IEEE VR 2009 Workshop on Perceptual Illusions in Virtual Environments

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Edited by
Frank Steinicke
Pete Willemsen
Cover Image Credits

From left to right

- PIVE logo.
  Marc Steinicke

- Subject interacting with a flat real table.
  Luv Kohli

- Example scene from a virtual city model in which users can walk.
  Gerd Bruder, Frank Steinicke, Klaus H. Hinrichs, Harald Frenz, Markus Lappe

- External view of a participant with a virtual avatar in a stressful environment.
  Brian Ries, Victoria Interrante, Cassandra Ichniowski, Michael Kaeding
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About PIVE

The IEEE VR Workshop on Perceptual Illusions in Virtual Environments (PIVE) is the first international workshop focused on the topic of perceptual illusions in virtual environments (VEs) and will be held to foster discussions among participants and to provide an intensive exchange between industrial and academic researchers working on various perception research problems.

Virtual environments provide humans with synthetic worlds in which they can interact with their virtual surrounding. However, while interacting in a VE system, humans are still located in the physical setup: they move through a laboratory space or may touch real-world objects. This duality of being in the real world while receiving visual, haptic, or aural information from the virtual world places users in a unique situation, forcing them to integrate (or separate) stimuli from potentially different sources simultaneously.

In these environments, a person’s actions can vary enormously as stimuli presented to the person is manipulated. Such perceptually influenced actions have potential to broaden the use of applications that take advantage of these illusions. In particular, these manipulations can be achieved through differing input stimuli:

- **Visual illusions** allow to exploit the fact that vision usually dominates proprioceptive and vestibular senses. Based on this, mechanisms like redirected walking can force users to be guided on physical paths which may vary from the paths on which they perceive they are walking in the virtual world.

- **Haptic illusions** may give users the impression of feeling virtual objects by touching real world props. The physical objects that represent and provide passive haptic feedback for the virtual objects may vary in size, weight, or surface from the virtual counterparts without users observing the discrepancy.

- **Acoustic illusions** may exploit aural information to assist with manipulating a user’s perception of a scene. For instance, such illusions may result in users perceiving (self-)motion (such as vection) when no such visual motion is being supplied.

The objective of the PIVE workshop is to foster discussions among participants and to provide an intensive exchange between industrial and academic researchers. The workshop will provide a venue for understanding perceptual thresholds in VEs and will facilitate exploratory discussion for how the related perceptual discrepancies can be further increased or where these concepts can be successfully applied.
International Program Committee

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Scene Instability During Head Turns

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ABSTRACT
Various experiments have shown scene-motion thresholds to be greater when the scene moves with the direction of the head turn than when the scene moves against the direction of the head turn. In fact, a virtual scene may appear to be more stable in space when moving slightly with the head turn than when the scene does not move. In this position paper, we discuss current investigations into this illusion and possible explanations.


1 INTRODUCTION
It is known that users perceive immersive virtual environments (IVEs) differently than the real world. However, researchers do not fully understand why. For example, egocentric distances in IVEs are perceived to be compressed, even when geometrically correct, compared to the real world [6].

In this position paper, we describe a perceptual illusion that we unexpectedly found in our research:

A scene can seem to move during a head turn when in fact it is not moving. The scene can appear to be more stable in space when it moves by a small amount in the same direction as a head turn than if the scene did not move.

We report our evidence for the illusion, possible explanations as to why it might occur, and future work that might be pursued to investigate the phenomena further.

2 EVIDENCE OF THE ILLUSION
We unexpectedly discovered in pilot studies of a previous experiment, where subjects made scene-motion judgments after viewing a projected scene with only subject-relative cues, that scene-motion thresholds seemed to depend upon the direction of the scene motion relative to head motion. Due to this discovery, we added conditions to our experiment comparing scenes moving with the direction of head turns to scenes moving against the direction of head turns. The difference between these conditions was statistically significant. We found subjects’ scene-motion thresholds when the scene moved with head turns to be twice that of scene-motion thresholds when the scene moved against head turns [4].

A later pilot study, with the first author serving as the subject, resulted in the data shown in Figure 1. The scene appeared more stable when moving at 0.1 m/s then when the scene did not move.

We found a similar finding in a separate study [8]. Rotational gains were added to a scene presented in a head-mounted display (HMD). When a rotation gain $g_R$ is applied to a real world rotation $\alpha$, the virtual camera is rotated by $\alpha \cdot g_R$ instead of $\alpha$. This means that if $g_R = 1$ the virtual scene remains stable considering the head’s orientation change. In the case $g_R > 1$ the virtual scene appears to move against the direction of the head turn, whereas a gain $g_R < 1$ causes the scene to rotate in the direction of the head turn. We found the point of subjective equality (PSE) to be at a gain of $g_R = 0.96$ meaning that, on average, subjects judged a scene to be moving slightly with the head to be the most stable.

After discovering this phenomena we went back and took a closer look at the literature. We found some researchers had mentioned similar findings.

In Wallach’s review of his own work [9], he claimed scene-motion thresholds to be the same whether the scene moved with the head or against the head. However, in his original work [10], he stated subjects judged scenes to be stable when the scene moved with 1.5% of head turns. Wallach stated this 1.5% to be negligible, even though the result was statistically different from zero. He argued this was due to the scene being at a finite distance from the subjects and that this would be further investigated. We could find no later report of Wallach investigating this finding.

Jaekl et al. [3] found for a monoscopic HMD that the ratio of visual to physical motion most likely to be regarded as perceptually stable resulted in 1.2 times more visual movement against head turns than was geometrically necessary. This is in the opposite direction of our findings. This implies that the illusion can occur in either direction depending on conditions.
3 Possible Explanations

We propose that the following factors might contribute to the illusion.

Eye stabilizing motions. The vestibular ocular reflex and optokinetic reflex causes the eyes to rotate in the opposite direction the head turns so that the visual representation of an object remains stabilized on the retinas. For an object at an infinite distance the eyes rotate in an equal and opposite direction of the head (a gain of 1.0). For closer objects, the eyes must rotate by a greater amount (a gain greater than 1.0) for the visual representation of the object to remain stabilized on the retina. Misinterpreting vestibular cues and other cues might cause a bias resulting in apparent motion when no motion exists.

Pivot hypothesis. The pivot hypothesis [2] states that a point stimulus at a distance will appear to move as the head moves if its perceived distance is different from its actual distance. A related effect is demonstrated by focusing on a finger held in front of the eyes and noticing that the background further in the distance seems to move with the head. Likewise if one focuses on the background then the finger seems to move against the direction of the head. For the case that objects appear to be closer to users than they should, as is the case for HMDs [6], the scene should appear to move with the head. In this case, the scene would have to move against the direction of the head turn to appear stable in space. This is consistent with the findings of Jaekl [3] but in the opposite direction of our measurements.

Spatial Frequency, Brightness, and/or Contrast. It is possible that our results could be a function of spatial frequency, brightness, and/or contrast. Freeman and Banks [1] found that the Filehne illusion (when tracking a moving object with the eyes, the background appears to move against eye motion) and the Aubert-Fleischl illusion (the false impression that objects move slower when they are pursued with the eyes as compared to when the eyes are kept stationary) could be reversed by manipulating spatial frequency. Manipulating spatial frequency, brightness, and/or contrast might be able to reverse the illusion we found.

Edge of HMD. The edge of an HMD may cause subjects to judge scene motion relative to the head instead of relative to the world. I.e., subjects could be biased towards greater thresholds when the scene moves with the head since the edge of the HMD serves as an object-relative cue.

Scene size. Our scene in our previous experiment [4] had a 20° horizontal span. We expect larger scenes to appear to be more stable and to reduce the illusion.

Magnitude of relative motions. It is possible the mind biases us to see scene motion in the opposite direction we are turning our head. If the eyes follow the scene, the difference between head motion and eye motion is larger when the scene moves against the direction of the head turn. If the eyes remains stabilized in space, the difference between head motion and motion on the retina is greatest when the scene moves against the direction of the head turn.

Latency. Latency in an HMD causes the scene to move with the head as the head accelerates and to move against the head as the head decelerates. This could cause bias if subjects pay more attention to scene motion as the head is accelerating or decelerating. However, in our original study [4], the scene was presented by a projector so that latency caused no scene motion.

4 Discussion and Future Work

Our current study emulates an HMD by using a projector and removing all object-relative cues. This was done to remove all confounding motion that occurs due to error inherent in HMDs (e.g., due to latency, incorrect field of view, incorrect accommodation, etc). The casing of an HMD was used so that the field of view was similar to a real HMD.

We presented a large stable scene (∼100 lux) that showed the true display surface between trials so that subjects could have a reference of a stable world.

The study investigates the illusion under different conditions:

- **Head Phase** Different phases of head turns (beginning, center, and end of single left-to-right / right-to-left head turns)
- **Brightness** One dark condition (∼1 lux) and one bright condition (∼400 lux) such that subjects might perceive the darker scene to be behind the display surface and the brighter scene in front of the display surface. We thought this might reverse the illusion due to the pivot hypothesis or find a result similar to Freeman and Banks [1].

Preliminary analysis suggests the illusion holds across all tested conditions. We suspect the differences in brightness did not cause subjects to perceive the scenes to be at different depths and/or the pivot hypothesis and brightness/contrast does not significantly affect the illusion.

In this study all scene motion was a constant velocity for each trial. However, at least one subjects perceived changes in velocity:

“It sometimes feels still up to the end then it moves when you stop your head” (Subject ID415).

This illusion makes sense since scene-motion thresholds increase as head motion increases [5].

4.1 Future Work

Future studies might include the following

- Binocular disparity in order to vary the perceived distance to further test the Pivot Hypothesis.
- Removal of the HMD casing such that subjects cannot use the edge of the HMD in peripheral vision as an object-relative cue. It may be the case that this illusion only occurs in HMDs due to this cue.
- Different scene sizes or different field of views. The illusion may decrease as the field of view in newer HMDs increase.
- Varying latency to determine if latency could have contributed to the results of Jaekl [3].

4.2 Discussion

We are curious as to why the results of Jaekl et al. [3] are the opposite of our results. We suspect the reasons are due to different conditions such as the monoscopic display, latency, etc. If we can determine the important factors of when the illusion can be reversed, then this would be very useful to control perception of scene motion in virtual environments.

Specifically, We believe understanding such illusions and under what conditions they occur will allow us to create better redirected walking systems. For example, our results suggest distractors used for reorientation purposes [7] could be used most effectively by moving the distractor in the same direction we wish to rotate the world. We also suspect the thresholds would be larger if subjects pay attention to a distractor or some distracting task.
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REFERENCES

Travel distance estimation from leaky path integration in virtual and real environments

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ABSTRACT
The estimation of the travel distance of a simulated movement in virtual environments shows characteristic errors. These errors may be explained by leaky path integration. We show that similar errors occur also in the estimation of travel distance in the real world, and that they are consistent with the leaky integration model. Thus, errors in travel distance estimation are not induced by factors of the virtual environment but by properties of perception.

Index Terms: H1.2 [Models and Principles]: User/Machine Systems—Human Factors; I.3.m [Computer Graphics]: Miscellaneous—Perception

1 INTRODUCTION
Spatial orientation and navigation is supported by the interaction of visual, proprioceptive, auditory, and vestibular signals, as well as efference copy signals from motor commands. Virtual environments can be used to study this interaction – and the contribution of individual senses – by manipulating the presence of or the relationships between these signals. We are particularly interested in the role of vision in the estimation of the travel distance of a movement, for instance a walk. Forward movement, such as walking, induces visual motion in the eye of the walker. This visual motion provides cues about direction, speed, and duration of the walk, which can be integrated to achieve a measure of the distance traveled [1, 15, 18].

To isolate visual motion from other sensory cues, we have previously performed distance estimation experiments in virtual environments with simulated observer movement through different scenes. We found that human subjects were quite good at discriminating the distances of two sequentially presented movement intervals, even when the two movements differed in speed, duration, scene visibility, or environmental layout [1, 3]. However, substantial errors were made when travel distance of a single movement had to be estimated by adjusting the size of a static distance interval within the virtual scene [4]. Unlike the discrimination task, which can be solved by using a comparison of speed and duration of the two movements, the target adjustment task requires the build-up of a true representation of distance based on the visual motion experience. Results showed that subjects could do this task consistently (i.e. reliably over multiple trials and correlated with the true distance) but not accurately with respect to magnitude, i.e., they systematically underestimated the travel distance [4]. This underestimation occurred for different types of displays (projection screen, stereographic projection, or a fully-immersive virtual environment [6]) and different perceptual reports (visual interval adjustment, verbal report, blindfolded walking [4]). It was also not due to the general compression of distance often observed in real [11, 2, 9] and virtual scenes [5, 7, 16, 20], since over the range of distances that were used in the above studies the perception of static distances in our virtual environment was quite accurate.

However, while results of the target adjustment task consistently gave an underestimation of the perceived travel distance, results from a seemingly similar task indicated an overestimation of perceived travel distance [17]. In that study, subjects briefly saw a target at a particular distance before a simulated forward movement. The task was to indicate the point in time at which the target’s position was reached. Subjects in this task typically responded too early, indicating that they felt they had reached the target before they had actually traversed the whole distance. Based on experiments comparing both tasks in the same subjects, [8] formulated a leaky integrator model of distance perception from visual motion which replicated both results.

2 LEAKY PATH INTEGRATION
Path integration [10, 12, 13, 14] assumes that the moving individual tracks the amount of space covered by the movement by integrating the changes of position over the course of the movement. Misrepresentation of the length of the movement may arise if the integration of the new position uses a misrepresentation of the momentary position change (which would essentially be an error in gain) or if the integration is leaky. The leaky path integration model assumes that a state variable, such as the current distance from the starting point, is incremented with each step by the distance of the step with a gain factor $k$, but that it is subsequently slightly reduced in proportion to a leak factor $\alpha$. Thus, the state variable is continuously incremented according to the movement but has a tendency to decay by itself. This can be formalized by the following differential equation:

$$\frac{dp}{dx} = -\alpha p + k,$$

where $dx$ is the change of position of the subject along the trajectory of the movement, $\alpha$ is the rate of decay of the integrator, and $k$ is the gain of the sensory (visual) input. If $k=1$ the visual motion is transformed perfectly into the instantaneous travel distance. In this equation, in each step $dx$, the state variable $p$ is reduced proportional to its current value (due to the leak) and incremented by the distance given by the gain $k$ of the step. For a true distance $x$ the integrated distance $p(x)$ then is:

$$p(x) = \frac{k}{\alpha} (1 - e^{-\alpha x}).$$

If the leak rate $\alpha$ is large, then the perceived distance $p$ of an extended movement is smaller than the true distance $x$, consistent with the results of [4, 6]).

The seemingly conflicting results of [17] can be explained with the leaky integration model by considering the necessities of the move-to-target task [8]. That task began with a static representation of a target in a given distance $D_0$. Then the target was extinguished and a movement towards the now invisible target was simulated. Participants pressed a button when they felt that they had arrived at the target position. This task can be simulated in the leaky integrator model by assuming that the state variable is the distance

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to the target, which has to be nulled by the movement. The state variable is decremented in every step proportional to the length of the step size. Moreover, leakage occurs with every spatial step and is proportional to the current value of the state variable according to the leak rate, $\alpha$. Thus, two processes lead to a reduction of the perceived distance to the target: the decrement according to the forward movement and the leakage of the integrator. Therefore, with ongoing movement the distance to the target becomes overproportionally smaller because of the leakage. The point of perceived distance zero is then reached early. Mathematically, this point is given by

$$p_{\ln}(D_h) = \frac{1}{\alpha} \ln(D_h + \frac{k}{\alpha}) - \ln\left(\frac{k}{\alpha}\right)$$  \hspace{1cm} (3)

3 Travel Distance Estimation in Virtual and Real Environments

The leaky integration model explains both the underestimation in the adjust-target condition and the overestimation in the move-to-target condition with the same mechanism and the same set of parameters [8]. In experiments in a fully immersive virtual environment subjects experienced motion through a virtual hallway, and either had to estimate the length of the travel path by adjusting a post-motion target, or had to terminate the movement when they felt that they had reached a specified distance. Although the travel distance was underestimated in the first condition and overestimated in the second, the leaky integration model predicted both results with the same values of the gain $k$ and leak rate $\alpha$. The best fit to both data sets indicated that $k = 0.98$ and $\alpha = 0.0076$. Values for individual subjects ranged between 0.002 and 0.015 for $\alpha$ and between 0.79 and 1.25 for $k$. Thus, the leak rate was always positive, indicating a decline in all subjects, while the gain could be lower than 1, indicating a general underestimation of distance, or greater than 1, indicating a general overestimation of distance. In the latter case, the underestimation over longer distances was solely due to the leakage.

To compare those results to real world situation in which subjects actually walked within a real environment we conducted similar experiments in a large open field (130 by 100 meters) devoid of visual landmarks. Each trial started in the middle of this field. In the move-to-target condition, an experimenter placed a pole (2 m x 4.5 cm) painted with bright orange lacquer in a certain distance from the subject. The subject was asked to estimate and memorize the distance to the target. The subject could view the target as long as desired. The subject then turned around 180 deg and started walking, guided by a second experimenter, until the subject thought he/she had covered the same distance as the reference distance. The walking distance was then measured with a tape measure. At the end of the trial the subject went back to the starting position to start the next trial.

In the adjust-target condition the subject walked a certain distance guided by an experimenter. The distance was not known to the subject. The experimenter stopped the subject when the predetermined distance was reached. The experimenter then walked further on until the subject indicated verbally that the experimenter had now reached the same distance as the one that the subject had previously walked. The distance between the experimenter and the subject was then measured with a tape measure. After the trial both subject and experimenter returned to the starting position.

Five different distances (8, 12, 16, 24, and 32 m) were used in a block design. Ten subjects (eight female, two male) participated. All subjects were students of the department and received course credit for their participation. All subjects had normal or corrected to normal vision.

We measured perceived distance in both condition for five different reference distances (8, 12, 16, 24, and 32 m) in a blocked design. Means and standard deviation were determined for each tested distance. This was done for the single subjects results as well as for the pooled data of all subjects. Afterwards, we fitted the leaky integrator model to the data to estimate the leakage and gain factor for both experiments. The fit was done simultaneously to the data from both conditions to obtain a single set of parameters $(k, \alpha)$ for both conditions.

Results were very similar to the results previously obtained in the VE. Distances were underestimated in the adjust-target condition and overestimated in the move-to-target condition. Both data sets were well fitted by the leaky integrator model. The average leak rate was $\alpha = 0.011$, quite similar to the value found in VE ($\alpha = 0.0076$). Values of individual subjects ranged between 0 and 0.24. The average gain was $k = 1.029$, with individual values ranging from 0.96 to 1.066. Compared to the values obtained in the virtual environment, the gain was higher and more consistent between subjects.

Figure 1 shows the data together with the fits of the leaky integrator model. Figure 1A shows the results in the adjust-target condition. B: move to target condition.
of the leaky integrator model to the data. Figure 1B shows the results in the move-to-target condition. In this plot, the x-axis is the distance in which the initially viewed target was placed. The y-axis gives the distance that was actually travelled until the subject indicated that the target distance was reached. The actual walking distance is usually lower than the initial target distance, i.e. the travel distance is underestimated. The continuous line gives the best fit of the leaky integrator model to the data. The leak rate and gain of the leaky integrator model are the same in both panels because the model was fitted to both data sets simultaneously. For comparison, the dashed lines in the two panels shows the predictions of the leaky integrator model that was fitted to the data from the prior VE experiment [8]. Although that experiment used a different environment, purely simulated self-motion, and different subjects the parameters of the model fit the real walking data very well.

The two parameters of the leaky integrator model for distance perception relate to different parts of the integration procedure. The leak rate describes how much the integrated distance value from the start decays over the length of the movement. The gain describes how much distance a particular movement (a single step, for instance) adds to the integrated distance value. Therefore, $\alpha$ should have a fixed value for a particular individual since the leak acts only on the actual state variable, whereas the gain $k$ might depend on the particular sensory signals that are available to estimate movement length. Specifically, there might be separate gains for the visual input, for the vestibular input, for the proprioceptive input, etc. Consistent with this, distance errors in walking tasks with different combinations of available information (static vision, vision and locomotion, blindfolded walking) varied depending on the cues available and the combination of conditions [19]. Likewise, a comparison between real walking experiments and virtual environment experiments showed that the leak rates were similar in both cases while the gains were higher and less variable between subjects in the real walking case. Since subjects in the real world experiment actually walked, and therefore had proprioceptive, vestibular and motor information available in addition to vision, this information might help to achieve a greater consistency between the movement of a single step and its perceived distance.

4 Conclusion

Estimation of travel distance can be modeled as leaky path integration. According to this model, a perceptual state variable accounts for the current distance from the starting point or the remaining distance to the goal, depending on the task to be completed. As the travel progresses, the state variable is incremented (when counting from the start) or decremented (when counting towards the goal) with a particular gain for each step. The gain depends on the sensory information that is available for the current movement. Moreover, the state variable has a tendency to decline over the movement, which corresponds to the leakage of the integrator. The combination of gain, leakage, and task results in distances appearing over- or underestimated. The model works well in explaining data from virtual environments and from real walking in the natural environment. Thus, estimation errors previously observed in virtual environments do not result from inefficiencies of the simulation or unnaturalness of the graphical display but rather are inherent in the perceptual mechanism of travel distance estimation.

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References

Impact of Gender on Discrimination between Real and Virtual Stimuli

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Abstract

Immersive virtual environments allow users to control their virtual viewpoint by moving the tracked head or by walking through the real world. Usually, movements in the real world are mapped one-to-one to virtual camera motions. With redirection techniques, gains are applied to user movements when the virtual camera is manipulated. Since male and female persons use different strategies for spatial cognition and navigation, it sounds reasonable that these gender differences also occur for redirection techniques. In this paper we examine the impact of gender on tasks where male and female subjects have to discriminate between virtual and real stimuli. 7 male and 6 female subjects have been tested in three different experiments: discrimination between virtual and physical rotation, discrimination between virtual and physical translation and discrimination of walking direction.

Keywords: Virtual reality, perception, redirected walking, gender differences.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities

1 Introduction

Walking is the most basic and intuitive way of moving in the real world. Keeping such an active and dynamic ability to navigate through large-scale immersive virtual environments (IVEs) is of great interest for many 3D applications demanding locomotion, such as in urban planning, tourism or 3D entertainment. IVEs are characterized, for instance, by head-mounted displays (HMDs) and a tracking system for measuring position and orientation data.

Many domains are inherently three-dimensional and advanced visual simulations often provide a good sense of locomotion. However, exclusive visual stimulation does not provide vestibular-proprioceptive motion cues as during real-world walking. Real walking through IVEs is often not possible [17]. Indeed, an obvious approach is to transfer the user’s tracked head movements to changes of the camera in the virtual world by means of a one-to-one mapping. This technique has the drawback that the users’ movements are restricted by a limited range of the tracking sensors and a rather small workspace in the real world. Hence, the size of the tracked laboratory space limits the size of the explorable virtual world so that a straightforward implementation of omnidirectional and unlimited walking is not possible.

It is known from perceptual psychology that vision often dominates proprioceptive and vestibular sensation when they disagree [1]. Furthermore, users tend to unwittingly compensate for small inconsistencies between real world movements and visually perceived motions during walking, so that it gets possible to guide them along paths in the real world, which differ from the path perceived in the virtual world. This redirected walking [14] enables users to explore a virtual world that is considerably larger than the tracked working space. Paths that users walk in the physical world can be scaled and bended, and real-world rotations of users can be increased or decreased when the motions are applied to the virtual camera [16].

It is generally accepted that gender differences in spatial cognition and navigation strategies exist [9, 13]. Most reports document that males outperform females in spatial tasks. Some authors argue that this may be a result of evolution, experience or training due to different interests, e.g., computer games [4]. Other authors argue that males and females use different cues for spatial orientation [15]. Until now, it has not been considered if gender has any impact on the ability to discriminate between real and virtual motions.

In this paper we analyze gender differences in sensitivity to redirected walking techniques. We performed a series of experiments in which we have quantified how much male and female subjects can be redirected without observing inconsistencies between real and virtual motions. Therefore, we have performed three psychophysical experiments in which subjects had to discriminate between real and virtual motions, in particular rotations, translations and walking directions.

The remainder of this paper is structured as follows. Section 2 summarizes previous work related to locomotion and perception in virtual reality (VR) environments as well as gender differences in spatial cognition. In Section 3 we explain the redirected walking gains that we have considered in our experiments. The experiments are described in Section 4. Section 5 summarizes the results and discusses implications for the design of virtual locomotion user interfaces. Finally, we give an overview about future work.

2 Related Work

From an egocentric perspective the real world appears stationary as we move around or rotate our head and eyes. Both visual and extraretinal cues from other parts of the mind or body help us to perceive the world as stable [18]. Extraretinal cues come from the vestibular system, proprioception, our cognitive model of the world, or from an efference copy of the motor commands that move the respective body parts. When one or more of these cues conflicts with other cues, as is often the case for IVEs (e.g., due to tracking errors or latency) the virtual world may appear spatially unstable.
Experiments demonstrate that users tolerate a certain amount of inconsistency between visual and proprioceptive sensation [2, 8, 10, 12, 14]. With redirected walking [14] users are manipulated by gains that are applied to tracked motions, causing users to unknowingly compensate scene motion by repositioning and/or reorienting themselves. Different approaches to redirect a user in an IVE have been proposed. An obvious approach is to scale translational movements, for example, to cover a larger virtual distance than the distance walked in the physical space. Interrante et al. suggest to apply scalings exclusively to the main walking direction in order to prevent unintended lateral shifts [7]. Most reorientation techniques are based on rotating the virtual world around the center of stationary users in order to reorient them in the real world [10, 12, 14]. Hence, in case an obstacle blocks a user’s path in the real world, this approach allows to reorient users so that later on they can continue to walk in the desired virtual direction. Alternatively, reorientation can be applied while users walk [14]. For instance, if users walk straight ahead for a long distance in the virtual world, small rotations of the camera redirect them to walk imperceptibly a circular path in the real world. In such cases the visual sensation is consistent with motion in the IVE, but proprioceptive sensation reflects real-world motion. However, if the induced manipulations are small enough, users get the impression of being able to walk in the virtual world in any direction without restrictions.

Preliminary studies [12, 14] have shown that redirected walking works as long as users are not focused on detecting manipulations. In these experiments users had to remark afterwards, if they noticed a manipulation or not. Other work has focused on identifying thresholds for detecting scene motion during head rotation [8, 18].

3 Locomotion Gains

In this Section we describe how gains are applied to tracked movements when these are mapped to the virtual camera.

3.1 Translation gains

When the tracking system detects a change of the user’s real world head position defined by the vector \( \mathbf{T}_{\text{real}} = \mathbf{T}_{\text{cur}} = \mathbf{T}_{\text{pre}} \), where \( \mathbf{T}_{\text{cur}} \) is the current position and \( \mathbf{T}_{\text{pre}} \) is the previous position, \( \mathbf{T}_{\text{real}} \) is mapped to the virtual camera with respect to the registration between virtual scene and tracking coordinate system. In case of a one-to-one mapping, the virtual camera is translated by \( \mathbf{T}_{\text{real}} \) units in the corresponding direction in the virtual world coordinate system. A translation gain \( g_t \in \mathbb{R}^3 \) is defined as the quotient of the mapped virtual world translation \( \mathbf{T}_{\text{virtual}} \) and the tracked real world translation \( \mathbf{T}_{\text{real}} \), i.e., \( g_t := \frac{\mathbf{T}_{\text{virtual}}}{\mathbf{T}_{\text{real}}} \).

When a translation gain \( g_t \) is applied to a translational movement \( \mathbf{T}_{\text{real}} \) the virtual camera is moved by the vector \( g_t \cdot \mathbf{T}_{\text{real}} \) in the corresponding direction. This is particularly useful if the user wants to explore IVEs whose size differs significantly from the size of the tracked space. For instance, if a user wants to explore molecular structures, movements in the real world must be scaled down when they are mapped to virtual movements, e.g., \( g_t \approx 0 \). In contrast, exploration of a virtual football field in a typical walking setup requires a translation gain \( g_t \approx 10 \). Generic gains for translational movements, for example, to cover a larger virtual distance or to move an object from one place to another are manipulated via gains that are applied to movements in strafe direction \( s \), up direction \( u \) and walking direction \( w \), which compose the translation.

In our experiments we have focused on sensitivity to translation gains \( g_{T[u]} \).

3.2 Rotation gains

Real-world head rotations can be specified by a vector consisting of three angles, i.e., \( \mathbf{R}_{\text{real}} := (\text{pitch}_\text{real}, \text{yaw}_\text{real}, \text{roll}_\text{real}) \). The tracked orientation change is applied to the virtual camera. Analogous to Section 3.1, rotation gains are defined for each component (pitch/yaw/roll) of the rotation. A rotation gain \( g_r \) is defined by the quotient of the considered component of a virtual world rotation \( \mathbf{R}_{\text{virtual}} \) and the real world rotation \( \mathbf{R}_{\text{real}} \), i.e., \( g_r := \frac{\mathbf{R}_{\text{virtual}}}{\mathbf{R}_{\text{real}}} \). When a rotation gain \( g_r \) is applied to a real world rotation \( \alpha \) the virtual camera is rotated by \( \alpha \cdot g_r \) instead of \( \alpha \). This means that if \( g_r = 1 \) the virtual scene remains stable considering the head’s orientation change. In the case \( g_r > 1 \) the virtual scene appears to move against the direction of the head turn, whereas a gain \( g_r < 1 \) causes the scene to rotate in the direction of the head turn. For instance, if a user rotates the head by 90°, a gain \( g_r = 1 \) maps this motion one-to-one to a 90° rotation of the virtual camera. The appliance of a gain \( g_r = 0.5 \) means that the user has to rotate the head by 180° physically in order to achieve a 90° virtual rotation; a gain \( g_r = 2 \) means that the user has to rotate the head by 45° physically in order to achieve a 90° virtual rotation.

Rotation gains can be expressed by \( g_{R[p]}, g_{R[y]}, g_{R[w]} \), where the gain \( g_{R[s]} \) specified for pitch corresponds to \( s \), the gain \( g_{R[w]} \) specified for yaw corresponds to \( u \), and \( g_{R[v]} \) specified for roll corresponds to \( w \). In our experiments we have focused on rotation gains \( g_{R[w]} \) for yaw rotation.

3.3 Curvature gains

Instead of multiplying gains with translations or rotations, offsets can be added to real-world movements. For instance, rotational offsets can be applied to the camera with respect to traveled distances while a user walks straight ahead in the virtual world. If the injected manipulations are reasonably small, the user will unknowingly compensate for these virtual camera rotations resulting in walking a curve in the real world. The curvature gain \( g_c \) denotes the resulting bending of a real path. When a user moves straight ahead in the virtual world, a curvature gain that causes reasonably small iterative camera rotations to one side enforces the user to walk along a curve in the opposite direction in order to stay on a straight path in the virtual world. The curve is determined by a circular arc with radius \( r \) and \( g_c := \frac{1}{r} \). In case no curvature is applied it is \( r = \infty \Rightarrow g_c = 0 \), whereas if the curvature causes the user to rotate by 90° clockwise after \( \frac{r}{g_c} \) meters the user has covered a quarter circle with radius \( \frac{r}{g_c} \).

In our experiments we have focused on curvature gains \( g_{C[w]} \), which enforce users to walk an circular arc.

4 Experiments

In this section we present three experiments in which we have quantified how much female and male subjects can unknowingly be redirected. We have analyzed the appliance of translation \( g_{T[w]} \), rotation \( g_{R[u]} \) and curvature gains \( g_{C[w]} \).

4.1 Experimental Design

The visual stimulus consisted of virtual scenes of the city of Münster in Germany (see Figure 2). Before each trial a random place and initial gaze direction were chosen. The only restriction for scenes was that no vertical objects were within 10m of the starting position in order to prevent collisions in the VE.
Hardware Setup

We performed all experiments in a 10 × 10m laboratory room. The subjects wore an HMD (eMagin Z800 3DVisor, 800x600@60 Hz, 40° diagonal field of view (FoV)) for stimulus presentation. On top of the HMD an infrared LED was fixed. We tracked the position of this LED in the room with an active optical tracking system (WorldViz Precise Position Tracking), which provides sub-millimeter precision and sub-centimeter accuracy. The update rate was 60 Hz providing real-time positional data of the active marker. For three degrees of freedom (DoF) orientation tracking we used an InterSense InertiaCube 2 with an update rate of 180 Hz. The InertiaCube was also fixed on top of the HMD. In the experiments we used an Intel computer with dual-core processor, 4 GB of main memory and an nVidia GeForce 8800 GTX for rendering and system control. We connected the HMD and InertiaCube with a 10m cable to the rendering computer.

The virtual scene was rendered using OpenGL and our own software with which the system maintained a frame rate of 50–60 frames per second. During the experiment the room was entirely darkened in order to reduce the user’s perception of the real world. Furthermore, ambient city noise was used as acoustic feedback during the experiment such that orientation by means of auditory cues from the real world was not possible. Prior to each experiment the subjects received instructions on slides presented on the HMD. A Nintendo WII remote controller served as input device. In order to focus subjects on the task no communication between experimenter and subject was performed during the experiment. Task instructions were displayed as insets in the visual scene and subjects responded via the WII device.

Participants

7 male (age 21 – 24, 22.7) and 6 female (age 19 – 50, 27.3) subjects participated in the experiments. Subjects were students or professionals with expertise in computer science, mathematics or psychology. All had normal or corrected to normal vision; 4 wore glasses and 3 contact lenses during the experiments. 3 of the males had some gaming experience and 4 had much gaming experience; 2 females had no, 3 some and 1 much gaming experience. All subjects were naïve to the experimental conditions. None of the subjects had experience with walking in VR environments using an HMD setup. Subjects were allowed to take breaks at any time. The total time per subject including pre-questionnaire, instructions, training, experiment, breaks, and debriefing took 3 hours.

Experiments

For all experiments we used the method of constant stimuli in a two-alternative forced-choice (2AFC) task. In the method of constant stimuli, the applied gains are not related from one trial to the next, but presented randomly and uniformly distributed. The subject choses between one of two possible responses, e.g. “Was the virtual movement smaller or greater than the physical movement?”; responses like “I can’t tell.” were not allowed. Hence, when subjects cannot detect the signal, they must guess, and will be correct on average in 50% of the trials. The gain at which a subject responds “greater” in half of the trials is taken as the point of subjective equality (PSE), at which the subject perceives the physical and virtual movement as identical. As the gain decreases or increases from this value the ability of the subject to detect the difference between physical and virtual movement increases. We define the detection threshold (DT) for gains smaller than the PSE to be the gain at which the subject has 75% probability of correctly choosing the “smaller” response and the detection threshold for gains greater than the PSE to be the gain at which the subject chooses the “smaller” response in only 25% of the trials (since the correct response “greater” was then chosen in 75% of the trials).

The range of gains will give us an interval of possible manipulations which can be used for redirected walking. The PSEs indicate how to map user movements to the virtual camera such that virtual motions appear natural to users.

4.2 Experiment 1 (E1): Discrimination between virtual and physical rotation

In this experiment we investigated the subjects’ ability to discriminate whether a physical rotation was smaller or greater than the simulated virtual rotation (see Section 3.2). Therefore, we instructed the subjects to rotate on the spot and we mapped the physical rotation to a corresponding virtual rotation to which different gains $g_{n\mu}$ were applied.

4.2.1 Material and Methods for E1

At the beginning of each trial the virtual scene was presented on the HMD together with written instruction to physically turn left or right until a red dot drawn at eye height was directly in front of the subject’s gaze direction. The subject indicated the end of the turn with a button press on the WII controller. Afterwards, the subject had to decide whether the simulated virtual rotation was greater (up button) or smaller (down button) than the physical rotation in the described 2AFC task. Before the next trial started, the subject had to turn to a new orientation. We indicated the reorientation process in the IVE setup by a white screen and two orientation markers (current orientation and target orientation). We implemented this reorientation in order to prevent adaptation of the subject to a certain pose and orientation.

The virtual rotation was always 90° either clockwise or counterclockwise. We varied the gain $g_{n\mu}$ between the physical and virtual rotation randomly in the range between 0.5 (180° physical rotation resulted in a 90° virtual rotation) and 1.5 (60° physical rotation resulted in a 90° virtual rotation) in steps of 0.1. We tested each gain 10 times in randomized order.

Figure 2: Example scene from the virtual city model as used for experiment E2. No obstacles were within a 10m distance from the user.
4.2.2 Results of E1
Figure 1(a) shows the mean detection rates together with the standard error over all male subjects (blue symbols) and female subjects (red symbols) for the tested gains. The x-axis shows the applied rotation gain \( g_R[w] \), the y-axis shows the probability for estimating a virtual rotation smaller than the physical rotation. In (b) the x-axis shows the applied translation gain \( g_T[w] \), the y-axis shows the probability of estimating a virtual translational movement smaller than the physical motion.

In summary, the experiment shows that both male and female subjects had serious problems discriminating rotations. Consequently, reorientation techniques based on rotation gains are a good choice in order to redirect subjects, since they allow strong manipulations for all users.

4.3 Experiment 2 (E2): Discrimination between virtual and physical translational movement

In this experiment we analyzed the subjects’ ability to discriminate between virtual and physical translational movements (see Section 3.1). The virtual movement was a forward movement mapped to physical walking.

4.3.1 Material and Methods for E2
In the IVE subjects always had to walk a distance of 5m. The walking direction was indicated by a green dot in front of the subjects. When the subjects traveled 5m in the virtual scene, the dot turned red to indicate the end of the trial (see Figure 2). The dot was constant in size and positioned in the subject’s eye height above the ground. The physical distance subjects had to walk varied between 3m and 7m, i.e., translation gain \( g_T[w] \) was between 0.6 and 1.4 in steps of 0.1. We presented the gains each 8 times in randomized order. The task was to judge whether the physical walking distance was larger or smaller than the virtual travel distance. After each trial the subject had to walk back to the start position, guided by two reference markers on an otherwise white screen. One marker showed the actual position of the subject relative to the second fixed marker, which represented the start position.

4.3.2 Results of E2
In Figure 1(b) we plotted the mean probability for a subject’s estimation that the virtual walking distance was shorter than the physical travel distance over all male subjects (blue symbols) and female subjects (red symbols) against the tested gains. The error bars show the standard errors. A translation gain \( g_T[w] < 1 \) resulted in a larger physical walking distance compared to the virtual distance,

![Figure 1](image-url)

Figure 1: Pooled results of the discrimination between (a) virtual and physical rotation, and (b) virtual and physical translation. In (a) the x-axis shows the applied rotation gain \( g_R[w] \), the y-axis shows the probability of estimating a virtual rotation smaller than the physical rotation. In (b) the x-axis shows the applied translation gain \( g_T[w] \), the y-axis shows the probability of estimating a virtual translational movement smaller than the physical motion.
male and female subjects could not be verified due to strong individual differences and the low number of subjects.

In this experiment we analyzed the subjects’ sensitivity to curvature gains, which enforce the user to walk a curved path in the real world in order to walk a straight path in the VE (see Section 3.3). In previous experiments we found that subjects had difficulty estimating the direction of path bending in similar discrimination tests particularly during the first steps [16]. For instance, after two gaits, they had left the sidewalk and had to reorient themselves to the target. Consequently, they tended to walk a triangular rather than a circular path. Therefore, we introduced a 2m travel distance without scene manipulation before curvature gains $g_{c[w]}$ were applied.

4.4 Experiment 3 (E3): Discrimination of direction of walk

In this experiment we analyzed the subjects’ sensitivity to curvature gains, which enforce the user to walk a curved path in the real world in order to walk a straight path in the VE (see Section 3.3). In previous experiments we found that subjects had difficulty estimating the direction of path bending in similar discrimination tests particularly during the first steps [16]. For instance, after two gaits, they had left the sidewalk and had to reorient themselves to the target. Consequently, they tended to walk a triangular rather than a circular path. Therefore, we introduced a 2m travel distance without scene manipulation before curvature gains $g_{c[w]}$ were applied.

4.4.1 Material and Methods for E3

To support the subjects’ task to walk straight in the virtual world, we introduced a 1m wide sidewalk. We added a green dot at the subject’s eye height in the scene, which turned red when the subjects had walked 5m. While the subject walked along the sidewalk, we rotated the scene to either side with a velocity linked to the subject’s movement velocity. The scene rotated by 5, 10, 15, 20 or 30 degrees after 5m walking distance. This corresponds to curvature radii of approximately 57.3, 28.65, 14.32, 19.10 and 9.55m. The curvature gains were $g_{c[w]} = \{ \pm \frac{\pi}{180}, \pm \frac{\pi}{90}, \pm \frac{\pi}{60}, \pm \frac{\pi}{30}, \pm \frac{\pi}{18} \}$. The rotation started after subjects walked the 2m start-up phase. After subjects walked further 5m in the virtual world, the scene turned white and the task instruction appeared. The subject’s task was to decide whether the physical path was curved to the left or to the right by pressing the corresponding “left” or “right” button on the WII controller. To guide the subject back to the starting position we used the two markers (as described above) on an otherwise white screen again.

4.4.2 Results of E3

In Figure 3 we plotted the mean probability of estimating that the physical path was curved to the left against the curvature gains $g_{c[w]}$ over all male subjects (blue symbols) and female subjects (red symbols). The variance is the standard error. The detection thresholds are given by the gains at which subjects correctly detect the bending of the path 75% of the time. We found no statistical significant difference whether we simulated a curvature to the left or right. For male subjects the DT is given by $g_{c[w]} = \pm \frac{\pi}{66}$, which corresponds to a circular arc with radius 17.4m. The DT for female subjects is $g_{c[w]} = \pm \frac{\pi}{66}$, i.e., a circular arc with radius 24.9m. Until these DTs subjects cannot reliably estimate if they walk straight or a curved path.

4.4.3 Discussion of E3

The results show that men can be reoriented by 16° to the left or to the right after walking a 5m distance, which corresponds to walking along a circular arc with radius of approximately 17.4m. Women can be reoriented by 11° after 5m walking distance, which corresponds to a radius of approximately 24.9m. The results for male and female subjects show no statistical significant bias for the PSE. Furthermore, a statistical significant difference for the detection thresholds between male and female subjects could not be verified due to strong individual differences and the low number of subjects.
5 Conclusion and Future Work

In this paper, we analyzed the ability of male and female subjects to recognize redirected walking manipulations in three different experiments. The results show that male subjects can be turned physically about 44% more or 16% less than the perceived virtual rotation without noticing the difference. Female subjects can be turned physically about 51% more or 21% less than the virtual rotation. We determined a bias for the point of subjective equality resulting in a PSE of 0.9447 for men and 0.9642 for women. Our results agree with previous findings [8, 16] that users are more sensitive to scene motion if the scene moves against head rotation than if the scene moves with head rotation. Considering also results of other researchers [3, 8, 16], it seems that male as well as female subjects tend to underestimate virtual rotation.

For male subjects, walked distances in the real world can be down-scaled by 20.6% and up-scaled by 11.2%, when they are mapped to virtual motions. For female subjects, physical walking distances can be down-scaled by 19.4% and up-scaled by 16.2%. The PSE for the pooled data of the male subjects is 1.0776, and 1.0535 for the female subjects. These results agree with previous findings that users tend to underestimate virtual distances [5, 6, 11]. Male subjects estimate that they have walked a distance of 5m after walking only 4.64m, whereas female subjects walk 4.75m.

When applying curvature gains users can be redirected such that they unknowingly walk a circular arc when the radius is greater or equal to 17.4m for male and 24.9m for female subjects. In this experiment the detection thresholds vary most for male and female subjects, which motivates that gender might have a significant influence on sensitivity to curvature gains. However, due to the low number of subjects this difference could not be verified with a test of significance.

We have performed further questionnaires in order to determine the subjects’ fear of colliding with physical obstacles. The subjects’ level of fear on a 4-point Likert-scale (0 corresponds to no fear, 4 corresponds to a high level of fear). On average the evaluation approximates 1.33 which shows that subjects felt quite safe even though they were wearing an HMD and knew that they were being manipulated. Further post-questionnaires based on a comparable Likert-scale show that subjects only had marginal positional and orientational indications due to environmental audio (0.6), visible (0.13) or haptic (1.33) cues. We measured simulator sickness by means of Kennedy’s simulator sickness questionnaire (SSQ). The Pre-SSQ score averages to 13.35 for male and 8.1 for female subjects, and the Post-SSQ score to 25.64 for male and 26.18 for female subjects. In [16] we conducted a follow-up test on another day for subjects with high Post-SSQ scores in order to examine whether the sickness was caused by the applied redirected walking manipulations. In this test the subjects were allowed to walk in the same IVE for a longer period of time while this time no manipulations were applied. Each subject who was susceptible to cybersickness in the main experiment, showed the same symptoms again after approximately 15 minutes. Hence, probably cybersickness was caused by the long period of time subjects had to wear the HMD.

In the future we will test for a significant difference in sensitivity to curvature gains with a larger number of male and female subjects and we will consider other redirection techniques, which have not been analyzed in the scope of this paper. Moreover, further conditions have to be taken into account and tested for their impact on redirected walking, for example, gaming experience, distances of scene objects, level of detail, contrast, etc.

References

An Approach to Redirect Walking by Modifying Virtual World Geometry

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ABSTRACT

We present an approach to redirect a user’s walking path by dynamically modifying the geometry of a virtual environment. This method allows real walking through environments that are much larger than the physical tracking area without requiring rotational or translational gains. We demonstrate this technique using a proof-of-concept example environment and explain the modifications at each stage of a walking path through the virtual world. We also discuss the potential advantages of this method and outline several open questions for future investigation.

Index Terms: H.5.1 [[Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

Keywords: virtual environments, real walking, locomotion

1 INTRODUCTION

Studies have shown that real walking provides a greater sense of presence, more efficient navigation, and cognitive benefits over other travel techniques [9] [11] [13]. While locomotion achieved entirely through real walking is now practical for many applications, the size of the virtual environment is ultimately limited by the physical tracking space available. A number of methods have been introduced to overcome this limitation, allowing the use of real walking in virtual environments that are much larger than the physical tracked area. Redirected walking is one such technique that introduces a continuous rotation to guide the user along a modified path [6]. This method introduces a visual-proprioceptive conflict which has been the subject of several recent studies [1] [8]. Alternatively, translational gain techniques have been proposed to increase the step size of the user without modifying rotation [2] [12]. Peck et al. noted that all these methods can be augmented by introducing reorientation techniques to handle failure cases and showed that visual distractors resulted in less awareness of the reorientation [5].

We propose a method to redirect the walking path of the user while maintaining natural rotation and translation. This technique relies on modifications to the geometry of the virtual environment that will cause the user to walk along a path that conforms to the boundaries of the physical tracking area. As a result, it is highly dependent on the particular structure of the environment in question. This method is not a generalized solution that will automatically work with all environments; rather, it is best conceived as a strategy to employ during the design phase for the virtual environment. Thus, the goals of this project are twofold: (1) implementing a proof-of-concept environment to evaluate this technique in a controlled study; and (2) developing guidelines for designing environments that employ this technique and/or methods to transform existing environments automatically.

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Figure 1: A static model of an example environment which is used as a proof-of-concept of this technique.

2 TECHNIQUE OVERVIEW

Environmental spatial knowledge is usually categorized into three levels: (1) landmark knowledge; (2) route knowledge; and (3) survey knowledge [10]. By manipulating the geometry of the environment, we present the user with conflicting spatial layout information, which could negatively influence formation of survey knowledge. This, in turn, could make it more difficult for users to orient themselves, which is particularly concerning given that spatial orientation is already difficult and error-prone in virtual environments [7]. However, recent research has shown that users tend to orient primarily using landmarks when this information conflicts with spatial layout [4]. Thus, it is important to preserve qualities of the environment which will contribute to landmark and route knowledge as much as possible when altering the layout. Specifically, we attempt to preserve the locations of salient objects (and relationships between them) and the direction of turns when the user is given a choice between two or more paths. We hypothesize that users will tend to ignore inconsistent spatial information and will instead orient using the salient objects in the scene.

This technique relies on modifications to the environment geometry which switches the orientation of doorways so that the walking path stays within the available tracking area. The overall environment is not rotated; instead, the environment dynamically changes around the user, but these modifications are always applied “behind the scenes” when the user is looking away. This is comparatively easy in a head-mounted display due to the low field of view of these devices relative to the real world. This method seems well-suited for interior environments where the transitions between rooms can be exploited for this purpose.

Figure 1 shows a static model of a proof-of-concept example environment - a corridor with several rooms, such as one would find in a typical office building. A virtual walking path is shown in which the user visits each room as he/she travels down the corridor. This example is intended to be used with a square tracking area that is slightly larger than one of the single rooms. Figure 2 demonstrates the process of modifying this virtual world at each stage of the walking path through the environment. Initially, the corridor and the first room of the environment are fitted within the available tracking area (State 1). When the user is inside the room, the ori-
State 1: Initially, the corridor and the first room are fitted to the tracking area.

State 2: When the user is inside the room, the direction of exit is changed and the corridor is realigned along the perimeter.

State 3: As the user transitions to the corridor, the next door is added.

State 4: As the user approaches the door, the first room is replaced by the second room.

State 5: As the user enters the second room, the first door is removed.

State 6: When the user is inside the room, the direction of exit is changed and the corridor is realigned along the perimeter.

Figure 2: A step-by-step explanation of the dynamic modifications to the virtual environment geometry. The visible area of the environment, calculated using a 45 horizontal field of view, is shown in gray. This measurement is approximately the field of view provided by the Virtual Research VR1280 head-mounted display.

entation of the door is changed, the corridor is realigned along the perimeter of the area, and the geometry of the room is adjusted to maximize the remaining usable area (State 2). Though the dimensions of the room are altered to allow space for the corridor, the overall area of the room is preserved. This transformation allows to the user to exit the room and continue down the seemingly long corridor while remaining within the boundaries of the tracking area.

The next three transformations are necessary to support the gradual transition into the next room, which lies within the same physical boundaries in the tracking area. As the user enters the hallway, the doorway to the second room is opened (State 3). As the user walks down the hallway, the geometry for the first room is replaced by the second room (State 4). When the user enters the room, the original doorway out of the room is removed (State 5). Finally, when the user is inside the second room, the orientation of the door and the geometry of the room changes again, allowing the user to proceed back out to the corridor and continue (State 6). This method can be repeated for an arbitrary number of rooms along the corridor, allowing a large environment to be represented.

3 Discussion

The strategy of dynamically modifying the environment geometry at runtime has several potential advantages over existing techniques. We believe that to provide a realistic and natural interaction, it is beneficial to maintain a direct mapping of the user’s physical position and orientation without introducing any discrepancies in translation or rotation. We also hypothesize that this technique will be less noticeable when used in tracking areas that are large enough to use real walking, but too small to easily support redirected walking without becoming perceptible to the user. As we do not yet have the data to back up these claims, we plan on conducting studies to formally evaluate this method against existing techniques.

It should be noted that this technique fails when the user chooses to skip visiting a room along the corridor or attempts to backtrack and revisit a room. In this case, a reorientation technique should be employed as suggested by Peck et al. [5]. At best, if the user follows the predicted path, no reorientations will be necessary. This technique may be more easily applied when the user’s path can be reasonably predicted, especially if cues can be given to guide the user along the intended path (such as opening and closing doors). Virtual tours are one such application which fit this constraint and may work well with this technique.

In our example, we did not directly address the question of how objects in the environment, such as tables or chairs, should be repositioned when the dimensions of the room are modified. Given that the landmarks in the environment are important for orientation, especially when altering the spatial layout, we believe that these objects should only be repositioned to preserve important conceptual relationships between them (for example, a chair to the left of the door should remain in that relative position after the door orien-
tation is switched). One potentially interesting question would be whether this technique could be combined with passive haptic feedback for objects in the environment, which has been previously explored in conjunction with redirected walking [3].

This technique introduces a number of open questions:

- To what degree are the perceptual “tricks” used by this technique noticeable to the user?
- How does this strategy influence user’s ability to spatially orient and form a cognitive map of the environment?
- How important is it to preserve landmark information when employing this technique?
- How does this technique compare against existing methods, such as redirected walking?
- What strategies can be used to automatically apply this technique to existing environment geometry?

We are currently implementing the example environment using a 224 square foot tracking area and are in the beginning stages of designing a user study to investigate some of these questions.

References


Radial Expansion and an Effect of Visual Scale on the Spatial Perception of 2D Vibrotactile Position Cues

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ABSTRACT

We summarize a newly-found effect of visual scale on perception of position for a 2D vibrotactile cue and propose this can be modeled to improve accuracy of display. In our experiment, a 2D array of vibrating motors presents a stimulus to the palm. Subjects indicate stimulus’s position under varying visual scales and presence or lack of visual reinforcement. To model apparent systematic errors, we define a radial expansion metric, roughly the radial difference in radial expansion and also show an interaction with reinforcement. We illustrate radial expansion with an error-warped stimulus grid and suggest some systematic process was responsible.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O; H.1.2 [Models and Principles]: User/Machine Systems—Human factors;

1 INTRODUCTION

This paper discusses a systematic error relevant to vibrotactile positioning cues in applications with graphical interfaces. When exploring a virtual dataset, users typically have restricted views of a wider-scoped rendering. These views may also be strewn with numerous annotations. Through these impediments, a user navigates the dataset to locate some interesting feature. If a haptic stimulus cues our user to this feature, a disparity in scale between haptic and visual stimuli can occur. We hypothesize this disparity in size and variability of visual reinforcement impact position accuracy for a vibrotactile stimulus to the palm. The resultant effects concerning visual scale show a potential for calibration. We intend to base our model for calibration on a radial error metric in which the stimulus’s radial distance and the ratio of visual to haptic scale are taken into account. This work is part of a larger study described in [3].

In his taxonomy of tactile illusions [2], Hayward discusses two instances of the mislocalization of vibrotactile stimuli. In the “funneling” illusion, placement of two vibratory stimuli is perceived as one stimulus in between the two sites. The “cutaneous rabbit,” an illusion investigated by several haptics researchers, causes several discrete stimuli to affect a continuous, traveling pulse. It is also suggested other such illusions exist, and that the research involving vibrotactile display devices contains a bounty of such knowledge.

2 METHODS

2.1 Apparatus

We used the palm-sized vibrotactile array developed by Borst et al. [1] to deliver stimuli during our experiment. Seen in Figure 1, it consisted of six rows of five DC motors. Each had a 14 mm diameter and was spaced with 18 mm separating motor centers. Thus, we refer to 18 mm as one array unit. We affixed nylon washers and foam pads to motors to isolate vibrations and allow a consistent contact for all regions of the palm.

Figure 1: The vibrotactile array used in our experiment. Six rows of five pager motors are mounted on a project box. Nylon washers and foam pads allowed consistent contact for all regions of the palm.

2.2 Design

For this experiment, we considered three Within-Groups variables: Subject, Visual Scale, and Reinforcement. Six experienced subjects with a median age of 26 years participated in the experiment. The Visual Scale had three levels: half-size (VSH), unit-size (VSU), and double-size (VSD). In the case of VSU, the size of the visual feedback matched the size of the vibrotactile display device exactly. The availability of correct answer reinforcement also varied, for the levels Without Reinforcement (WOR) and With Reinforcement (WR). For WR we visually displayed the correct stimulus position after the subject gave a response, as in Figure 2.

We also considered one Between-Groups variable, Point Type (5 levels), that indicated a stimulus’s position relative to adjacent motors. All Point Types were rendered by converting a position cue to motor intensities via area sampling, as in [1]. First, C1M denoted a point rendered on the center of one motor. The second and third cases, E2H and E2V, indicated a point between two horizontally or vertically adjacent motors, respectively. The fourth case, E4N, was equidistant to four neighboring motors. These cases are illustrated in Figure 3. We also generated a group of random points, RAN, spanning the area of interest.

2.3 Procedure

We conducted an open response experiment to investigate accuracy in locating vibrotactile position cues. Each session consisted...
Figure 2: A view of the data collection software with stimuli (red) and response (green) marker circles. A timer (top-right) was active during the stimulus, and a counter (bottom-right) informed subjects of their progress during the trials.

Figure 3: The first four Point Types. Squares represent motors and circles are stimuli. a) C1M: center of one motor. b) E2V: equidistant to two vertically adjacent motors. c) E2H: equidistant to two horizontally adjacent motors. d) E4N: between four neighboring motors.

of a Demonstration, Training, and Testing Stage. Starting in the Demonstration Phase, subjects placed their left hand on the palm and felt a series of short vibrations (each lasting two seconds). We allowed, but did not instruct, subjects to look at the hand receiving stimuli, as would be the case during real use. During Training, subjects marked the position of ten random points in a rectangle on a graphical interface, Figure 2, with the current day’s experimental condition. The Testing Stage followed with 162 points per day. Subjects rested for at least 30 seconds at the mid-point of testing. Sessions generally lasted 30-40 minutes. Over six days of testing, our subjects encountered 36 unique permutations of a point set. At least one day separated successive testing sessions of a subject.

The order of conditions (6 Subjects × 3 Visual Scales × 2 Reinforcement Levels) was randomized but adhered to the following rules. On any given day, for six subjects, we presented all six condition combinations, one per subject. The experiment presented visual levels in one order over the subject’s first three days, then the reverse order. Reinforcement levels alternated between days of testing; half the subjects started with reinforcement, half without.

Figure 4: Error magnitude against Visual Scale and Reinforcement. The large change between the last pair of error bars illustrates the interaction between Visual Scale and Reinforcement.

3 RESULTS AND DISCUSSION

3.1 Main Results

We performed an ANOVA for Repeated Measures over the 36 experimental conditions of Within-Groups variables (6 Subjects × 3 Visual Scales × 2 Reinforcement Levels) and the dependent variable error magnitude. The analysis also included a Between-Groups variable of Point Type.

Our analysis reported significant effects for each Within-Groups factor. Most notably, the Subjects exhibited significant differences ($F(4,5) = 92.57$, $p < 0.001$), as did the Visual Scales ($F(4,2) = 8.72$, $p < 0.001$). WR had less overall error than WOR ($F(4,1) = 8.43$, $p < 0.005$). The analysis also detected interactions between Visual Scale and Reinforcement ($F(4,2) = 3.51$, $p < 0.05$). For Visual Scale, Post-Hoc Tests with Bonferroni corrections showed VSH to produce less error than both VSU and VSD.

The interaction between Visual Scale and Reinforcement was evident in the last pairing of Figure 4. Recall from our results that VSH contributed less error than VSU and VSD. As Visual Scale increased, it was initially the dominant effect. Though not shown explicitly here, pooled VSU and VSD had similar error magnitudes. Once we noted this, Reinforcement showed more of an influence for VSD. This observation gave credence to our hypothesis that Visual Scale and Reinforcement affect accuracy.

3.2 Radial Error

To investigate possible systematic error in the data, we computed the mean error vector at stimulus points and warped the illustrated stimulus grid by these amounts, see Figure 5. Grid points for this illustration consisted of C1M, E2H, E2V, and E4N, resulting in a nine by eleven stimulus grid. Despite significant differences between our subjects, a general trend of expanding cells still occurred around the center of the grid. This can be visually verified by comparing areas of warped cells to those of unwarped cells. The expansion caused a general shift of neighboring cells, verified by comparing cell centers. Finally, a contraction appeared near the edges of the grid. Excluding the four corners where a pinching effect occurred, subjects marked near-edge points more toward the grid center.

We considered an error model in which our independent variable was stimulus radius, the length of a radial vector from array center to the stimulus point. We defined a radial expansion metric, radial error, as the signed magnitude of a position error vector projected onto the corresponding normalized stimulus vector. We then performed an ANOVA over this metric. Post-Hoc
Tests attributed less radial error to VSH than to VSU and VSD ($F(4, 2) = 33.136, p < 0.001$). Thus, the effect is dependent on Visual Scale, further illustrating the cross-modal perceptual illusion. In Figure 5 this change was most noticeable between levels VSH and VSU. Corresponding quadrilaterals were generally smaller in VSH near the array center. Also, VSH maintained more of the underlying, regular grid. This observation was consistent with the summary statistics and, as was the case for error magnitude, VSD experienced less radial error when paired with WR.

As a preliminary model, we approximated the relationship between radial error and stimulus radius as quadratic. Investigation of Local Linear Regression Smoothers, see Figure 6, strengthened this idea. The curves had low radial error for points near the array center, then increased to a global maximum before decreasing. These plots also demonstrated differences between Visual Scales consistent with that above. Each contained a dip after the global maximum. Occurring near a radius of 2.0 radians, the upper right portion of the array.

We have demonstrated radial expansion as a systematic effect within our experimental data. While the degree of error was found to be dependent on visual scale and visual reinforcement, it existed in every case of these variables. The effects of visual scale and reinforcement show that expansion cannot be explained solely by device features such as device-hand contact characteristics. The center and edges of the array demonstrated the lowest radial error. On the edges, and in particular the corners, subjects were restricted by the visual and haptic borders. Thus, the misjudgment of a stimulus’s radius was restrained.

The impact of radial expansion is not limited to position cues. Perceptual artifacts of radial expansion may include non-uniform speed of a point rendered across the palm. Primitives such as circles might feel asymmetric if rendered off-center, and those centered on the array might seem larger or smaller than intended. Investigating such effects will produce knowledge for improving the accuracy and communicative power of haptic displays.

**References**

Exploiting Perceptual Illusions to Enhance Passive Haptics

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ABSTRACT

Passive haptic feedback is very compelling, but a different physical object is needed for each virtual object requiring haptic feedback. I propose to enhance passive haptics by exploiting visual dominance, enabling a single physical object to provide haptic feedback for many differently shaped virtual objects. Potential applications include virtual prototyping, redirected walking, entertainment, art, and training.

KEYWORDS: Virtual environments, haptics, perception.

INDEX TERMS: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems-Artificial, augmented, and virtual realities; H.5.2 [User Interfaces]: Haptic I/O; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism-Virtual reality

1 INTRODUCTION

A major deficiency of virtual environments (VEs) is that purely virtual objects cannot be felt. The absence of haptic feedback from VEs makes interaction unnatural.

Passive haptics (physical props providing haptic feedback) significantly enhance a VE user’s experience [4]. Traditionally, passive haptics have been implemented using a one-to-one mapping between real and virtual objects. In actuality, this mapping is not strictly required. A single physical object can provide haptic feedback for multiple virtual objects of the same shape, assuming the physical object can move [8][14] or the VE can move [5][13] such that the virtual and real objects are collocated before being touched by the user.

I propose that, by exploiting visual dominance, a single physical object can provide haptic feedback for many differently shaped virtual objects.

2 THE IDEA: HAPTIC DISTORTION

Research has shown that in the presence of conflicting sensory stimuli, vision usually dominates. A subject moving her hand along a straight surface while wearing distorting glasses feels the straight surface as curved [2]. Rock and Victor asked subjects to hold an object through a cloth while viewing the same object through a distorting lens [11]. Subjects matched the test object that was most similar to the distorted visual image they saw, rather than the shape that they felt.

Such visual distortions can be introduced into VEs in a more localized manner. By distorting a virtual object’s shape or size relative to a real object, and by distorting the motion of a user’s avatar hand relative to her real hand, a user can feel a virtual object that is different from its physical counterpart.

3 BACKGROUND

Unnoticed haptic distortion is known to be feasible for some cases. Shalev demonstrated that it is possible to make a physical elastic deformable surface seem more or less elastic by changing the amount of deformation effected by a user’s hand on a virtual object [12]. Similarly, Lécuyer et al. had participants push a thumb against a piston that was in turn pushed against an isometric Spaceball™ device. Simultaneously, participants were visually shown the compression of a virtual spring. Even though the Spaceball™ did not compress, stiffness perception was influenced by the virtual spring [6].

Visual dominance is not, in general, complete. Nakahara et al. found that when mixed-reality users are presented with haptic and visual cube-shaped objects with discrepant edge curvatures, they perceive the curvature to be somewhere in between the two [9]. Helbig and Ernst showed that humans weight sensory information from multiple modalities based on reliability; more reliable signals are given more weight [3].

4 PRELIMINARY EXPLORATION

In informal pilot studies, a flat physical surface (24” x 24” on the top) was made to feel, in turn, curved, sloped, and tapered (Figure 1). The surface of the curved virtual table was a full cycle of a cosine wave with 4cm amplitude. The distortion succeeded in creating the intended illusion for three out of six participants. All participants reported that a simpler curved surface (not shown) using a 4cm amplitude sine wave in [0, π] was more effective. Virtual surfaces with 3.5- and 7.5-degree slopes were compelling to all participants, but two participants mentioned a strange feeling when presented with 14.7- and 26.2-degree slopes. Formal study is needed to determine a detection threshold.

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For haptic distortion to be effective within the context of a large-scale VE, the user must transition from the undistorted portion of the VE to interacting with distorted objects. An unnoticeable position discrepancy between the real and virtual (avatar) hands must be introduced as the real hand approaches a distorted object.

Burns, in his MACBETH technique, employed visual dominance over proprioception to address the problem of missing haptic feedback in VEs [1]. By clamping the avatar hand’s motion to virtual surfaces, he made users believe that the avatar did not penetrate virtual objects, when in fact the real hand penetrated the objects’ real space. This discrepancy between the positions of the real and avatar hands was removed over time by introducing a velocity distortion along the user’s hand motion vector. For passive haptics, the real and avatar hands must reach the real and virtual objects simultaneously. To satisfy this constraint, the direction of the user’s avatar hand motion must also be distorted.

Two types of distortion are thus required to enable a user to freely move her hand around a VE employing haptic distortion: object surface distortion, and a warping of space around distorted objects. Figure 2 shows a tapered virtual table and its associated warped space, used in a small informal pilot study. The compressed edge of the distorted table was 18” wide (75% of the physical table’s width). The space warp was constructed manually, but automatic construction is planned for future work. In this particular case, the amount of distortion fell off linearly over 2 meters in the +y direction, and over 1 meter in both the –x and +x directions. The sharpest change in direction was ~9.3 degrees. Neither pilot participant reported having detected the space warp when questioned about it, despite the abrupt changes in direction. It remains to be seen how much direction distortion is possible without detection, and whether a smooth (e.g. spline-based) space warp would be more effective for some cases.

5 DIRECTION DISCREPANCY DETECTION

It is likely that the detection thresholds for direction discrepancy are different along different egocentric directions. There are an infinite number of egocentric directions, but we may be able to assume that detection thresholds in arbitrary directions are linear combinations of thresholds in a spanning subset of component directions, as in [1]. There are also different methods of distorting avatar hand motion; it may undergo a constant distortion, a gradual curvature distortion, or an abrupt distortion (Figure 3).

The probability that detection thresholds are different implies a 3x3 series of psychophysical studies with different conditions (egocentric directions: left/right, up/down, toward/away; types of direction distortion: constant, gradual curvature, abrupt).

6 POTENTIAL APPLICATIONS

Haptic distortion has several potential applications:

- **Virtual prototyping and design** – Imagine designing and interactively changing the curved shape of a dashboard. Now imagine providing haptic feedback for all of these variations through a single, reusable physical surface. The cost of developing individual prototypes for each desired shape would be reduced. Haptic distortion would not replace traditional prototyping, but would enable rapid iteration to shrink the set of promising designs.

- **Redirected walking** – Redirected walking [10] is a promising solution to the problem of exploring a large VE in limited tracker space. It does, however, hinder the use of passive haptics because it rotates the virtual world relative to the real world. Recent efforts have introduced passive haptics into redirected walking environments with certain constraints [5][13]. By understanding how well users can detect haptic distortion, VE system builders may be able to exploit a higher error tolerance in situations where exact alignment of real and virtual objects is not convenient.

- **Entertainment** – VEs are fun to explore, particularly when virtual objects can really be touched. By using a single physical object to represent many virtual objects, users can experience a large set of haptic interactions without the need to track and maintain many physical props. Haptic distortion would enable a more varied and engaging virtual experience.

- **Precise interaction and art** – Passive haptics enable VE users to perform precise manipulations such as dragging virtual sliders or positioning virtual objects [7]. With haptic distortion, users may benefit from this precise interaction on a variety of shapes. For example, artists could paint textures on different virtual surfaces represented by a single physical object.

- **Training** – Different models of aircraft or vehicles may have slightly different control layouts. Given a single basic physical layout, a different virtual control layout could be overlaid for each model, enabling a training environment for different models while using a single physical interface.

7 CONCLUSION AND FUTURE WORK

I have presented an idea for enabling a few passive haptic objects to represent many differently shaped virtual objects. Haptic distortion has several potential applications, but its effectiveness may be limited. For virtual prototyping, haptic distortion should be conservative, so that valid potential prototypes are not rejected. Users may experience shapes that do not reflect the true nature of an intended design because of discrepancies between real and virtual objects. Training environments using haptic distortion have the potential to mislead users by giving them an unrealistic perception of their environment. Radical distortions in topology or even geometry, such as adding or removing surface edges, may be
ineffective without additional techniques (e.g., using vibrotactile feedback to add edges).

Formal study is required before any general claims about the effectiveness of haptic distortion can be made. Several avenues must be explored to determine when and how much haptic distortion can be done without user detection (given an engaging task, the detection threshold for real/virtual discrepancies may be rather high):

- **Object surface distortion** – How curved a surface can be effectively represented by a flat one? When can a flat surface be represented by a flat physical surface of different slope? Can a virtual surface with edges be represented by a physical object with fewer edges? In each case, how much visual distortion is possible without user detection?
- **Space warping** – Determine the detection threshold for distortions in hand motion direction.
- **Hand orientation** – Determine the detection threshold for distortions in hand orientation.
- **Case studies** – Evaluate haptic distortion in the context of an application scenario (e.g., prototyping or redirected walking).

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Investigating the Physiological Effects of Self-Embodiment in Stressful Virtual Environments

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1 ABSTRACT
In this paper we explore the benefits that self-embodied virtual avatars provide to a user’s sense of presence while wearing a head-mounted display in an immersive virtual environment (IVE). Recent work has shown that providing a user with a virtual avatar can increase their performance when completing tasks such as ego-centric distance judgment [5]. The results of this research imply that a heightened sense of presence is responsible for the improvement. However, there is an ambiguity in interpreting the results. Are users merely gaining additional scaling information of their environment by using the representation of their body as a metric, or is the virtual avatar heightening their sense of presence and increasing their accuracy? To investigate this question, we conducted a between-subjects design experiment to analyze any physiological differences between users given virtual avatars versus ones that were not. If the virtual avatars are increasing a user’s sense of presence, their physiological data should indicate a higher level of stress when presented with a stressful environment.

2 INTRODUCTION
Virtual reality promises to be a useful tool in 3D design, particularly in the field of architecture. It allows its users to experience and explore a modeled environment at correct scale and with proper depth cues. However, research has indicated a noticeable compression in egocentric distance perception in virtual environments while wearing an head-mounted display (HMD). Many possible factors have been explored such as graphics fidelity and HMD ergonomics, but nothing has accounted for the full discrepancy [6, 8]. Recent research by Interrante et al. suggests that a lack of presence may be the cause of this problem [1]. This hypothesis was explored further in additional work by including virtual avatars in the perception tasks, and the results showed a significant improvement [5]. The question arises, are the fully-tracked virtual avatars enhancing presence and can we design an experiment to test this?

Several studies have investigated the physiological reactions to stressful virtual environments, generally as a method for treating phobias, post-traumatic stress syndrome, and similar conditions using biofeedback as an objective tool [3, 9]. Most notably, Meehan et al. presented four studies supporting the reliability, validity, sensitivity, and objectivity of heart rate and, to a lesser extent, galvanic skin response as an objective measure of presence in IVEs [4]. Furthermore, they also found that presence measures decrease over multiple exposures to the same IVE, though not to zero, and that passive haptics cues increase presence significantly. While this research did not include the use of a fully-tracked avatar, its findings suggest the importance of including passive haptics and a limited number of exposures when designing an experiment to assess presence.

Additional research has investigated some of the possible benefits of avatars in virtual environments. One of these benefits is an increase in task performance. Lok et al. compared time to complete a task between a purely virtual environment and two different hybrid approaches [2]. The pure virtual environment involved manipulating blocks with a pinch-glove and a modeled avatar representation, while the hybrid conditions consisted of mapping real-time video from an HMD-mounted camera to grant a view of the users hands. Their study found that users performed the task better in the conditions where the users manipulated real objects, and found only a small effect of the accuracy of the avatar representation to the user. This encourages us to design a manipulation task that is natural to perform in the virtual world, and ensure a reasonable amount of faithfulness in our avatars.

3 EXPERIMENT
To investigate the feeling of presence granted by virtual self embodiment, we conducted an experiment with a between-subjects design. Physiological differences were compared between two different conditions; receiving a virtual avatar and not. Each subject encountered two exposures, the first being a high fidelity replica of the room they occupied. The second exposure altered the room to create a stressful environment, in this case, a twenty foot drop surrounding the viable tape-marked walkway. Each subject was equipped with a PromComp2 physiological monitoring device made by Thought Technology Ltd. This equipment monitored their heart beat (EKG) and galvanic skin response during the trial.

The physiological data was statistically analyzed to measure the difference in response between the two exposures for each individual participant. This difference was then compared between-subjects to see if there was a significant effect of granting one group a virtual avatar. The physiological analysis was also supplemented with a subjective presence questionnaire based on the Slater-Usoh-
Steed questionnaire [7]. The participants filled out the questionnaire following the experiment, which inquired them to rate their sense of presence in both conditions. Our hypothesis is that providing users with virtual avatars will show a significant difference in subjective and physiological measurements that is correlated to a heightened sense of presence.

We recruited 20 participants for this experiment, with 10 in each of the two conditions (avatar vs. no avatar). Using a sign advertising our experiment and its corresponding $5 dollar gift card, we were able to recruit our subjects from the sidewalk in front of our building. This gave us access to a pool of naive subjects on demand, which decreased the downtime compared to experiment scheduling. The experiment took approximately 20-30 minutes per individual.

### 3.3 Procedure

On entry to the lab, each subject was given the two piece body suit to put on over their clothing. Retro-reflective markers were properly placed on their body and the subjects were instructed to begin a capture of their range of motion. This capture involves moving each limb of the body through a scripted series of movements to aid in the automatic calibration that Vicon uses to construct a unique skeleton for the user. Once this range of motion was complete, the subjects read and signed the consent forms for the experiment while the manual phase of the Vicon calibration was conducted. After signing the consent form, the subjects were instructed to put on the heart rate monitor. This involved attaching three electrodes to their chest, and wearing the galvanic skin receptors on two fingers of their left hand. Once the subject was done suiting up for the experiment, the Vicon calibration process was typically finished and the experiment could begin.

Following calibration, the participants were guided to the starting point of the experiment which consisted of marked square in masking tape on the floor. The HMD was placed on their head while the experimenter adjusted its binding to fit comfortably. The virtual environment presented to the user was a replica of the laboratory they occupied with a chair supporting a small virtual block across the room. The virtual floor was marked off with masking tape showing a path from the user’s starting position to the chair. Roughly halfway to the chair was the set of two wooden tiles that stuck out from the path.

The users were instructed to walk down the path to the chair and pick up the virtual block. When the user reached out their right hand in close proximity to the block, an experimenter hit a key to make the block stick to their hand. Then the users turned around and carried it halfway down the path to the wooden tiles. They stepped onto the tiles and walked out until their toes hung slightly over the edge. This provided the user with haptic feedback of their current position and generated a physical disconnect from the carpeted laboratory floor. From the edge of the tile, they were instructed to look down at the numbered target on the floor and report verbally the number they saw (which was randomized each trial). This gave us confirmation that each user performed the task of looking down with their eyes open. The users then extended and shook their hand with the goal of releasing the block having it land on top of the virtual floor.
target. This dropping action was also externally controlled by an experimenter to ensure that each user got similar feedback.

This experimental procedure was repeated in a second exposure, where the virtual floor was lowered twenty feet to create a stressful environment. These two trials were conducted identically for the group of participants not receiving an avatar. Because of the lack of visual feedback, the carried block floated in space relative to where the participant’s hand was located, and they could not see their feet when stepping onto the wooden tiles (though passive haptic feedback still aided in their positioning). Following the experiment, the users filled out a presence questionnaire and were given a gift card for participation.

4 Results

At this time, the results for this experiment are not yet compiled and are withheld from this position paper.

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Transforming Perception for Virtual Reality Art

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ABSTRACT
This paper discusses non-photorealistic virtual reality artwork and designing navigational cues. Virtual reality art that does not rely on realism for visual navigation cues relies on imagination, perceptual drama and the integration of computer generated illusions with the actions of the visitor. The immersive art experience is a navigational journey that relies on visual perception and kinesthetic awareness as a means of poetic locomotion through the computer generated artwork.

KEYWORDS: Fine arts, virtual environments, multimodal perception.

INDEX TERMS: J.5 [Computer Applications]: Arts and Humanities—Fine Arts; I.2.10 [Computing Methodologies]: Vision and Scene Understanding—Perceptual Reasoning; H.5.2 [User Interfaces]: Graphical User Interfaces (GUI); D.2.2 [Design Tools and Techniques]: User Interfaces

1 INTRODUCTION
This position paper will discuss aesthetic considerations for creating virtual reality artwork and how these considerations take into account the visitor's perceptual experience in the design process. For the purpose of this paper virtual reality is defined as a stereo visual and auditory experience with visitor tracking and participation for unique projection and theater settings. An example would be a computer generated reality created for CAVE and similar CAVE-like devices [1]. The ACM Computing Classification system lists the term "virtual reality" only once and that is under "Three Dimensional Graphics and Realism" along with Factals, Radiosity and Raytracing [2].

For artists who struggle to create poetic virtual reality or virtual environments, this comes with little surprise. A poetic virtual reality or environment is defined here as an environment that employs a personal creative and artistic license to perhaps reveal philosophical observations and/or metaphorically about life in the real world. In effect, it is our everyday realism that generates artistic commentary and makes it possible to reconstruct these observations as art environments in virtual reality. The most compelling virtual art worlds do not employ pure realism but rather reference real world actions in virtual dimensions. This paper will touch on some of the real world spaces that offer models for effective perceptual illusions and how these illusions are employed in virtual environments.

The perception of real world spaces give us a location with a purpose. This in turn sets the stage for an experience which is further developed as work, play or daily maintenance. This extending these activities into virtual reality art requires perception based on visual illusions that establish more than a time and space: they set the stage for drama within a space. The staging enhances the immersive quality of the virtual environment and does not necessarily require a realistic appearance. Rather, it requires that the visitor develops a suspension of disbelief and a surrendering to the world and its navigational demands. These demands are elicited through the audio and visual components that guide the visitor through the virtual environment.

2 ENVIRONMENT AS ART
Real world environments are often designed to hold our attention and guide us towards discovery and exploration. Typical examples of such places include churches, garden parks, shopping malls, cultural attractions, theme parks and Disneyland. These types of places offer an outlet from our everyday lives and shift our attention from routine activities towards other levels of contemplation. These spaces and the structural dynamics of their activities can be guides to understanding how events can be created in virtual environments for experiential awareness and immersion.

Figure 1. Blue Window Pane II. M Dolinsky.

The virtual environment Blue Window Pane II opens in a setting that has arched doorways and windows with walls decorated in brightly colored tiles. The scene simultaneously invokes elements of churches and mosques. In the real world, places of prayer are entered with a sense of wonder and contemplation. Architecturally, they are created in an effort to shift perception from thoughts of the everyday to a different sense of place that connotes grandeur and elicits awe. Blue Window Pane II's setting is important because it situates the visitor in a main environment that is the central location. After navigating to other environments, the visitor will return here, forming a ritualistic behavior.

The liturgical references are not readily apparent in the environment because it is typically read as a place of exploration. Although the space itself is not a directly infused with religious objects, the objects act as icons throughout the space. In addition, the navigational movement is purposely slow and the sound is contemplative to match that kinesthetic experience.
The windows are guarded by tall columns that I, as the artist, refer to as the "angels of the room." When the angel columns are approached, they gesticulate and shatter in an attempt to warn the visitor away. If the visitor ignores these warnings and penetrates the colonnade barrier, the visitor will discover a change in the environment. The behavior of ignoring a warning is met with being resituated in conditions that are initially unfamiliar. The entire scene is a metaphor for psychic dilemmas. By using proximity sensors, the visitor triggers changes in the environment that causes dynamic changes which tries to transform or ignite the multimodal perceptions. Elements in the design of the environment include changes in the physical state of three dimensional objects: size, shape, color, placement and movement ware coupled with a shift in sound. In order to foster a sense of immersion, the dynamic changes in the environment are meant to exploit the anxiety and/or attention of the visitor in an effort to maintain their attention through the experience.

In a single place environment or one which does not offer other worlds to travel to, the demands on the visitor are higher. The attention is localized to one scene where various tasks are required. In an effort to allow the visitor to translate what is demanded from the environment, repetition is helpful. Stations that act similarly, for example, as teleports or sound machines can learned quickly to promote prolonged active engagement.

Beat Box presents networked CAVE visitors with a playful arena of interactive virtual sound instruments. There are three major instruments that include audio sequencers with unique periodic durations and controls. Each instrument operates similarly but sound and appear wholly different. Visitors choose from sound selections and place a sound at an interval on the instrument. In Beat Box, an instrument is depicted by a row of heads, each “singing” in turn. The graphics and sounds continually change with the resultant delivery of the collective instruments. [3] See Figure 2 and 3.

Cabinet of Dreams “Cabinet of Dreams” is a 3D virtual reality (VR) showcasing highlights of the Chinese art collection from the Indianapolis Museum of Art (IMA). Objects were recreated as 3D computer graphics and studied in inspiration towards developing virtual environments for their display. The objects range in date from 1000 BC to the mid-1800s and include wood, bronze, and earthenware ceremonial pieces as well as household items. Among them are an ink stone with mountains and a dragon, a brush pot with scenes of country pursuits, a ritual cooking vessel, a model of a wellhead, soul urns, pillows and figures including a boy with a dog.

One of the objects is a Qing dynasty cabinet made of cloisonné, glass, and zitan wood that was a gift of Mrs. George Philip Meier. The cabinet is the metaphoric center of the installation, reflected in the art and the display device as if it were a modern day Wunderkabinett. By combining the actual cabinet with the virtual dreams inspired by the real objects, computer graphic environments represent a structure of times past as well as a sense of virtual space. The real cabinet stands outside of the gallery space near the upcoming Asian galleries. Its presence hints at the collection of rarities that are hidden within the virtual environment and the museum itself.

The cabinet appears in various forms throughout all of the environments. In the main environment, it appears in its entirety to hold all of the objects that are from the Asian collection. It is surrounded by rooms which hold an abbreviated version of the cabinet.

METHODS OF TRAVEL

In the Cabinet of Dreams' main environment, many small cabinets represents separate worlds. These small cabinets can be entered for transportation to a dedicated world. The visitor quickly learns that the cabinet will take him to a new world. In each of the peripheral worlds, a fully formed cabinet without the objects on it
will return the visitor to the main environment with all of the 
objects and the options to explore any of their environments.

Blue Window Pane II's environmental design strategy of creating 
a main environment as the point of return establishes a place of 
refuge or familiarity where the visitor can in a sense reestablish 
familiarity with the virtual experience. This in turn will be a signal 
that there may be a new direction to explore. By turning and 
facing a different wall, or entering another chamber in the initial 
mosque-like setting, a new environment is revealed, and in effect, 
brought to light.

This type of main environment that offers a return refuge 
creates a non-linear and non-hierarchical movement in the virtual 
world. The design is an effort to create a stream of consciousness 
sense of navigation. Moreover, the situations ignite multimodal 
perceptual moments which are connected yet dynamically 
changing due to the actions and processes of the virtual 
environment. The resultant experience is a culmination-the virtual 
environment-working a tandem between the art, the visitor and 
the computer software and hardware. The artwork is synergistic in 
that the aesthetic elements must be decoded experientially in order 
to fully acknowledge the perceptual experience. In theology, 
synergism is the doctrine that man will work with the Holy Ghost 
to seek regeneration for the individual. Metaphorically, the visitor 
is working cooperatively with an unknowable force-the code, the 
virtual environment to regenerate a renewed sense of self.

This method of navigation has been employed in other 
environments. "Dream Grrlls" explores the non-linearity of 
dreams. It begins in a labyrinth which presents three dimensional 
objects as doorways to other dream states, by entering one of the 
objects that resembles a head or character, one is transported a 
representative dream world. In that world, when the visitor 
navigates to the horizon of the environment from the central 
location, they will exit that environment or dream state and return 
to the familiar place of the labyrinth to, in effect, "wake up".

The stairwell scene becomes a critique of social graces and 
dynamics. The scene is also ripe for pure exploration. It offers a 
number of stairwells to meet new characters, see through new 
windows and doorways, and to experience the world from a 
variety of heights. By ascending through the highest stairwell, the 
visitor is led out of the environment to return to the main starting 
area. This center stairwell is particularly difficult to navigate due 
to its sharp curve and excessive height. This tends to be a 
welcome challenge for visitors familiar with gaming devices and 
tenuous methods of navigating. There are also alternative methods 
of travel. If a visitor is adventurous enough to jump from one of 
the stairwells, flying is enabled until they enter another stairwell 
or they leave the stairwell scene. See Figure 5.

4 VISITORS' VIEWPOINTS

Typically, we train ourselves not to stare and to travel by not 
looking directly at anything for an inordinate amount of time. 
Often while we walk and drive, we hardly realize details of the 
environment or recognize people as they pass. Yet, in virtual 
environments we expect people to not only 
be aware of their 
environment but to intervene. As the visitor approaches a 
new set of 
objects, the music changes as if a new conversation is starting. 
The characters are controlled by sound activated graphics so that 
every moment in the scene/stairwell 
connection to a thoroughly odd indigenous head. Each head 
represents a distinct moment in a sequence that contributes to the 
resultant delivery of the collective instruments. As each head has a 
turn in the interval of the audio sequencer, it expands to play an 
instrument and to make a sound, giving a voice to that head and 
its musical role in the sequence's interval.

In Blue Window Pane II, groups of characters inhabit the 
scene/stairwell scene. As visitors travel the stairwells, they meet 
individual or groups of characters. Each group ignites its own 
music to fill the dance hall. As the visitor approaches a new set of 
characters, the music changes as if a new conversation is starting. 
The characters are controlled by sound activated graphics so that 
all the characters in the scene react according to what music is 
playing. The parameters of each set of objects change according to 
the characteristics of the sound. In effect, the characters 
accommodate one another's musical expression and dominance as 
the music changes by dancing to the new tune.

6 LEVELS OF ENGAGEMENT

Art environments are challenging to navigate with or without 
knowing the entire narrative behind the artists' intentions. The 
point here is that the artist must attend to design aspects of the 
environment with attention to visitors' placement and movement. 
It is a combination of artistic expression coupled with 
accommodating the visitor in an action reaction scenario. 
Attention to interactive details woven into the aesthetics are essential to an effective experience of immersion.

Virtual art transports the visitor to an alternative three-
dimensional stereo world that situates them in time and space to make decisions that help them find their way. Colors, shapes, 
textures, size and sounds – formal elements of art – establish the 
lines of navigation and construct the ambiance, which encourages 
participant movement and interaction. As the artwork is identified 
art, a relationship to the work is constructed based on judgment 
and perception. For example, when viewing a painting, the

Figure 5. Visual imagery act as navigation tools that indicate the possibilities of the environment. Blue Window Pane II. M Dolinsky.
visitor is fixed on a single moment in time with the frame frozen to a particular viewpoint. In film, which is time based, we begin to identify with certain characters and weave ourselves into the narrative. In virtual environments, we have elements of both of these activities occurring as well as movement in space, time and interaction with intention, purpose and reaction. Immersion within VR enhances with the state of presence when the environment exploits perception and the senses: visual, auditory, kinaesthetic, mental and emotional. By igniting multiple modalities at once, significant cross modal effects occur where the sensory streams interact. [4] When these sensory streams are significant, a sudden and fleeting moment of extra experience – a perceptual shift – can occur within the participant. [5] See Figure 6.

Figure 6. Design should exploit levels of engagement. Blue Window Pane II stairwell scene. M Dolinsky.

7 CONCLUSION

Virtual environments created as artwork integrate an understanding of perception and social consciousness in order to develop human-to-computer synergies. It is critical that artists attend to aesthetic elements when working and to keep the methodologies of developers and visitors in mind. Virtual reality is a technology that promotes sensory stimulation, establishes socialization and communication. There is more work to be done to learn how to exploit these environments creatively as well as technologically. Integrating the arts and communication with data and in virtual environments allows developers to dynamically experiment with creativity and innovation.

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