Walking Up and Down in Immersive Virtual Worlds: Novel Interaction Techniques Based on Visual Feedback

Category: Paper

ABSTRACT

We introduce novel interactive techniques to simulate the sensation of walking up and down in immersive virtual worlds based on visual feedback. Our method consists in modifying the motion of the virtual subjective camera while the user is really walking in an immersive virtual environment. The modification of the virtual viewpoint is a function of the variations in the height of the virtual ground. Three effects are proposed: (1) a straightforward modification of the camera's height, (2) a modification of the camera's navigation velocity, (3) a modification of the camera's orientation. They were tested in an immersive virtual reality setup in which the user is really walking. A desktop configuration where the user is seated and controls input devices was also tested and compared to the real walking configuration. Experimental results show that our visual techniques are very efficient for the simulation of two canonical shapes: bumps and holes located on the ground. Interestingly, a strong "orientation-height illusion" is found, as changes in viewing orientation produce perception of height changes (although camera's height remains strictly the same in this case). Thus, our visual effects could be applied in various virtual reality applications such as urban or architectural project reviews or training, as well as in videogames, in order to provide the sensation of walking on uneven grounds.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—evaluation/methodology, haptic I/O, input devices and strategies, interaction styles, user-centered design; H.5.1 [Information Interfaces and Presentation]: Multimedia Informations Systems—evaluation/methodology H.1.2 [Information Systems]: User/Machine Systems—human factors, human information processing

1 INTRODUCTION

Virtual Reality technologies immerse users inside a 3D synthetic world simulated in real-time by a computer. In such a virtual world, the user is given the possibility to manipulate virtual objects, and/or walk and explore virtual scenes.

Surprisingly, most current virtual reality setups restrict users to walk on flat workspaces. Whilst this might seem appropriate for walking inside virtual buildings or virtual streets, which are often flat, it becomes rapidly counter-immersive and unappropriate for any outdoor walking experience, such as when exploring a natural landscape. A main reason lies in the current difficulty to simulate, in the physical workspace, uneven grounds by means of mechanically actuated interfaces. As for today, few achievements have been reported on the design of haptic devices that can render uneven grounds such as locomotion interfaces [2, 5]. These haptic interfaces remain costly, cumbersome and difficult to spread at the moment.

In videogames, the user is generally seated and interacts through input devices. Mouse and keyboards are often used to control avatar and walk in the 3D virtual world in "first-person view". In this case, a technique commonly employed when navigating on uneven grounds consists in constraining the motion of the virtual camera to follow the terrain. The camera stays always at the same height, according to ground level. This results in a continuous change in height of the view point, as if the user was "sliding" on the virtual ground.

In this paper, we study the use of such kind of visual techniques to simulate uneven terrains and provide the sensation of walking up and down in an immersive virtual environment while walking on flat real ground. The proposed techniques use only visual feedback and consist in modifying the motion of the camera as function of the relief of virtual grounds. Three techniques are proposed: (1) a modification of the camera's height (as in videogames), (2) a modification of the camera's advance speed, (3) a modification of the camera's orientation. These techniques are implemented and tested in two different configurations. The first one is an immersive virtual reality setup in which the user is really walking while visual feedback of an Head Mounted Display (HMD) is automatically modified by superimposing one or more of the aforementionned visual effects. The second configuration is a more classical desktop setup in which user is seated and controls the 3D walking with mouse/keyboard such as in videogames. We use these two setups to evaluate the influence of the different visual effects (and their composition) within various applications. The Desktop configuration can be considered as a control population, in order to compare the use of visual techniques in an immersive situation (i.e. when the user is really walking) with a more classical desktop situation.

The remainder of the paper is organized as follows. First, the paper begins with a description of related work in the field of simulation of walking in virtual environments. Then, we describe the concept of our visual effects and how they were implemented for the simulation of two simple shapes: a bump and a hole. In the following parts, we describe the results of the experiment conducted to evaluate the efficiency of the techniques for simulating uneven terrains. The paper ends with a conclusion and a description of potential perspectives and applications.

2 RELATED WORK: FROM HAPTIC TO PSEUDO-HAPTIC WALKING INTERFACES

As of today, the simulation of the physical sensation of walking on uneven grounds has mainly been proposed through locomotion interfaces. When using these locomotion devices, the user is self-propulsed through a repetitive gait, while his motion is compensated with an inverse motion produced by the device. Hence, the interface directly controls the position of the user in the virtual world. In parallel, most of the devices try to enable natural walking. In spite of the fact that there is a significant amount of locomotion devices specifically designed for virtual reality systems and exploration of virtual worlds, most of them can only enable walking on flat surfaces, without obstacles. However, the action of walking over uneven terrain and cluttered environments is fundamental in our daily life (e.g. walking up and down the stairs), and critical on some occasions, such as when exploring outdoors environments. To date, only a few systems are capable of simulating human walking on non-flat ground.

The Sarcos Treadport [4], a treadmill with a mechanical tether attached to the back of the user, is an example of an attempt to provide a feeling of climbing slopes. Originally, the mechanical tether was used to compensate missing inertial forces and to simulate obstacles in the virtual path by applying forces on the user's torso. The concept was then extended so that the tether could also render the forces required to simulate a slope [3, 2]. A force on the opposite direction of motion was used when simulating walking uphill, with a magnitude equal to the horizontal component of the force in the real world case, and, analogously, a force was applied on the direction of motion when going downhill. Simulation of side slopes were also possible when applying lateral forces.

Leaving the kinesthetic simulation and entering the haptic realm, the ATLAS [8] treadmill, mounted on an actuated spherical joint, was able to provide slopes by allowing the pitching and rolling of the platform. With a different approach, the Groud Surface Simulator GSS [9] was able to simulate uneven terrain through a linear treadmill with a deformable belt. Six long platforms could locally raise the belt, allowing the display of small bumps up to 5° in slope. The Sarcos Biport and the GaitMaster [5], both made of foot motion platforms, could simulate uneven terrains but not inclined floors.

While these devices offer uneven terrain rendering to some extent, they all suffer from common limitations that restrict their widespread use, such as their huge size and weight, their cost or their lack of accuracy and degrees of freedom. Therefore, they have not yet been widely adopted outside the laboratory. Other smaller, less complex and more affordable locomotion devices exist that enable locomotion following the same motion compensation principle. Foot-wearable devices like the Powered-Shoes [6] and, more recently, the Gait Enhancing Mobile Shoe [1], compensate the user's motion without being attached to a bulky structure. However, they cannot render slopes or any kind of uneven terrain.

In order to simulate haptic sensations without haptic interfaces, other solutions have thus been proposed such as sensory substitution and pseudo-haptic feedback. Pseudo-haptic feedback was studied mainly through the perceptual evaluation conducted on the modification of the speed of a mouse cursor according to the "height" of a texture [7]. As the mouse cursor explored an image representing a top view of a texture, an acceleration (or deceleration) of the cursor indicated a negative (or positive) slope of the texture. Experimental evaluations showed that participants could successfully identify macroscopic textures such as bumps and holes, by simply using the variations of the motion of the cursor.

In some "first-person view" videogames, the camera velocity is progressively scaled up or down whether the avatar is going up or down a hill, providing a slope information. This effect could be considered as a straight transposition of the aforementioned pseudo-haptic texture. However, to the authors' best knowledge there has been no study of the influence of such visual effects on the user's perception of heights and slopes in virtual environments, and these effects have never been implemented within an immersive VR setup when walking.

3 Novel Interactions Techniques Based on Visual Feedback

3.1 Concept of the Interaction Techniques

The objective of the interaction techniques is to reproduce the sensation of walking on an uneven ground without the use of any haptic or locomotion interface. The main idea consists in modifying the motion of the subjective camera while the user is walking in the virtual environment. The concept is to control the camera position and orientation, depending on the uneven virtual terrain displayed either on the screen or on a Head-Mounted Display (HMD). The camera motion is adjusted in function of the simulated height of the terrain on which the user is walking. The variations of the camera motion are used here to transpose the perception of climbing or descending a slope.

Three different types of modifications to the camera motion have been studied: height variation, orientation variation and velocity variation. The amount in the different effects is computed using the height information of the 3D virtual environment. Thus, the technique can be used to simulate any uneven 3D terrain, assuming that we know its height map. The implemented algorithm computes an iterative solution (depending on the user motion) for the modification of the camera motion. When the user is moving in the virtual environment, a theoretical displacement is measured and the amount of the camera motion is computed using this measurement. Then, the new position of the user is computed and transmitted to the camera position and/or orientation. The visual techniques described here recall the ones used in videogames. However, unlike most gaming situations, our intention is to use them when the user is actually walking, i.e. superimposed to the visual feedback of the real virtual scene.

3.2 Implementation

The three different effects (Height, Orientation, Velocity) are displayed in Figure 1. The combination of the three effects was also implemented.

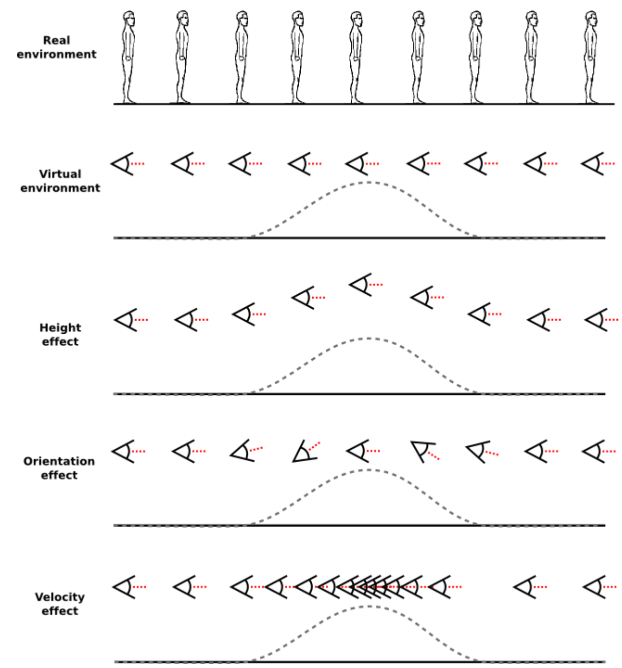


Figure 1: Principle of the three different effects: the user is walking on a flat environment while the virtual environment is composed of a bump. The camera motion is modified in three different ways: height variation (the camera moves parallel to the slope), orientation variation (the camera is oriented following the curvature of the slope), velocity variation (the camera velocity decreases as the user is going up a virtual bump and increases as the user is going down with a run up at the end of the bump).

3.2.1 Height Variation

The height effect consists in modifying the subjective camera height with a translation along the vertical axis. This effect allows the user to move parallel to the ground surface during his navigation in the virtual world. The height variates following the equation:

$$\text{Height}^t = \text{Height}^{t-1} + \Delta_{\text{Height}} \,.\, R_{\text{Height}} \quad (1)$$

where Height^t represents the camera height value at time t where the image is updated. R_{Height} is the ratio applied to the difference of height Δ_{Height} between times $t-1$ and t. In our experiment, we chose $R_{\text{Height}} = 0.5$.

3.2.2 Orientation Variation

The orientation effect consists in applying a variation in pitch angle to the subjective camera in order to look down when descending and up when ascending. This effect is supposed to mimick postural changes when walking on uneven grounds. The camera angle at time t, Angle^t, is proportional to the tangent angle of the Gaussian curve α^t where the user is at time t:

$$\text{Angle}^t = \alpha^t \,.\, R_{\text{Orientation}} \quad (2)$$

where $R_{\text{Orientation}}$ is the ratio applied to the angle. In our experiment, we chose $R_{\text{Orientation}} = 0.5$.

3.2.3 Velocity Variation

The velocity effect is based on the variation of the camera velocity. In a real environment, a subject is generally going slower on ascending slopes, and faster on descending slopes. We try to translate this effect in our experiment by modifying the camera motion when the user is walking in a virtual environment. Thus, the camera velocity is decreased when the user is going up and increased when the user is going down. This effect could be considered as a straightforward transposition of the pseudo-haptic textures effect [7], adapted here to the simulation of walking on uneven reliefs at a first-person view. We used a different algorithm for the ascending and descending cases. The algorithms compute the ratio R_{Velocity} applied between the real user velocity and the virtual camera velocity. The camera velocity is then modified following the equation:

$$\text{Velocity}^t = \text{Velocity}^{t-1} \,.\, R^t_{\text{Velocity}} \quad (3)$$

- Ascending case:

  $$R^t_{\text{Velocity}} = exp(-R_{\text{AscendingV}} \,.\, \alpha^t) \quad (4)$$

  where α is the tangent angle of the Gaussian curve and $R_{\text{AscendingV}} = 0.1$ in our experiments.

- Descending case:
  This algorithm is designed to give a run up for a while after the bump or at the beginning of the hole. At time t, the ratio is updated regarding the difference between the user height in scene at times $t-1$ and t :

  $$R^t_{\text{Velocity}} = R^{t-1}_{\text{Velocity}} + \Delta_{\text{Height}} \,.\, R_{\text{DescendingV}} \quad (5)$$

  where the ratio $R_{\text{DescendingV}}$ is equal to 2.0 in our experiments. When the subject reaches the end of the descent, his speed is at a maximum. If he is walking in a hole, then he starts to go up and his speed value will be given by the ascending algorithm. If the subject is on a bump, he will reach the plane ground after the bump. His speed ratio R_{Velocity} will start decreasing at 0.1 unit per second, until another bump/hole is reached or the ratio is back to normal.

3.3 Simulating Bumps and Holes

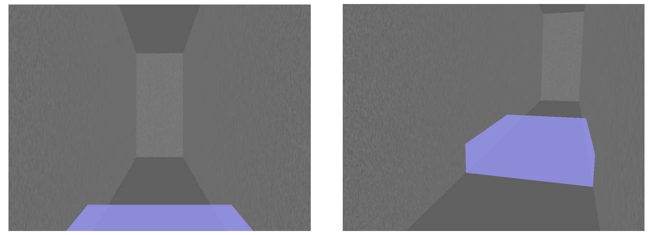
Our visual techniques were used to simulate two classical shapes: a bump and a hole. Our simulations used a known mathematical profile: a Gaussian profile, which defines the height maps of the shapes during the evaluations. It corresponds to a mathematical distribution of heights along a line perpendicular to the walking path. The same profile was used for the simulations of holes and bumps.

4 EVALUATION

The investigation of the perception of 3D holes and bumps while walking in a virtual environment was performed using an experimental protocol consisting of a comparison of the different effects. The experiments were conducted using 3D virtual environments displayed either on a HMD or on a screen.

4.1 Virtual Environment Description

The virtual environment is a simple corridor with given dimensions (height=3.0m, length=19.0m, width=2.0m). There is a part in the center of the corridor where the height can be modified during the experiments: the user can walk either on a bump, a hole or a plane. To symbolize this variable part of the corridor, a transparent cube is represented on the ground with a height of $0.5m$ and a bump/hole/plane surface of $3m \times 2m$, as illustrated in Figure 2. The variable height of the ground is not visible in order to exclude visual context cues from the scene.



(a) (b)

Figure 2: (a) Description of the virtual environment composed of a corridor; (b) a transparent blue cube is placed in the center in order to represent to the participant the location of the height modifications on the ground surface.

4.2 Population and Visual Conditions

4.2.1 Group 1: Immersive VR Configuration with HMD

Twelve participants (4 females and 8 males) aged from 21 to 59 (mean=28.7, SD=11.0) were in Group 1 and exposed to a first visual condition. One of them was left-handed, and none of them had known perception disorders. They were all naïve to the purpose of the experiment.

For this group, the experiments were conducted in an immersive room large enough to walk straight forward 6 meters. We used the eMagin Z800 Head Mounted Display as display device, at 60 Hz and with stereoscopy enabled. The user was wearing an opaque fabric on top of the HMD to hide the surrounding real world. An unique wire was transmitting the data, allowing the user to move freely during the experiments, as illustrated in Figure 3. The user's head was tracked by an ART ARTtrack2 infrared tracking system with 9 surrounding cameras for tracking the entire path of the experiment (corresponding to the virtual corridor). The available tracking space dimensions were: height=2.5m, length=6m, width=3m.

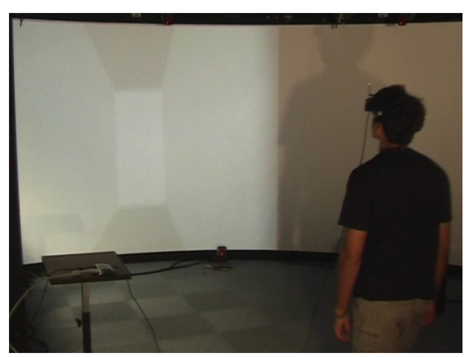


Figure 3: Configuration of the immersive room for the experiments using the HMD. The scene displayed on the HMD is also displayed on the screen in this picture as an illustration of what the user can see during the experiments.

4.2.2 Group 2: Desktop Configuration with Monitor Screen

Twelve participants (12 males) aged from 21 to 59 (mean=27.8, SD=6.1) were in Group 2 and exposed to a second visual condition. The twelve participants were all different from participants of Group 1. One of them was left-handed, and none of them had known perception disorders. They were all naïve to the purpose of the experiment and they were different from the experiments conducted with a HMD.

For this group, the experiments were conducted with a PC, by using a classical keyboard for the answers. There was no stereoscopic effect and the experiment room was without any additional environment information. This second group can be considered as a control population, to compare the use of visual techniques in an immersive configuration, i.e. when the user is really walking, with the more classical desktop case.

4.3 Experiment: Efficiency of Visual Effects to Simulate Bumps and Holes

4.3.1 Experimental Plan

In the experiment, our goal was to evaluate and compare the three different effects (Height, Orientation and Velocity) for the simulation of two canonical shapes: bumps and holes located on the surface ground of an immersive virtual environment. We also evaluated a fourth effect which is a combination of the three effects. We used:

- three different *profiles*: Bump, Hole and Plane;
- two different types of walking locomotion: Forward and Backward *movements*;
- four visual *effects*: Height (H), Orientation (0), Velocity (V) and a combination of the three last effects (HOV).

The experimental plan was made of the combinations [Profile x Movements] x 9 trials, for each effect (54 trials per effect). The subject alternates Forward and Backward movements, within a random sequence of the [Bump, Hole, Plane] x [Forward, Backward] = 6 combinations. The 4 series (one for each effect) are presented using a Latin square and a defined sequence [H-O-V-HOV], counterbalanced with 4 sub-groups. The 12 participants of each Group (Group 1 with HMD and 2 with PC) were thus equally divided into 4 sub-groups of 3 people each. The order in the sequence had no significative effect on the results.

The motivation for testing backward movements relies on the fact that gait postures of human bodies are generally different when moving forward or backward on a slope. Thus, our hypothesis was that backward movements could potentially lead to different physical sensations for our visual effects.

4.3.2 Procedure

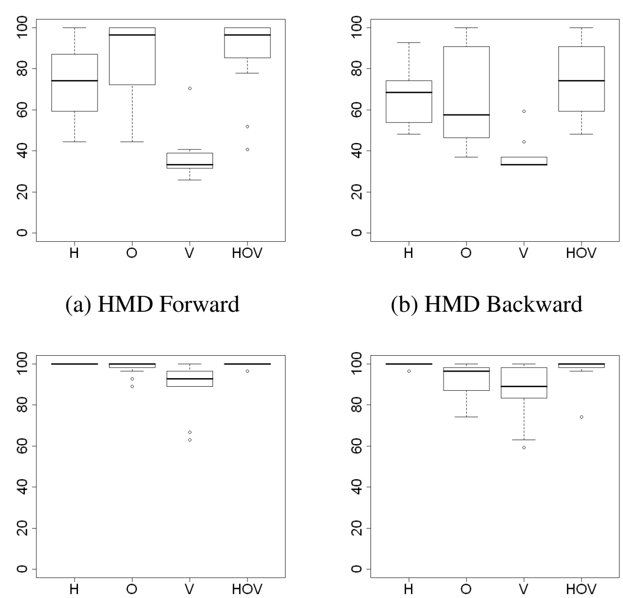
The experiment consists of 216 trials per participant (54 per effect). The subject has to go forward and then backward in the virtual corridor. At the end of each movement (either forward or backward), a black screen appears (either on the HMD or on the screen) and the participant can give his answer concerning the identified shape (hole, bump, or plane).

4.3.3 Results

For each participant, the percentage of correct answers was estimated for the different experimental conditions. An ANOVA on the 4 different effects was conducted on the percentage of correct answers. ANOVA were performed separately for the two experimental configurations (HMD and Desktop) and by differenciating Forward and Backward movements. The results concerning the different effects are represented in Figure 4 for the HMD and the Desktop configurations. Results concerning Forward and Backward movements are distinguished for each group, as they gave different values.

In the following paragraph, we present the results obtained for the four different configurations as a combination of HMD and Desktop groups, Forward and Backward movements. The ANOVA accounting for the four different effects revealed a significant dependency between the effect and the probability of giving a correct answer for all the configurations.

For the Forward movement performed with the HMD configuration, the ANOVA performed between the four different effects revealed significant results for the Effect ($F(3,11) = 19.447$, $p < 0.0001$). Restricting the ANOVA to only three modes for the Effect (Height, Orientation and the Sum of the effects) did not show any significance: $F(2,11) = 1.5665$, $p = 0.224$, which argues in favor of a difference between the Velocity effect and the three other effects. This observation is confirmed by pairwise analyse. t tests performed between pairs of effects revealed also significant differences: the percentage of correct responses in the Height ($M = 73\%$) condition was significantly higher than in the Velocity ($M = 37\%$) condition, $t = 5.95$, $p < 0.0001$; the percentage of correct responses in the Orientation ($M = 85\%$) condition was significantly higher than in the Velocity condition, $t = 6.75$, $p < 0.0001$; and the percentage of correct responses in the Sum of the effects ($M = 87\%$) condition was significantly higher than in theVelocity conditions, $t = -7.52$, $p < 0.0001$. No significant difference was found between the other pairs of effects.



(a) HMD Forward

(b) HMD Backward

(c) Desktop Forward

(d) Desktop Backward

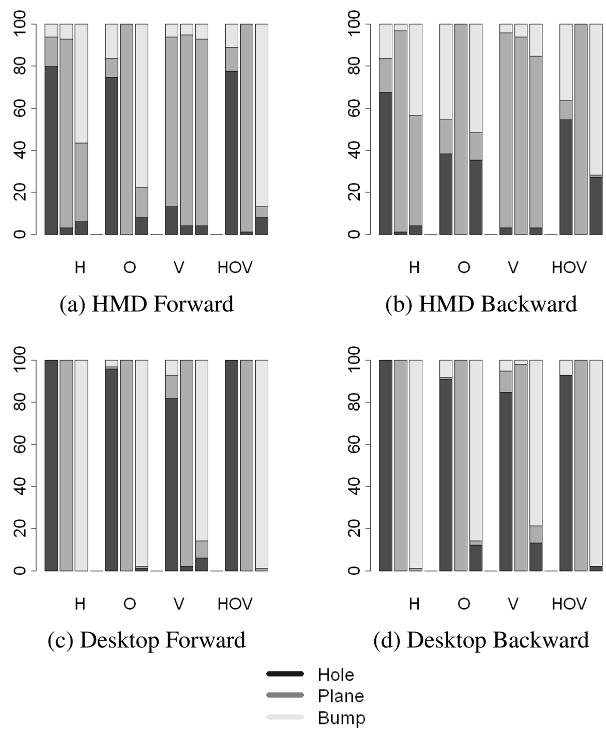
Figure 4: Results: Percentage of correct answers for HMD configuration ((a) and (b) boxplots) or Desktop configuration ((c) and (d) boxplots). (a) and (c) represent the results for Forward movements, (b) and (d) represent the results for Backward movements. The 4 different effects are represented on each picture: Height (H), Orientation (O), Velocity (V) and the combination of the three previous effects (HOV). Each boxplot is delimited by the quartile (25% quantile and 75% quantile) of the distribution of the effect over the individuals. The median is also represented for each effect.

For the Backward movement performed with the HMD configuration, the ANOVA performed between the four different effects revealed significant results for the Effect ($F(3,11) = 11.646$,

$p < 0.0001$). The ANOVA performed between Height, Orientation and the Sum of the effects did not reveal any significative effect: $F(2,11) = 0.9093$, $p = 0.4126$. t tests performed between pairs of effects revealed also significant differences: the percentage of correct responses in the Height ($M = 67\%$) condition was significantly higher than in the Velocity ($M = 37\%$) condition, $t = 16.65$, $p < 0.0001$; the percentage of correct responses in the Orientation ($M = 65\%$) condition was significantly higher than in the Velocity condition, $t = 3.95$, $p = 0.0016$; and the percentage of correct responses in the Sum of the effects ($M = 75\%$) condition was significantly higher than in the Velocity conditions, $t = -6.84$, $p < 0.0001$. No significant difference was found between the other pairs of effects.

For the Forward movement performed with the Desktop configuration, the ANOVA performed between the four different effects revealed significant results for the Effect ($F(3,11) = 7.77$, $p = 0.0003$). The percentages of correct responses in the Height condition ($M = 100\%$), the Velocity condition ($M = 89\%$), the Orientation condition ($M = 98\%$) and the Sum of the effects condition ($M = 99\%$) did not have any significant difference when we performed t tests between the different pairs.

For the Backward movement performed with the Desktop configuration, the ANOVA revealed significant results for the Effect ($F(3,11) = 11.646$, $p < 0.0001$). The percentages of correct responses in the Height condition ($M = 99\%$), the Velocity condition ($M = 87\%$), the Orientation condition ($M = 92\%$) and the Sum of the effects condition ($M = 97\%$) did not have any significant difference when we performed t tests between the different pairs.



(a) HMD Forward

(b) HMD Backward

(c) Desktop Forward

(d) Desktop Backward

Figure 5: Results: Percentage of correct answers. Results are given for the 4 effects and the 3 different shapes (Hole, Plane and Bump in this order). The percentage of correct answers is decomposed for each shape, additionally with the incorrect shapes identified for each shape. The Forward and Backward movements are distinguished.

At first glance, regarding the percentage of correct answers for the different effects, it seems that the sensation of bumps and holes was identified among the participants. HMD and Desktop configurations give relatively different results. The Velocity effect with Desktop configuration gives namely higher percentages of correct responses compared to HMD configuration. On the other hand, the Velocity effect is significantly different from other effects only for HMD configuration. Forward and Backward movements are distinguished for both configurations. Experiments conducted with a HMD and Backward movement globally obtained lower results compared to the experiments conducted with the same experimental configuration but with Forward movements. We can particularly notice the lower results for the two effects containing the Orientation effect (O and HOV).

For HMD group, we can also notice the presence of two individuals (represented by individuals dots on Figure 4.a and 4.b). These two individuals have obtained lower percentages of correct answers for the HOV effect and higher percentages for the Velocity effect, compared to the rest of the population, and could be considered as outlayers.

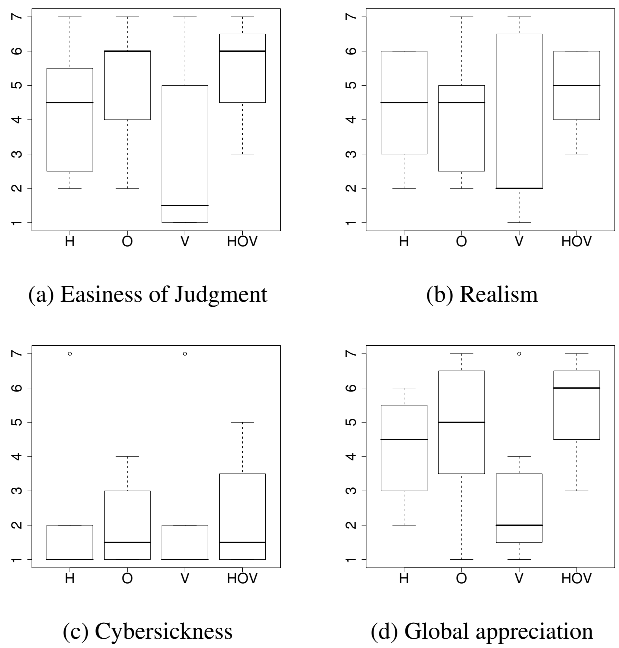
We conducted also an analysis concerning the percentage of correct answers for the different shapes identified (i.e. Hole, Plane and Bump). The results are reported in Figure 5 for HMD and Desktop configurations, and detailed for Forward and Backward movements. Experiments conducted with HMD contain a higher number of incorrect answers: interestingly, the higher number of incorrect answers for each effect are Plane shape for Height effect, Bump/Hole shape for Orientation and HOV effects. Thus, the Orientation effect seems to have an influence on the shape perception. For Velocity effect with HMD configuration, almost all answers are incorrect: Plane shape solution is almost always chosen, meaning that holes and bumps are almost never detected. On the opposite side, shapes with Velocity effect on Desktop configuration are well recognized. Thus, velocity effect in an immersive situation leads to significantly different results, as observed also in Figure 4. Concerning backward movements with HMD configuration, we can notice that the percentage of incorrect answers is higher than for forward movements, for Height, Orientation and HOV effects.

4.4 Subjective Questionnaire

After both experiments, a preference questionnaire was proposed in which participants had to grade from 1 (low appreciation) to 7 (high appreciation) the four different effects (H, O, V, HOV) according to 4 subjective criteria: easiness of judgment, realism, cybersickness and global appreciation. Figures 6 and 7 show the results concerning the grades obtained by the four different effects for each of the subjective criteria, for HMD and Desktop configurations.

Ordinal data, as obtained from the questionnaire, suggest the use of a Friedman test which is based on rank statistics. However, in our context, the high number of modalities (7 grades) and the low number of individuals (12) tend to decrease drastically the power of a Friedman test. As the number of modalities is high, we assume data to be normally distributed and perform a more traditional ANOVA test to compare the four types of algorithm. Thus, an ANOVA on the 4 different effects was conducted on the grade of each criterion. ANOVA were peformed separately for the two experimental configurations. The ANOVA accounting for the four different effects revealed no significant dependency between the effect and the grading value for Realism ($F(3,11) = 1.30$, $p = 0.28$) and Cybersickness ($F(3,11) = 0.17$, $p = 0.91$) for HMD experiments.

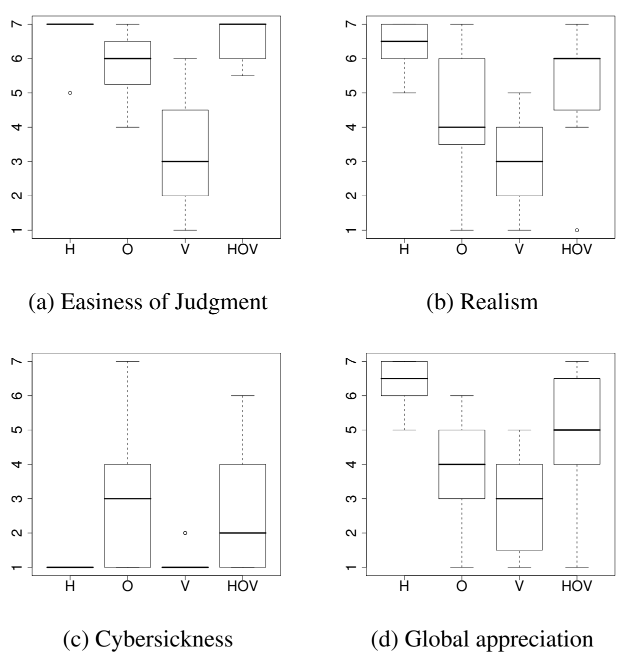
Concerning global appreciation, the ANOVA performed between the four different effects revealed significant results for the Effect for both configurations ($F(3,11) = 13.27$, $p < 0.0001$ for Desktop configuration, $F(3,11) = 6.9$, $p < 0.0001$ for HMD configuration). The HOV effect obtains the best global appreciation for HMD experiments, followed by Orientation and Height effects. Restricting the ANOVA to only three modes for the Effect (Height, Orientation and the Sum of the effects) for HMD experiments did not show any



(a) Easiness of Judgment (b) Realism

(c) Cybersickness (d) Global appreciation

Figure 6: Results for subjective ratings about the different criteria for the four effects for HMD experiments: each boxplot is delimited by the quartile (25% quantile and 75% quantile) of the distribution of the effect over the individuals. The median is also represented for each effect. The 4 different effects are represented on each picture: Height (H), Orientation (O), Velocity (V) and the combination of the three previous effects (HOV).



(a) Easiness of Judgment (b) Realism

(c) Cybersickness (d) Global appreciation

Figure 7: Results for subjective ratings about the different criteria for the four effects for Desktop experiments: each boxplot is delimited by the quartile (25% quantile and 75% quantile) of the distribution of the effect over the individuals. The median is also represented for each effect. The 4 different effects are represented on each picture: Height (H), Orientation (O), Velocity (V) and the combination of the three previous effects (HOV).

significance: $F(2,11) = 2.01$, $p = 0.15$, which argues in favor of a difference between the Velocity effect and the three other effects.

Concerning global appreciation, an ANOVA was also performed between the two configurations for each effect and revealed significant results only for Height technique ($F(1,11) = 18.531$, $p < 0.001$). Indeed, Height technique was less appreciated in HMD experiment. On the contrary, the other techniques were better accepted and fairly evaluated for HMD configuration.

Concerning Easiness of Judgment criterion, the ANOVA performed between the four different effects revealed significant results for the Effect for both configurations ($F(3,11) = 30.1$, $p < 0.0001$ for Desktop configuration, $F(3,11) = 4.53$, $p < 0.001$ for HMD configuration). Restricting the ANOVA to only three modes for the Effect (Height, Orientation and the Sum of the effects) for HMD experiments did not show any significance: $F(2,11) = 2.12$, $p = 0.14$, which argues in favor of a difference between the Velocity effect and the three other effects, like for global appreciation.

Concerning Cybersickness and Realism criteria, the ANOVA performed between the four different effects revealed significant results for the Effect only for Desktop configurations ($F(3,11) = 6.56$, $p < 0.0001$ for Cybersickness, $F(3,11) = 14.6$, $p < 0.0001$ for Realism). For Cybersickness criterion, only the ANOVA restricted to two modes with one including the Orientation effect (the Orientation effect alone or combined to the other effects) gives significant results, arguing in favor of the exaggerated perceptions of the Orientation for Desktop experiments due to parameter values (the different ratios explained in section 3), which seem to play a key role in the subjective appreciation of the participants.

Participants were also asked to evaluate the height of the shapes (Bump or Holes) of the experiments. Means and standard deviations of the participant answers are given in table 1 for HMD configuration and in table 2 for Desktop configuration. The real height of the Bump/Hole was 1.0 meter, with a ratio coefficient equal to 0.5 for Height, Orientation and Combination effects.

	H	O	V	HOV
Bump	0.32 (0.28)	0.79 (0.56)	0.06 (0.15)	0.68 (0.45)
Hole	-0.3 (0.32)	-0.77 (0.55)	-0.05 (0.12)	-0.59 (0.40)

Table 1: Means and standard deviations (in brackets) of the heights (in meters) given by the participants to holes and bumps for HMD configuration experiments. The four different effects (H, O, V, HOV) are distinguished.

	H	O	V	HOV
Bump	0.59 (0.52)	0.97 (0.54)	0.42 (0.46)	1.32 (1.12)
Hole	-0.58 (0.52)	-0.99 (0.53)	-0.42 (0.46)	-1.28 (1.10)

Table 2: Means and standard deviations (in brackets) of the heights (in meters) given by the participants to holes and bumps for Desktop configuration experiments. The four different effects (H, O, V, HOV) are distinguished.

The estimated values are globally lower for HMD configuration. Interestingly, participants gave the Orientation effect the highest height for HMD configuration. The Orientation effect is always evaluated with an over-estimation of the correct height, although there is no variation in the camera height. The height values are under-estimated for Height effect for HMD configuration but slightly under-estimated for Desktop configuration. For Desktop configuration, the highest height is given to the experiments conducted with the HOV effect. For HMD configuration, the Velocity effect conducts to a height value near to zero, but it is not the case for the Desktop configuration where the evaluation is better, as already observed in the results in Figures 4 and 5.

5 General Discussion

At first glance, results show that slope presence was identified for some of the effects in the immersive configuration. The slope appreciation greatly varies according to the experimental setup, and in a lesser way according to the motion direction. When immersed in a virtual environment with an HMD setup, it appears that users do not perceive any change in height when subject to the Velocity effect. Hence, one could think that the direct transposition of the pseudo-haptic effect from the 2D to the 3D realm does not provide the expected visual cues in an immersive configuration. Thus, when using the non-immersive desktop setup, the same Velocity effect, although not as efficient as the others, yields much better results than in the immersive setup, reaching up to an almost perfect score. A possible explanation for this behaviour might be related to the optical flow of the virtual scene. In the immersive setup, the walls of the corridor were situated at the sides of the user's field of view due to the use of an HMD, while in the desktop setup the entire display was largely contained in the field of view. Hence, the optical flow visible on the walls had a greater effect in the desktop setup. The Velocity effect might produce better results with a different virtual scene.

The Height and the Orientation effects yielded positive results in an immersive configuration. Users clearly felt a change in height, and could distinguish in most of the cases whether it was a bump or a slope. In the forward case for the immersive setup, the Orientation effect shows better results than the Height effect. Although there was no change in height, users were able to perceive it more accurately than in trials where the height itself changed. The success and the accuracy of the Orientation effect was confirmed with the subjective questionnaire since users had no trouble in drawing the outline of the shapes they encountered during the experiments. When estimating the height of these shapes, results were not so far from real heights. Interestingly, the sum of the effects did not give better results than one effect taken alone for HMD configuration. However, the HOV effect was more appreciated in the subjective questionnaire for the immersive situation.

On the other hand, Height technique was less appreciated in HMD experiments. A possible explanation might be that users, particularly gamers and people familiar with navigation in VR, are used to see camera height variations when navigating in virtual uneven terrains in desktop environments. The Height effect is used in every desktop simulation involving slopes and landscapes. They have rarely or never been exposed to the other effects. Hence, they find the Height effect more natural and more appreciated. However, these same users have obviously spent less time in immersive simulations, and might not be used to the conditions of an immersive setup. Consequently, they are less trained for the Height effect under these conditions and did not perceive any "real inclines/declines" sensations. Hence, the other techniques were better accepted and fairly evaluated for the immersive configuration.

As planned in our working hypothesis, backward and forward movements led to different results. The different shapes were less identified for backward movements in an immersive configuration. A reason for this difference between the two directions of walking locomotions might be the tuning of the different parameters, namely when Orientation effect is used.

Indeed, parameters of the different effects play a key role for letting the participant identify a bump or a hole. We chose to tune the parameters of our different effects based on the HMD configuration. This choice leads us to non-optimized parameters for Desktop configuration, explaining some differences in the results and subjective questionnaires (namely for the Orientation effect which parameter was too high for Desktop configuration). The choice of our parameter values was arbitrary but could be based on more sophisticated models or on the application objectives. Although a very simple and straightforward implementation of the orientation motion was enough to achieve a good performance with the Orientation effect, other models closer to real life motions and gaits might improve these results. The physically-based model of an avatar representing the user in the virtual world, coupled to the motion of the user in the real world, might provide changes in head orientation, and hence in camera orientation, that are closer to what the user expects. The use of real data on head orientation of users walking up and down on slopes could also be an alternative solution to tune the camera parameters. To conclude, a higher degree of realism, something actually critisized by many users as shown in the subjective questionnaire results, might improve the efficiency of the Orientation effect.

6 Conclusion and Perspectives

In this paper, we introduced novel interactive techniques to simulate the sensation of walking up and down in immersive virtual worlds based on visual feedback. Our method consists in modifying the motion of the virtual subjective camera as function of the variations in the height of the ground. This method has been widely used for deskop applications for videogames for example but never explored for providing real relief sensation when walking in an immersive virtual environment. In this paper, three effects were proposed: (1) a straightforward modification of the camera's height, (2) a modification of the camera's navigation velocity, (3) a modification of the camera's orientation. They were tested in an immersive virtual reality setup in which the user is really walking. A desktop configuration where the user is seated and controls input devices was also used to compare the results.

The experiments were conducted to evaluate the influence of our visual techniques for the perception of simple and canonical shapes: virtual bumps and holes located on the ground. Experiments showed that changes in height and orientation of the camera are indeed very efficient effects in an immersive configuration. On the contrary, the speed effect seems to be not well perceived. Interestingly, in the immersive configuration, the consistent combination of all visual effects together led to the best results (although this result was not found significant) and was thus subjectively preferred by the participants. Experiments suggest also a strong perception of height changes caused by the orientation effect (although camera's height remains strictly the same in this case). This is confirmed by subjective questionnaire in which participants estimated a higher amplitude for bumps and holes simulated with orientation technique. This "orientation-height illusion" opens challenging questions in terms of human perception and challenges our interpretations.

One of our objective was also to obtain real posture modifications of the user when he is walking on virtual inclines/declines in an immersive world. Some head movements have already been observed during the experiments and further experiments are planned to measure with accuracy the posture (and especially the head position) modifications when the visual effects are superimposed to a virtual scene.

Taken together, our results suggest that our visual techniques could be applied in an immersive virtual environment to simulate the sensation of walking on uneven surfaces. Our techniques could be used in various applications of virtual reality such as for urban and architectural reviews or training, as well as in videogames in an immersive configuration.

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