objectives. The first one is to inform and display the limits of the workspace in a natural way, without break of immersion, in order to avoid the collision with physical objects outside the workspace boundaries or leaving the tracking area. The second one is to provide an integrated navigation technique to reach any location in the virtual scene, beyond the walking workspace.

To overcome the mismatch between the restricted size workspace and the potentially infinite size of the virtual scene, we followed the concept of hybrid position/rate control [Dominjon et al. 2005], used in a different context for object manipulation, where position control is used inside the available workspace for fine positioning, while rate control is used at the boundaries for coarse positioning. This concept can be found in common desktop applications and games where the mouse switches to rate control when it reaches the edge of the screen: in a file manager when doing multiple selection, or in top-view strategy games such as Starcraft when panning on the map. In our context, we applied the concept to navigation, with the available workspace being the walking workspace. The boundaries of the workspace are represented by a virtual barrier at mid body height textured with slanted black and yellow stripes, evoking the use of barrier tape and its implicit message: "do not cross".

The real workspace, delimited by the physical boundaries, is mapped to a virtual workspace inside the scene, delimited by the virtual barrier tape. Inside the workspace, we use position control: the user can freely walk, and objects inside the virtual workspace can be reached and manipulated through real walking and real life movements. When reaching the boundaries of the workspace, we switch to rate control: the user can move farther in the scene by "pushing" on the virtual barrier tape, hence translating the virtual workspace in the scene. He can then perform a task inside the virtual workspace at the new location.

The Magic Barrier Tape concept is not subject to a specific technology. It can be implemented in many different virtual reality systems. Any object or body part can be used as an actuator for the virtual barrier tape, depending on the application, and the rate control law can be fitted to specific behavioral needs. In the remaining of this section, we detail the Magic Barrier Tape concept. We take as implementation example our own virtual reality environment, consisting of a Head Mounted Display (HMD) with a 1.5m radius cylindrical tracking space, and one of the user's hands as actuating object.

3.1 Display of the Workspace Limits

The boundaries of the workspace are displayed through 3 complementary visual cues: the main virtual barrier tape, the warning virtual barrier tape, and their grey shadow on the floor.

The main virtual barrier tape is presented as a band that matches the shape of the workspace boundaries, such as a square for a CAVE or a circle for a cylindrical tracking system. It is positioned at a safe distance ahead of them, high enough from the virtual floor so that the user does not need to look down to see the barrier tape, and low enough so that it does not occlude the user's forward vision. The boundaries of the workspace are therefore clearly and continuously visible. The tape is made slightly translucent so what would have been normally hidden by the tape is still discernible.

The warning virtual barrier tape appears when the user's body is close to the main tape, as a warning signal. This second tape has the same shape and origin than the main one, and has a red glow to capture the user's attention. For the same reason, it is positioned at the user's eyes height. The tape is fully transparent when the user is at a reasonably safe distance from the main tape, and becomes progressively opaque as the user gets closer, therefore making the warning signal also progressive, from dim to strong. The warning virtual barrier tape is complementary to the main tape, since it is triggered as a safety measure, and it gives an idea of when to stop walking and start "pushing".

The tapes shadow is drawn on the floor as if the barrier tapes were lit from above, in order to have a visual cue about the limits of the workspace when the user looks down. Hence, at least one of the 3 visual components is always visible at almost any viewing direction, which is particularly helpful with an HMD setup where there is usually a narrow field of view. Figure 2 shows the three components of the Magic Barrier Tape: the main barrier tape, the warning barrier tape (here visible) and the tapes' shadow.

In our virtual reality environment implementation, the main virtual barrier tape is 30 cm high and at 30 cm from the boundaries. It is shaped as a ring with a 1.2m radius and the center of the tracking area as origin. It is positioned at 1.3m from the virtual floor. The warning tape is activated when the user is at 30 cm from the main tape.

3.2 Navigation Through Rate Control

The Magic Barrier Tape allows the use of position control inside the workspace, and rate control at the boundaries. The user is switched from position control to rate control whenever his hand (or any other tracked body part) penetrates the boundaries represented by the virtual barrier tape. The speed of the resulting translation in the virtual scene is a function of the hand penetration distance. When the user's hand is pulled back inside the workspace, the user is switched back to position control.

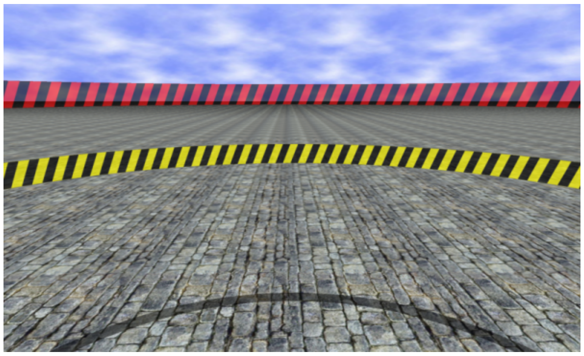


Figure 2: *The three Magic Barrier Tape visual cues to show the workspace boundaries: the main virtual barrier tape (middle), the warning tape (top) and the tapes shadow (bottom).*

The virtual barrier tapes (main and warning) are deformed when the user's body (preferentially, the hand) penetrates the boundaries. This elastic behavior allows the user to see how deep he is "pushing", and therefore to evaluate how fast he will move in the virtual scene. A visual feedback on the rate control is also important so the user can know where the neutral position is located [Dominjon et al. 2005].

The deformation follows the shape of a centered Gaussian curve D, of equation:

$$D(p) = p\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{x^2}{2\sigma^2}}$$

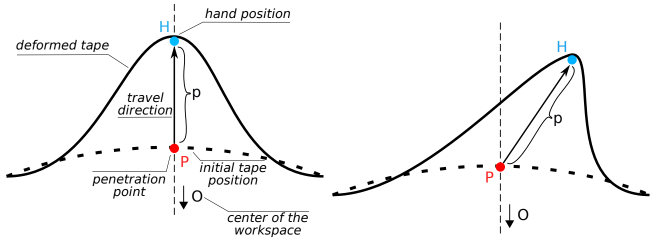
where p is the penetration length (in meters), and σ the standard deviation, which controls the "width" of the deformation. The virtual barrier tape is rotated so that the center of the Gaussian curve matches the penetration point P, the collision point between the hand and the virtual barrier tape. Therefore, as shown in Figure 3, the Gaussian deformation is centered around the penetration point, and its symmetry axis is given by the $\overrightarrow{OP}$ direction, where O is the center of the virtual barrier tape. Since the deformation follows the user's hand, the Gaussian curve has to be shifted to take into account the lateral deviation of the hand position H with respect to the Gaussian axis, as shown in Figure 3. The final result gives the impression of having an elastic region around the penetration point than can be deformed in any direction. This deformation direction, $\overrightarrow{PH}$, gives the travel direction of the virtual workspace (Figure 3).

The velocity V, a function of p, gives the speed of travel. It has the following equation:

$$V(p) = k * p^n$$

where k and n are constants. We use a polynomial function in order to have both slow speed when the user is close to the boundaries for small distances, and high speeds to move fast for distant targets. In our implementation, after preliminary testing, we used $\sigma = 0.15$, $k = 1.4$ and $n = 3$.

Our Magic Barrier Tape implementation provides both a safe walking environment and a natural and efficient navigation technique.



(a) **(b)**

Figure 3: *The Gaussian deformation of the Magic Barrier Tape in top-view (a) and its shifted version (b) to follow the hand position.*

4 Extending Resetting Techniques for Omni-Directional Walking

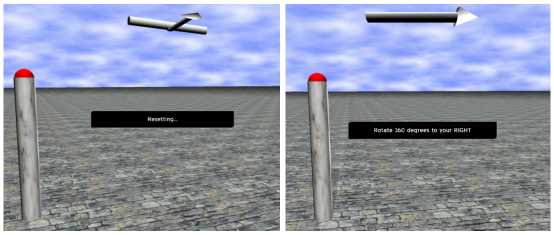
In order to conduct the evaluation of the Magic Barrier Tape, we chose similar purpose techniques among existing navigation techniques. Among the surveyed active navigation techniques, based on real walking, only the resetting techniques developped by Williams et al. [Williams et al. 2007] provide collision free and infinite navigation capabilities. However, the resetting techniques were originally designed for straight paths and right angle turns, where in most virtual reality applications the user is allowed to freely explore his surrounding virtual environment, taking arbitrary paths and freely rotating around him. For fair comparison throughout the evaluation, since our Magic Barrier Tape technique enables such a navigation, we propose to add visual cues to these techniques in order to make them well suited for omni-directional navigation.

Extended Freeze-Backup Technique. In the original Freeze-backup technique, in order to reset his position the user has to walk backwards in a straight line, until he reaches the resetting position. Since he is not guided while walking backwards, paths can only be straight. Otherwise, he could reach the workspace boundaries prematurely and find himself "locked" in a very short path resetting loop.

In the extended Freeze-backup technique, backups now need to take the user to the center of the real workspace. Before the reset, the user can be at any position in the real workspace, and with any orientation. Hence, we propose to add visual cues to guide the user through his resetting motion, which is divided in two steps. First, the body needs to be oriented towards the resetting position. An horizontal segment is drawn on the screen representing the user's orientation with respect to the resetting position, like his shoulder line seen from above in the real workspace reference frame. The user has to change his orientation until the segment becomes parallel to his body. Then, as a second step, the user has to walk to the resetting position by following an arrow direction. The arrow becomes smaller as the user gets closer to the resetting position, indicating how far he is from his target. Through this mechanism, the user can reach the center of the real workspace from anywhere in the real workspace. Figure 4a shows the segment and the arrow drawn at the top of the screen.

Extended 2:1-Turn Technique. In the original 2:1-Turn technique, a 180° real rotation of the user is mapped to a 360° virtual turn, and the user stays on the same real path but on the opposite direction. Since real turns are always of 180°, walking paths need to be straight with eventually right angle turns to avoid the same "locking" problems mentioned above.

In the extended 2:1-Turn technique, real turns can no longer be of only 180°. The resetting angle is given by the non oriented angle between the viewing direction and the body position - resetting position vector. The virtual angle remains the same, 360°. For any orientation before resetting, two turning directions are possible: to the left and to the right. To each direction corresponds an angle, with usually one greater than the other. The direction with the largest angle is chosen, so that the rotation gain when mapping the turn to a 360° virtual turn is lower, and the illusion is therefore less perceivable. As show in Figure 4b, an arrow drawn at the top of the screen indicates the turning direction to the user.


Resetting...

Rotate 360 degrees to your RIGHT

(a) **(b)**

Figure 4: *The visual cues (top of the screen) from: (a) the extended Freeze-backup technique, giving the shoulder orientation and the walking direction, and (b) the extended 2:1-Turn technique, giving the rotation direction.*

5 Evaluation

In order to demonstrate its suitability for infinite navigation within a restricted workspace, we evaluated the Magic Barrier Tape by comparing it to two other existing navigation techniques that enable collision free infinite walking within a restricted workspace, namely the Freeze-Backup and the 2:1-Turn resetting techniques [Williams et al. 2007] with our extensions for omni-directional walking. We conducted two experiments, a pointing task and a path following task.

5.1 Experiment #1

In Experiment #1, our goal was to compare the 3 techniques over a pointing task where the user had to move from a central initial location to a new location, indicated by a target, as fast as possible. We a priori assumed that the Magic Barrier Tape will be faster, since rate control allows speeds greater than the average walking speed.

5.1.1 Description

Population. Twelve participants (1 female and 11 males) aged from 24 to 59 (mean = 30.3, sd = 5.7), took part in this experiment. Two of them were left-handed, and none of them had known perception disorders. They were all naïve to the purpose of the experiment.

Experimental Apparatus. The experiment was conducted in a closed room with dim light. We used the eMagin Z800 Head Mounted Display as display device, at 60 Hz and with stereoscopy enabled. The user was wearing an opaque fabric on top of the HMD to avoid seeing the surrounding real world. The user was carrying a backpack with the laptop computer running the application, and could therefore move freely (Figure 5). The user's head and hand were tracked by an ART ARTtrack2 infrared tracking system with

9 surrounding cameras for 360° tracking. The available tracking space was a cylinder with a 3m diameter and a 2.5m height.

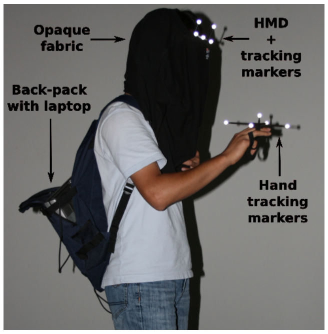


Figure 5: *A subject wearing the tracking equipment, the opaque fabric for occlusion and the backpack with the laptop computer.*

The scene consisted of a flat infinite floor with a rockwall texture, a cloudy blue sky, and a target made of a 1.4m high and 0.2m radius marble textured cylinder with a 0.2m radius red hemisphere on top, as illustrated in Figure 6.

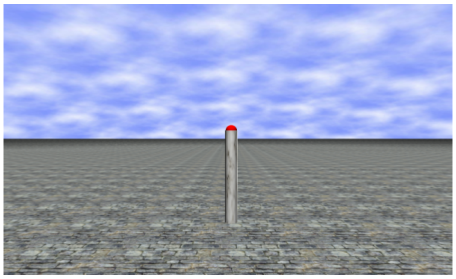


Figure 6: *Virtual environment used in Experiment #1 with a target.*

Procedure. Before the beginning of the experiment, the three techniques were explained to the subject. Before each trial, the subject had to go back to the initial position and orientation at the center of the workspace. Then, the experimenter launched the next trial. The participant was instructed to look for the target in the scene and to walk towards it until collision. For each technique, he had 3 trials for training. The experiment lasted about 30 minutes, including training trials.

Experimental Plan. Participants completed all the three technique conditions (Barrier Tape, Freeze-backup, and 2:1-Turn) and the order of the conditions was counterbalanced across participants. In each condition, the participants were exposed to 3 successive blocks of 6 trials (2 different distances × 3 different directions). The 3 possible directions are at 120° each, one of them being the user's initial direction, and the two possible distances are 2.2m and 5m. In each block, the presentation order of these trials was randomized. Participants completed a total of 54 trials (6 target positions × 3 technique conditions × 3 trials per condition). During a learning phase, prior to each technique condition, participants were exposed to 3 trials that did not enter in the final data set.

Collected Data. For each trial and each subject, we recorded the completion time (in seconds) and the amplitude of walking in the real world (in meters). The completion time is the time took by the subject to complete the trial. The amplitude of walking in the real world corresponds to the distance traveled when walking in the real *and* the virtual world. It is the movement in the real world that makes the user move forward in the virtual world (as opposed to a resetting movement where the user moves in the real world, but not in the virtual one).

5.1.2 Results

For the different comparison analyses, a correction for experiment-wise error was realized by using Bonferroni-adjusted alpha level ($p = 0.05$ divided by the number of tests). Thus, in order to compare the Barrier Tape technique to the two other techniques (Freeze-backup and 2:1-Turn) the alpha level was adjusted to $p = 0.025$.

Completion Time. Using the completion time data collected during the experiment, we conducted a statistical analysis. For each participant, statistics (mean M, standard deviation SD) were computed on the 18 trials in each condition. A one-way within subject design ANOVA (Techniques: Barrier Tape, Freeze-backup, 2:1-Turn) on the mean completion time (in seconds) revealed a significant main effect of the technique ($F(2, 22) = 183.22$, $p < 0.001$) (Figure 7). Follow up t tests revealed that completion time in the Barrier Tape technique ($M = 6.37$ sec, $SD = 1.30$ sec) was significantly shorter than in the Freeze-backup technique ($M = 21.49$ sec, $SD = 3.11$ sec, $t(11) = -19.15$, $p < 0.001$). Similarly, completion time in the Barrier Tape technique was significantly shorter than in the 2:1-Turn technique ($M = 14.54$ sec, $SD = 2.41$ sec, $t(11) = -14.61$, $p < 0.001$).

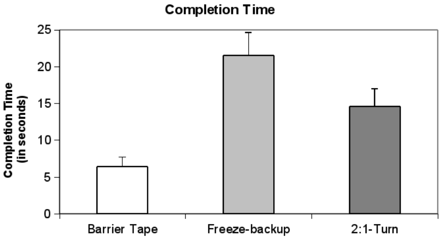


Figure 7: *Experiment #1: mean and standard deviation of the completion time (in seconds) for the three techniques (Barrier Tape, Freeze-backup, and 2:1-Turn).*

Amplitude of Walking in the Real World. An ANOVA on the mean amplitude of walking in the real world (in meters) revealed a significant main effect of the technique ($F(2, 22) = 434.75$, $p < 0.001$). Follow up t tests revealed that the amplitude of walking in the real world in the Barrier Tape technique ($M = 1.46$ m, $SD = 0.16$ m) was significantly shorter than in the Freeze-backup technique ($M = 4.42$ m, $SD = 0.30$ m, $t(11) = -30.13$, $p < 0.001$). Similarly, the amplitude of walking in the real world in the Barrier Tape technique was significantly shorter than in the 2:1-Turn technique ($M = 3.37$ m, $SD = 0.23$ m, $t(11) = -20.80$, $p < 0.001$).

5.2 Experiment #2

In the second experiment, our goal was to compare the 3 techniques over a path following task where the user had to follow a path delimited by two virtual walls, as fast as possible and as accurately as possible by trying to stay right between the two walls. We a priori assumed that the Magic Barrier Tape will be faster, as in Experiment #1, but less precise due to the controlability of rate control [Zhai 1995].

5.2.1 Description

Population. The population that participated in this experiment was the same as for Experiment #1.

Experimental Apparatus. We used the same experimental apparatus than in Experiment #1, except that we replaced the targets by two possible paths: a 2.5m radius circle or a 6m side length square (Figure 8). The walls at both sides of the path were in a semi-transparent blue material, 1m high, and at 1m from the path, creating a 2m wide corridor. Red arrows on the floor indicated the direction to follow, and a red 1m high and 0.2m radius cylinder indicated the start and finish position. The paths alternated throughout the experiment. Figure 9 shows the virtual scene with the circular path as seen from the user's point of view.

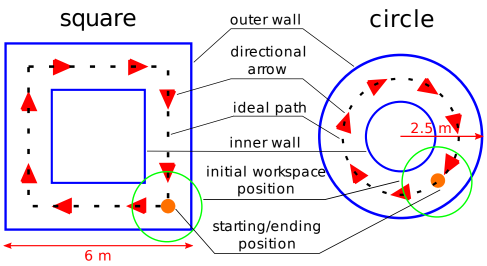


Figure 8: *Two paths used in Experiment #2, in top-view, with the initial cylindrical walking workspace position.*

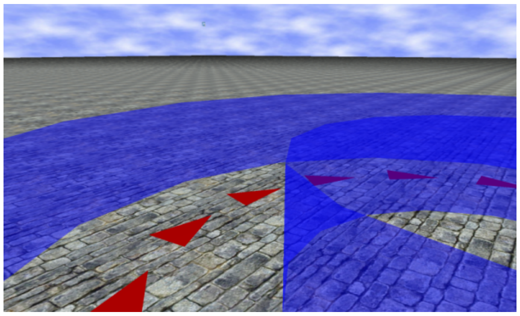


Figure 9: *The virtual environment used in the Experiment #2 with circular path, walls and directional arrow cues on the ground.*

Procedure. Before each trial, the subject had to go back to the initial position and orientation at the center of the workspace. Then, the experimenter launched the next trial. The participant was instructed to try to follow the path right between the two walls in the direction given by the arrows on the floor, until he reached the target cylinder. For each technique, he had 2 trials for training. The experiment lasted about 30 minutes, including training trials.

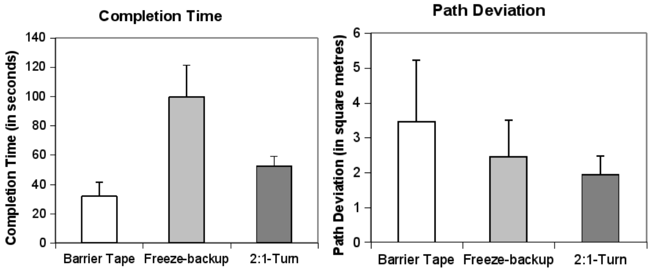
Experimental Plan. Participants completed all the three technique conditions (Barrier Tape, Freeze-backup, 2:1-Turn) and the order of the conditions was counterbalanced across participants. In each condition, the participants were exposed to 2 successive blocks of 2 trials with 2 different paths (square and circle). In each block, the presentation order of these trials was randomized. Participants completed a total of 12 trials (2 paths × 3 technique conditions × 2 trials per condition). During a learning phase, prior to each technique condition, participants were exposed to 2 trials that did not enter in the final data set.

Collected Data. Along with the same data as in Experiment #1, we also collected the path deviation. The path deviation (in m^2) is given by the area delimited by the subject's path in the virtual scene and the ideal path (exactly between the two walls).

5.2.2 Results

For the different comparison analysis, a correction for experiment-wise error was realized by using Bonferroni-adjusted alpha level ($p = 0.05$ divided by the number of tests). Thus, in order to compare the Barrier Tape technique to the two other techniques (Freeze-backup and 2:1-Turn) the alpha level was adjusted to $p = 0.025$.

Completion Time. An ANOVA on the mean completion time (in seconds) revealed a significant main effect of the technique ($F(2, 22) = 84.01$, $p < 0.001$) (Figure 10). Follow up t tests revealed that completion time in the Barrier Tape technique ($M = 31.62$ sec, $SD = 9.71$ sec) was significantly shorter than in the Freeze-backup technique ($M = 99.54$ sec, $SD = 21.63$ sec, $t(11) = -12.06$, $p < 0.001$). Similarly, completion time in the Barrier Tape technique was significantly shorter than in the 2:1-Turn technique ($M = 52.33$ sec, $SD = 6.59$ sec, $t(11) = -6.48$, $p < 0.001$).



(a) (b)

Figure 10: *Experiment #2: means and standard deviations of the completion time (a) and the path deviation (b) for the three techniques (Barrier Tape, Freeze-backup, and 2:1-Turn).*

Path Deviation. An ANOVA on the mean path deviation (in square meters) revealed a significant main effect of the technique $F(2, 22) = 4.77, p = 0.019$ (Figure 10). Follow up t tests revealed that the path deviation in the Barrier Tape technique ($M = 3.46$ m^2, $SD = 1.76$ m^2) was not significantly different from the path deviation in the Freeze-backup technique ($M = 2.45$ m^2, $SD = 1.04$ m^2, $t(11) = 1.72$, $p = 0.1143$.). By contrast, the analysis indicated that the path deviation in the 2:1-Turn technique ($M = 1.93$ m^2, $SD = 0.54$ m^2) was significantly lower than in the Barrier Tape technique, $t(11) = 2.81$, $p = 0.017$.

Amplitude of Walking in the Real World. An ANOVA on the mean amplitude of walking in the real world (in meters) revealed a significant main effect of the technique ($F(2, 22) = 379.81$, $p < 0.001$). Follow up t tests revealed that the amplitude of walking in the real world in the Barrier Tape technique ($M = 6.81$ m, $SD = 1.33$ m) was significantly shorter than in the Freeze-backup technique ($M = 19.03$ m, $SD = 1.25$ m, $t(11) = -32.63$, $p < 0.001$). Similarly, the amplitude of walking in the real world in the Barrier Tape technique was significantly shorter than in the 2:1-Turn technique ($M = 13.61$ m, $SD = 1.54$ m, $t(11) = -13.17$, $p < 0.001$).

5.3 Subjective Questionnaire

After both experiments, a preference questionnaire was proposed in which participants had to grade from 1 to 7 the 3 techniques according to 6 subjective criteria: *easiness of use*, *fatigue*, *navigation speed*, *navigation precision*, *general appreciation* and *naturalness*. Figure 11 shows the means and standard deviations of the 3 techniques for each of the subjective criteria.

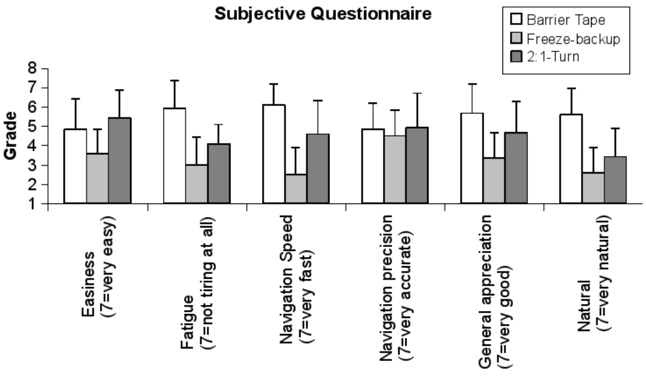


Figure 11: *Mean and standard deviation of subjective ratings about the different criteria for the three techniques.*

Wilcoxon signed rank tests with Bonferroni correction showed significant differences: for the *fatigue*, between the Barrier Tape and the Freeze-backup techniques ($z = 2.69$, $p = 0.007$) and between the Barrier Tape and the 2:1-Turn techniques ($z = 2.41$, $p = 0.016$); for the *naturalness*, between the Barrier Tape and the Freeze-backup techniques ($z = 2.77$, $p = 0.006$) and between the Barrier Tape and the 2:1-Turn techniques ($z = 2.53$, $p = 0.011$); for the *navigation speed*, only between the Barrier Tape and the Freeze-backup techniques ($z = 2.82$, $p = 0.005$); and for the *general appreciation*, only between the Barrier Tape and the Freeze-backup techniques ($z = 2.65$, $p = 0.008$).

6 General Discussion

Both experiments showed that the Magic Barrier Tape is faster compared to the other techniques. Indeed, results show that Experiment #1 trials were completed more than 3 times faster with the Magic Barrier Tape than with the Freeze-backup technique, and more than 2 times faster than with the 2:1-Turn technique. In Experiment #2, completion time using the Magic Barrier Tape was also roughly 3 and 2 times faster respectively. This result is consistent with the user's impression from the questionnaire regarding the navigation speed of the different techniques (Figure 11). It is mainly due to the fact that there is no time lost in the resetting of the position when using the Magic Barrier Tape, and that the control law allows navigation speeds greater than the average walking speed. Completion times could be further reduced by tuning the control law for greater speeds, although controlling the Magic Barrier Tape could become increasingly difficult, as testified by 3 users which complained about an acceleration behavior that was sometimes hard to control.

The experiments also showed that users walked less when using the Magic Barrier Tape than with the other 2 techniques, which was expected due to the use of rate control at the boundaries of the workspace. However, an interesting observation can be made when considering that trials were completed significantly faster with the Magic Barrier Tape. If we do a ratio between the amplitude of walking in the real world and completion time, in a per user basis, we obtain similar values for the Magic Barrier Tape ($M = 0.24$, $SD = 0.04$), the Freeze-backup ($M = 0.21$, $SD = 0.04$) and the 2:1-Turn ($M = 0.24$, $SD = 0.04$) techniques in Experiment #1, as well as in Experiment #2 with ($M = 0.22$, $SD = 0.036$), ($M = 0.20$, $SD = 0.037$) and ($M = 0.26$, $SD = 0.052$) respectively. Hence, the amount of "useful walking", contributing to moving forward in the virtual world, relative to time is as large with the Magic Barrier Tape as with the other techniques. If we consider that walking speeds are the same for the 3 techniques, users spend roughly the same percentage of the total time doing useful walking with the Magic Barrier Tape technique than with the other 2 techniques.

Experiment #2 showed that the Magic Barrier Tape was less precise when following a given path, with a higher path deviation when compared to the 2:1-Turn technique (roughly 2 times less precise). We cannot conclude on the comparison with the Freeze-backup technique, since results were not significantly different. Again, these results were expected. By nature and design, the use of the Magic Barrier Tape is meant for coarse positioning. The user gets close enough to the navigation target in order to have it inside his workspace, and can then reach it by fine positioning navigation through real walking. As explained by one of the subjects of the Experiment #2, when asked about the strategies he used: "I sent the barrier tape as far as possible without going into the walls in order to take advantage of the workspace". However, path deviation could be improved by allowing users to cutomize their control law, like when they choose the mouse speed in desktop computers. Moreover, Zhai [Zhai 1995] observed that, with sufficient training, rate control and position control can achieve similar performances. Hence, further user training on the Magic Barrier Tape rate control might improve its mean path deviation.

Overall, users graded the Magic Barrier Tape higher in all criteria of the questionnaire where comparisons were significantly different. We highlight that 6 subjects complained about having cybersickness when using the 2:1-Turn technique, while 2 said it made them loose balance. Many subjects found the Freeze-backup technique exhausting and frustrating. It is also important to note that 2 subjects had a very hard time using the Magic Barrier Tape. They used an inadequate strategy, and complained about the control law. They might have needed a longer training time, or more guidance on the strategy to adopt. They consistently graded it lower than the other techniques in every criteria of the questionnaire.

In a nutshell, the Magic Barrier Tape is faster than the Freeze-backup and the 2:1-Turn techniques, but is less precise when using it in rate control. The 2:1-Turn technique is the most precise, but seems to induce cybersickness to users, as well as stability issues. There is a general dissatisfaction with the Freeze-backup technique, mainly due to its physical exertion and slow speed, leading to a frustrating experience. People generally prefer the Magic Barrier Tape, and find it more natural and less tiring.

7 Perspectives

Through user feedback on the experiments and our own observations, we found some ways of potentially improving the Magic Barrier Tape.

The user could use any part of his body in order to "push" on the virtual barrier tape. Figure 1 (right) shows the virtual barrier tape being triggered by using the elbow when the user's hands are busy carrying an object. One could think about using the shoulders, the pelvis or the feet, since we often naturally use these body parts when we are unable to use our hands.

In their "Bubble" technique [Dominjon et al. 2005], a hybrid position/rate control haptic interaction technique for devices with restricted workspace, Dominjon et al. successfully used haptic feedback to represent the workspace boundaries and their virtual elasticity. In the RubberEdge technique [Casiez et al. 2007], Casiez et al. used a passive haptic feedback through an elastic ring on top of a tracking surface such as a touchpad to allow the user to switch from position to rate control when reaching the elastic boundaries. Similarly, the Magic Barrier Tape could be augmented with haptic feedback when "pushing" on the tape. A possibility could be the use of passive haptics through tangible objects such as queue barriers with retractable belts as one could find in airports and queue-up places. The queue barriers could follow the workspace boundaries, and the virtual barrier tape would match the queue barriers position. Since retractable belts are elastic, the haptic feedback of the virtual barrier tape elastic deformation would be straightforward. Many users complained about the translation speed when using the Magic Barrier Tape, since the acceleration could be hard to control. A solution to this problem could be the use of a discrete approach. The control law, according to the hand penetration, would deliver one of three discrete velocities, corresponding to a human walking, jogging or running. Side-stepping human velocities could be used when moving in a direction orthogonal to the body orientation. The translation speed would therefore be more predictable, although capped by the running speed.

Last, although the barrier tape is made semi-transparent to reduce occlusion, visibility might be reduced in environments were the dominant color is close to the tape color. A way to enhance visibility in such cases would be to use different tape textures using the complementaries of the dominant colors of the surrounding environment, in order to emphasize the presence of the Magic Barrier Tape while increasing the visibility of the scene.

8 Conclusion

This paper introduces the Magic Barrier Tape, a new interaction metaphor for navigating in a potentially infinite virtual scene while confined to a restricted walking workspace. Using the barrier tape metaphor and its "do not cross" implicit message, the walking workspace is surrounded with virtual barrier tape in the virtual scene. The technique uses a hybrid position/rate control mechanism: real walking is used inside the workspace, while rate control navigation is used to move beyond the boundaries by "pushing" on the virtual barrier tape. Moreover, the technique naturally informs the user about the boundaries of his walking workspace, providing a walking environment safe from collisions and tracking problems.

We conducted two experiments in order to evaluate the Magic Barrier Tape by comparing it to other state-of-the-art navigation techniques previously extended for omni-directional navigation. In Experiment #1 participants had to walk to a target, while in Experiment #2 they had to navigate inside a scene following a path. Results showed that the Magic Barrier Tape was faster than the other techniques. Experiment #2 results confirmed that, by design, navigation through rate control with the Magic Barrier Tape is not meant for precise path following, but rather for coarse positioning between fine positioning tasks. Overall, the Magic Barrier Tape was more appreciated, while being more natural and less tiring.

Future work will focus on exploring the different perspectives highlighted in this paper, namely the use of haptics for a more compelling and immersive experience, and the use of discrete velocities to produce a more predictable and realistic motion in rate control.

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