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# NIW
# Natural Interactive Walking

# Deliverable 5.1

# Assessment of multi-modal and pseudo-haptic ground cues from augmented floors

**A. Lécuyer, M. Marchal, G. Cirio, T. Regia-Corte, L. Terziman, L. Bonnet (INRIA)**
**Y. Visell, G. Millet, J. Cooperstock (McGill)**
**V. Hayward, N. Ouarti (UPMC)**
**F. Fontana (UNIUD), S. Papetti, M. Civolani (UNIVR)**
**S. Serafin, L. Turchet, R. Nordahl (AAU)**

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# Contents

# 1. Introduction

This document is the report and main deliverable of work-package N°5 of NIW European Project. This Work-Package (WP) is entitled "**Pseudo-haptics and perceptual evaluations**". It focuses on two main aspects: (1) **designing** novel "pseudo-haptic" cues for ground feedback simulation, and (2) **evaluating** the various technologies developed in the NIW project.

As a recall and reference to the technical Annex of NIW project (page 32), the main objectives of WP5 are: "*to select a coherent and compact corpus of experiments; To evaluate augmented floors and virtual ground attributes displayed using different (auditory, haptic, visual) modalities and their combinations; To iteratively develop pseudo-haptic techniques using a perception-based and user-centered approach; And to perform experimental tasks with different categories of real and simulated surface materials as well as simulated feet-floor contact events*".

The method that we have adopted in the WP5 to address all these objectives is iterative and progressive, i.e., from low-level evaluations of technological developments, to high-level psychological studies about ground perception.

First, we have studied and evaluated individually the technologies developed in the project, i.e., the **uni-modal ground cues** (visual, haptic, and auditory) developed by the five different partners of the project. In parallel, we have more specifically studied the design of **pseudo-haptic ground cues** which involve visual feedback to distort the perception of ground properties when walking in virtual environments. Then, we have worked in close collaboration to associate progressively the different cues together. We have thus studied the subsequent **multi-modal combinations** of all the sensory cues together (visual+haptic, visual+auditory, haptic+auditory). This led to an intense activity, with lots of collaborations and exchanges between the partners to associate, assemble, and combine the elementary technologies together, and define and achieve the corresponding evaluations. Last, we have also initiated a complementary high-level study of perception of **affordances of virtual grounds**, which seems to be a promising and different psychological approach for the design and evaluation of ground cues in virtual reality.

In this document, we will present the results of all these efforts. We will describe the main results obtained for all these four steps, by successively addressing: (1) the study of uni-modal ground cues, (2) the study of pseudo-haptic ground cues, (3) the study of multi-modal ground cues, and (4) the study of affordances of virtual ground. For space constraints, and for readability reasons, the results will be presented in a summarized manner. Complementary materials can be found listed in Annex. This corresponds to all the papers and documents published about these experiments by the partners. These additional materials can be downloaded from the NIW website, at www.niwproject.eu.

# 2. Study of uni-modal ground cues

The first step of the work done in WP5 concerns the study of uni-modal ground cues. Various experiments have indeed been conducted by the five partners to evaluate the different technologies developed in the NIW Project. These experiments assessed the potential and limits of each technology and each uni-modal cue alone (visual, haptic, and auditory). This work has been carried out individually by each laboratory and each partner in which the technology has been developed.

| Modality | Partner | Technology | Type of experiment(s) | Reference/Additional material |
|---|---|---|---|---|
| ***Visual*** | ***INRIA*** | Oscillating visual camera motions | Perception of traveled distance | Paper published at IEEE VR 2009 (Terziman et al., 2009) |
| ***Haptic*** | ***McGILL*** | Vibratory feedback of tiles | Perception of ground compliance | Paper in progress |
| ***Haptic*** | ***UPMC*** | Vibratory feedback of shoes | Perception of self-motion | Paper in progress |
| ***Auditory*** | ***AAU*** | Sound of footstep | Identification of ground type (various grounds: snow, leaves, wood, etc) | Paper published at IEEE VR 2010 (Nordahl et al., 2010) |
| ***Auditory*** | ***AAU*** | Sound of footstep | Perception of bumps and holes | Paper submitted at Digital Audio Effects Conference 2010 (Serafin et al., 2010) |
| ***Auditory*** | ***AAU*** | Sound of footsteps plus soundscape | Role of soundscape to enhance recognition. | Paper published at SMC 2010 (Turchet et. Al, 2010a) |
| ***Auditory*** | ***UNIVR+ INRIA*** | Sound of contact with ground | Identification of ground type (aggregate vs. solid material, influence of temporal vs. spectral cues of sound) | Paper submitted at ICAD (Fontana et al., 2010) |

**Table 1. Overview of the studies on uni-modal ground cues conducted in the NIW Project.**

An overview of the different studies conducted in the NIW project on uni-modal ground cues is given in Table 1. This shows that all the sensory modalities have been well addressed (visual, auditory, haptic), using various experimental protocols and complementary approaches.

The main results obtained in these various experiments are described in the following sub-sections.

## 2.1 Visual cue (INRIA): Perception of traveled distance in VR with camera motions

We have first conducted an experiment to evaluate the influence of oscillating visual camera motions on the perception of travelled distances in virtual environments.

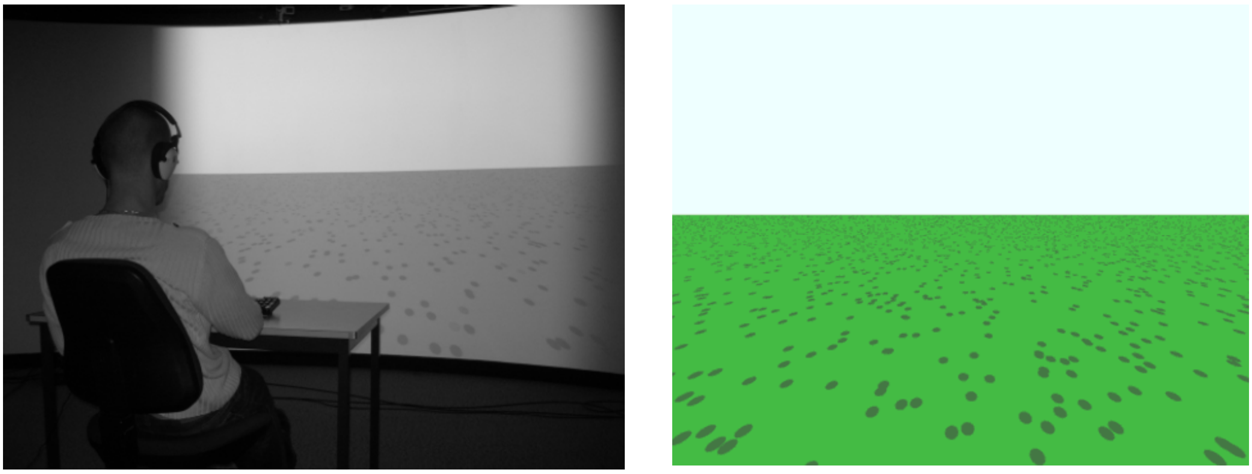


**Figure 1. Study of visual camera motions: experimental apparatus used in (Terziman et al., 2009).**

In our experiment, 12 participants were exposed to passive navigations, i.e., visual projections of translations along straight paths, with various conditions of camera motions. They were then asked to reproduce the travelled distance during an active navigation phase using keyboard keys (Figure 1-Left). The experiment was performed within an empty 3D virtual environment with all possible landmarks removed (Figure 1-Right).

We found that the accuracy of the reproduced traveled distances seems indeed to be increased by an oscillating visual camera motions, at least for short traveled distances. This is suggested by a significant decrease in standard deviations of participants' responses and a marginally significant decrease of absolute distance error values, in the oscillating camera motion condition for short distances. Taken together, our results suggest a positive influence of the camera motions on the perception of traveled distances and on the sensation of walking in VE.

More details about this experiment can be found in the additional material (Terziman et al., 2009) which is a paper published at IEEE VR 2009 conference.

## 2.2 Haptic cue (McGILL): Plantar vibration feedback increases haptic perception of surface compliance during walking

The haptic perception of ground compliance is used for stable regulation of dynamic posture and the control of locomotion in diverse natural environments. Although rarely investigated in relation to walking, vibrotactile sensory channels are known to be active in the discrimination of material properties of objects and surfaces through touch. This study investigated how the perception of ground surface compliance is altered by plantar vibration feedback.

We conducted experiments in which 60 subjects walked in shoes over a rigid floor plate that provided supra- or near-threshold vibration feedback, and responded indicating how compliant it felt, either in subjective magnitude or via pairwise comparisons. In one experiment, the effect of plantar vibration feedback on ground compliance perception was measured via a novel apparatus that allowed both the mechanical stiffness of a floor plate and vibration feedback presented through it to be manipulated (see Figure 2).

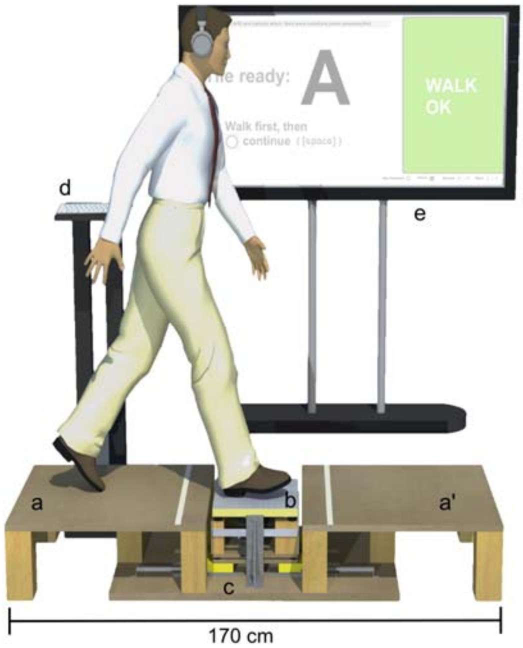



**Figure 2. Experiment configuration and apparatus for producing compliance and vibration stimuli.**

Results showed that perceived compliance of the plate increased monotonically with vibration feedback intensity, and depended to a lesser extent on the temporal or frequency distribution of the feedback. When both plate stiffness (inverse compliance) and vibration amplitude were manipulated, the effect persisted, with both factors contributing to compliance perception. A significant influence of vibration was observed at low amplitudes (< 0.5 m/s^2) that were close to psychophysical detection thresholds for the stimuli.

Taken together, the results of these experiments demonstrate that the perceived haptic compliance of a walking surface is increased in the presence of plantar cutaneous vibration feedback. We also found that an increased perception of compliance could be achieved with types of vibration feedback that differed in waveform, amplitude envelope, or the frequency distribution of their energy.

None of the experiments involved training, and the effects observed did not require awareness that vibration feedback was being provided. We concluded that vibration felt during stepping on a rigid surface is combined with the mechanical stiffness of the surface in the haptic perception of compliance. In addition, the results show that the variation of vibration feedback alone is sufficient to elicit a percept of compliance. One hypothesis consistent with the observations is that plantar vibration feedback simulated the effect of increased displacement during stepping. This interpretation is also consistent with a basic mechanical description of the mechanics of material deformation underfoot during stepping.

These findings show that vibrotactile sensory channels are highly salient to the perception of ground surface compliance, and suggest that correlations between vibrotactile sensory information and motor activity may be of broader significance for the control of human locomotion than has been previously acknowledged.

An article presenting these experiments is being prepared for journal submission.

### 2.3 Haptic cue (UPMC): Perception of ground motion from vibratory feedback using haptic shoes

We have completed a series of experiments where the subjects were standing, blindfolded, on vibratory soles depicted in Figure 3. These devices can deliver strong, calibrated vibratory signals to the feet of the person standing on them. Our hypothesis is that certain type of mechanical stimuli can have an effect on the physiology of balance, and in certain cases, can yield perceptual effects.

Participants were tested while standing on the active soles and exposed to a variety of signals. Unfortunately, the results of the first campaign of experiments produce large amount of data that is very difficult to exploit for the reason that it is hard to disentangle the effects of background postural balance movements from those due to the stimuli.

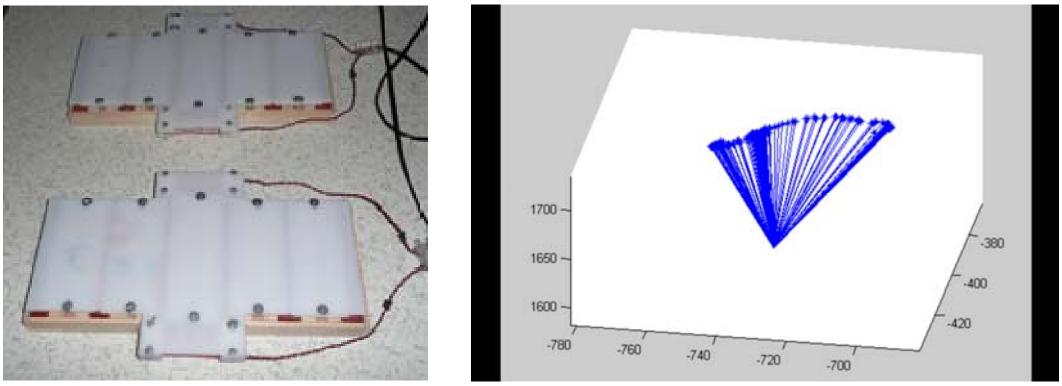



**Figure 3. Vibratory soles (left), measured head motion when the signal was applied.**

We are in the process of analyzing the large amount of existing data, and we have started a second campaign of experiments where the subjects are in conditions promoting a quite stance and where the goal is simply to increase the signal-to-noise ratio.

### 2.4 Auditory cue (AAU): Perception of different types of ground with sounds of footsteps

We conducted an experiment to assess the ability of subjects to recognize several synthetic footsteps sounds they were exposed to. The experiment was conducted as a between-subjects study with three conditions: recognition of recorded footstep sounds, recognition of synthesized footstep sounds played offline and recognition of footstep sounds generated online by using the interactive system shown in Figure. Specifically, the system consisted of a medium density fiberboard board where four contact microphones are placed.

**Figure 4. Experimental apparatus used in (Nordahl et al., 2010).**

Such microphones are used to detect in real-time the footstep sounds of subject stepping on the board, and extracting from it the ground reaction force (GRF). The GRF is used to control several synthetic footstep sounds based on physical models.

Results of the experiments show that subjects are able to recognize with high accuracy most of the synthesized surfaces. Similar accuracy can be noticed in the recognition of real sound, which is an indication of the quality of the synthesis.

Details concerning the experiment can be found in (Nordhal et al., 2010).

## *2.5 Auditory cue (AAU): Perception of bumps and holes on ground with sounds of footsteps*

We have then conducted a preliminary experiment whose goal was to assess the role of temporal aspects in sonically simulating the act of walking on a bump or a hole. In particular, we investigated whether the timing between heel and toe and the timing between footsteps affects the perception of walking on unflat surfaces. The parameters which were varied in the experiment were heel-toe distance and distance between steps (see Figure 5).

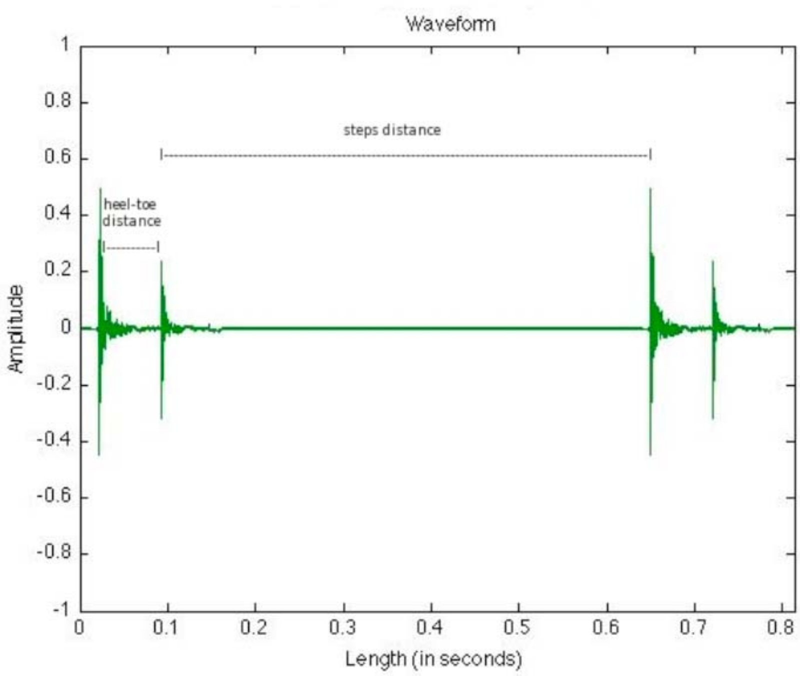



**Figure 5. Sound parameters used in footstep generation and recognition in (Serafin et al., 2010).**

Results show that it is possible to simulate a bump or a hole by only using temporal information in the auditory modality. A detailed explanation of the experimental conditions and results can be found in (Serafin et al., 2010).

## 2.6 Auditory cue (AAU): Role of context on the recognition of synthetic footstep sounds

We have conducted an experiment whose goal was to assess the role of soundscape design in the recognition of walking sounds.

Forty three subjects participated to a between-subjects experiment where they were asked to walk on a limited area in a laboratory, while the illusion of walking on different surfaces was simulated, with and without an accompanying soundscape. Specifically, soundscapes for five different environments were designed (beach, farm, skislope, forest, park), and rendered together with interactive footstep sounds on different materials.

Results show that, in some conditions, adding a soundscape significantly improves surfaces' recognition. Moreover, when conflicting cues are provided, such as a soundscape of a beach side with footstep on snow, subjects tend to focus their recognition to the soundscape rather than to the footstep sounds.

A detailed explanation of the results appears in (Turchet et al., 2010a).

## *2.7 Auditory cue (UNIVR+INRIA): Perception of different types of ground with by footstep sounds*

In a multiple choice auditory experimental task, listeners had to discriminate walks over floors made of concrete, wood, gravel, or dried twigs. Sound stimuli were obtained by mixing temporal and spectral signal components, resulting in hybrid formulations of such materials. In this way, we analyzed the saliency of the corresponding cues of time and frequency in the recognition of a specific floor. Results show that listeners differently weigh such cues during recognition, however this tendency is not polarized enough to enable interaction designers to reduce the functionality of a walking sound synthesizer to simple operations made on the temporal or spectral domain depending on the simulated material.

We hypothesize that spectral cues are more salient in the recognition of solid materials, conversely temporal cues are more salient in the recognition of aggregate materials. In particular, we experiment using concrete (C) and wooden (W) floors, representative of solid materials, as well as with gravel (G) and dried twigs (T), representative of aggregate materials. Figure 6 illustrates this hypothesis:

| MATERIAL | PHYSICAL PROPERTIES | ACOUSTIC PROPERTIES |
|---|---|---|
| C , W | Solid | Spectral Cues |
| G , T | Aggregate | Temporal Cues |

**Figure 6. Experimental plan (C: concrete, W: wood, G: gravel, T: twigs) (Fontana et al., 2010).**

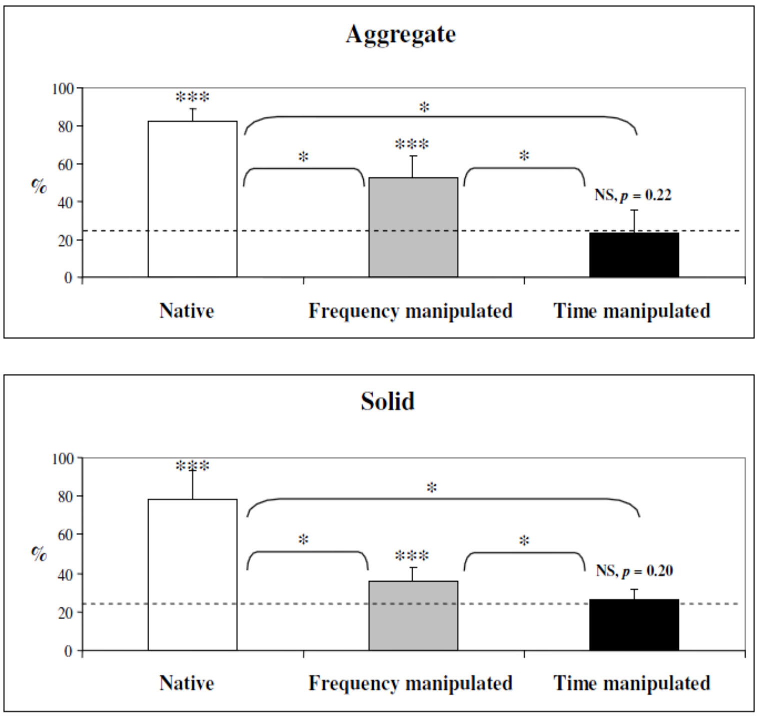


**Figure 7. Mean percentages of choice (bars represent std) for material categories (Aggregate and Solid) as a function of the auditory stimulus.**
**The difference from random choice (line at 25%) was tested using one-proportion (two-tailed) z tests. The differences between the three audio conditions were tested with two-proportion z tests (two-tailed and Bonferroni-adjusted alpha level with p = 0.05/3 =0.0167). Note: *: p < 0:05, **: p < 0:01, ***: p < 0:001, NS: not significant: (Fontana et al., 2010).**

Figure 7, in spite of the low significance of the data from time manipulations (i.e. black bars), shows that subjects are primarily sensitive to temporal substitutions between solid and aggregate materials. In parallel, spectral changes are more tolerated during the recognition of aggregate material compared to solid floors.

The proposed experiment confirms that solid and aggregate floor materials exhibit precise temporal features, that cannot be interchanged while designing accurate walking sounds. Within such respective categories, color represents an important cue for the recognition of solid materials, conversely sounds of aggregate materials seems to tolerate larger artifacts in their spectra.

A more detailed exposition of the experimental methodology is included as part of the companion material to this deliverable, in the form of a manuscript ready for publication, also containing a deeper discussion of the experimental results also through disaggregated data analyses: (Fontana et al., 2010).

# 3. Study of pseudo-haptic ground cues

The second step of the work done in WP5 concerns the study of pseudo-haptic ground cues. This work has been carried out by INRIA, which has a long history of research in the area of pseudo-haptics. A novel concept of pseudo-haptic feedback has been proposed to simulate walking on grounds with various reliefs. It uses visual feedback to distort perception of virtual ground. Several experiments have been carried out to study this novel pseudo-haptic effect, for simulating the sensation of walking over various shapes of ground, such as bumps and holes.

Therefore, this section will first detail the novel concept of pseudo-haptic ground cues that has been developed. Then, it will report on the experiments conducted to evaluate these pseudo-haptic cues when walking over virtual bumps and holes.

## *3.1 Concept of pseudo-haptic slopes*

We have developed novel interactive techniques to simulate the sensation of walking up and down in 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. Three possible 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.

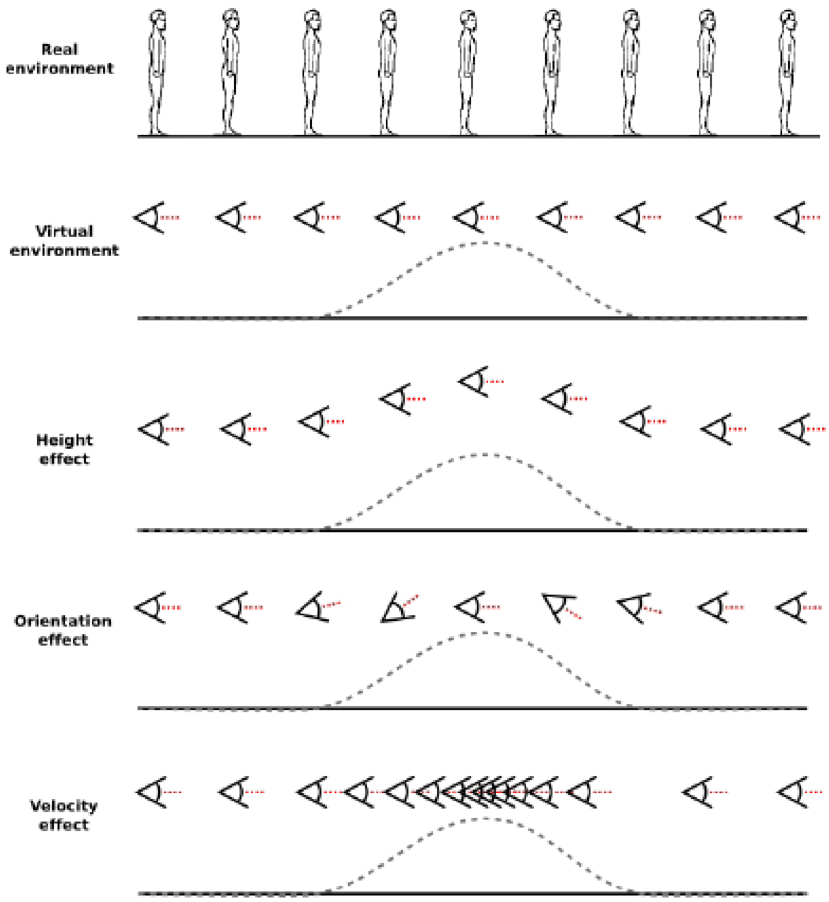



**Figure 8. Principle of the three pseudo-haptic effects when passing over a bump.**

The use of these three pseudo-haptic effects is illustrated on Figure 8 in the case of passing over a virtual bump. The user wears a Head-Mounted-Display (HMD). We can assume that he/she is walking on a flat physical environment while the virtual environment is composed of bump. We can then distort the visual camera motion corresponding to the real walking motion. 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). All these effects are expected to alter the perception of the physical walking, and to generate the “illusion” or “pseudo-haptic” effect of walking over a virtual bump. All implementation and technical details can be gathered in additional material (Marchal et al., 2010).

### *3.2 Evaluation*

Our pseudo-haptic effects were tested in an immersive virtual reality setup in which the user is really walking using an HMD, and in a desktop configuration where the user is seated and controls input devices. The experimental setup is illustrated on Figure 9.

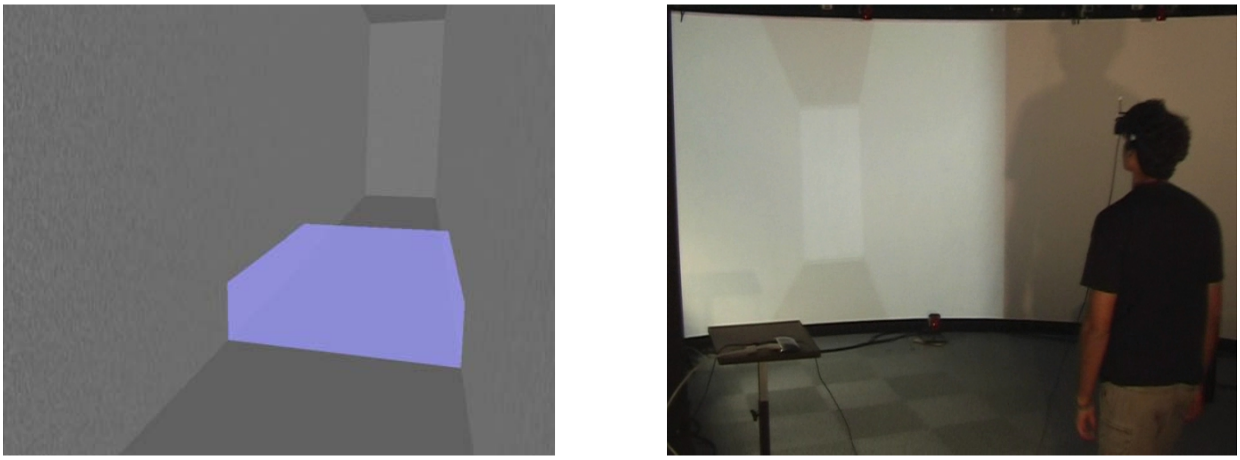


**Figure 9. Experimental evaluation of the three pseudo-haptic effects: (left) virtual environment, (right) participant during the experiment in immersive configuration = wearing an HMD (Head-Mounted Display).**

Experimental results show that our visual techniques are very efficient for the simulation of two canonical shapes: bumps and holes located on the ground under a virtual semi-transparent blue cube (Figure 9, left). The height and the orientation effects yielded highly positive results in the immersive configuration. Users clearly felt a change in height, and could distinguish in most of the cases whether it was a bump or a hole. The velocity effect seems to be less perceived. Interestingly, in the immersive configuration, the consistent combination of all visual effects together led to the best results and was subjectively preferred by the participants (Figure 10). Experiments suggest also a strong perception of height changes caused by the orientation effect changes (although camera’s height remains strictly the same in this case). This is confirmed by the 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.

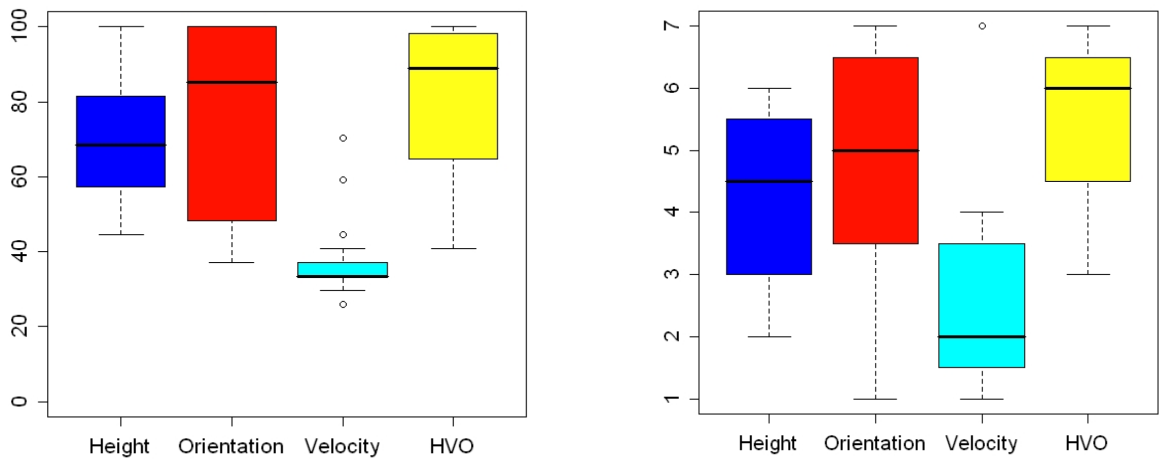



**Figure 10. Experimental results of the three pseudo-haptic effects (height, orientation, velocity) and their combination (HVO): (left) percentage of correct answers for the different shapes in the immersive configuration, (right) global appreciation of the participants for the different effects.**

Taken together these experimental results suggest that our pseudo-haptic ground cues could be applied in an immersive virtual environment to simulate the sensation of walking on uneven grounds. Our techniques could be used in various virtual reality applications, such as for urban or architectural project reviews, training, or videogames.

# 4. Study of multi-modal ground cues

The third step of the work done in WP5 concerns the study of multi-modal ground cues. Numerous experiments have also been conducted by the partners to evaluate the various combinations of the different technologies developed in the project. These experiments assessed the potential and limits of each subsequent combination of multi-modal cues (visual+haptic, visual+auditory, haptic+auditory). This work corresponds to an intense activity, with lots of collaborations and exchanges between the partners who associated, assembled, and combined the elementary technologies, and then had to define and achieve the corresponding experiments together.

| Modalities | Partners | Technology | Type of experiment(s) | Reference/Additional material |
|---|---|---|---|---|
| ***Haptic+Visual*** | **INRIA+UPMC** | Visual camera motion + Force in hands | Perception of self-motion (vection illusion) | Patent (Ouarti et al., 2009), Paper submitted at IEEE ToH (Ouarti et al., 2010) |
| ***Haptic+Visual*** | **UPMC** | Visual motion + Vibrations | Perception of self-motion | Paper in progress |
| ***Visual+Audio*** | **AAU+INRIA** | Visual camera motions + Footstep sounds | Perception of bumps and holes (with or without sensory conflict) | Paper published at ACM VRST 2010 (Turchet et al., 2010b) |
| ***Audio+Haptic*** | **AAU+UPMC** | Footstep sounds (ears/helmet)+ Vibratory shoes | Identification of ground type (various grounds: snow, leaves, wood, etc; with or without sensory conflict) | Paper published at Eurohaptics 2010 (Nordahl et al, 2010b) and (Serafin et al, 2010a) and HAID 2010 (Turchet et al, 2010c) |
| ***Audio+Haptic*** | **UNIVR+INRIA +UPMC** | Footstep sounds (loudspeakers)+ Vibratory shoes | Illusory vibrotactile changes induced by variable acoustic energy in the low-frequency | Paper in preparation for ACM TAP (Papetti et al., 2010b) |

**Table 2. Overview of the studies on multi-modal ground cues conducted in the NIW Project.**

An overview of the different studies conducted in the NIW project on multi-modal ground cues is given in Table 2. This table shows again the large variety of sensory combinations, and the large number of studies using, again, various experimental protocols and complementary approaches.

The main results obtained in these various experiments are described in the following sub-sections.

### *4.1 Haptic+Visual cues (INRIA+UPMC): Perception of self-motion with force-feedback and visual motion*

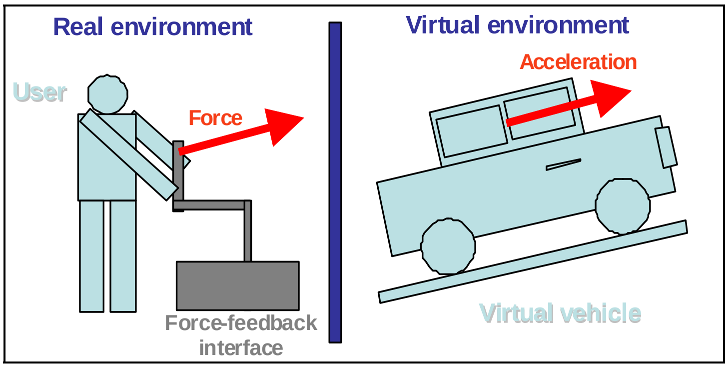



**Figure 11. Concept of Haptic Motion: a force-feedback corresponding to a virtual acceleration.**

We have developed a new visuo-haptic method for navigation in virtual worlds called "haptic motion". Haptic motion allows the user to feel an important sensation of displacement of his body by applying a force in his hands (Figure 11). This force is coherently produced together with a visual 3D environment.

We addressed the question of how *haptic motion* can influence the perception of self-motion compare with visual stimulation alone. We did not only want to measure qualitatively this influence but also quantitatively. To this aim, we designed two experiments.

**Figure 12. Experimental apparatus used for generating "Haptic Motion": A force-feedback is sent in the hands of the user in a synchronized way with visual feedback of motion in the VE.**

In the first experiment we submitted the subject to step of virtual acceleration (Figure 12). The visual and haptic displays are coherent physically, i.e. the visual acceleration correspond to the haptic force (inertial force).There were three different conditions in this experiment: haptic stimulation, visual stimulation and visuo-haptic stimulation. We found that the haptic force strongly influenced the occurrence, the onset and the duration of a well-known illusion of self-motion: the "vection" illusion.

To understand more deeply how haptic information is merged with visual information, in a second experiment we used different patterns of haptic force to observe in which fashion the fusion with the visual pattern is done. We found that the sensation of self-motion corresponding to haptic motion can be generated in more complex 3D trajectories, and is more important when subjects received a force in the hand proportional to the virtual acceleration instead of virtual speed.

Taken together, our results suggest that haptic motion could be used in various VR applications to enhance sensation of self-motion, such as in virtual reality and video games, or in driving simulators. More details can be found in additional material (Ouarti et al., 2010) which is a paper submitted to IEEE Transactions on Haptics.

### 4.2 Visual+Haptic cues (UPMC): Perception of self-motion with visual and vibrotactile cues.

The principle of the experiment is to investigate the role of vibrotactile stimulations in self motion perception. We used visual cues to represent more realistic stimulations. To this aim we design an immersive room where the experiment can be achieved. We tried different type of vibrotactile stimulation to find the one who give the most important sensation of self-motion.

To test our hypothesis we designed a vibrotactile apparatus that can stimulate the two feet (see Figure 13).

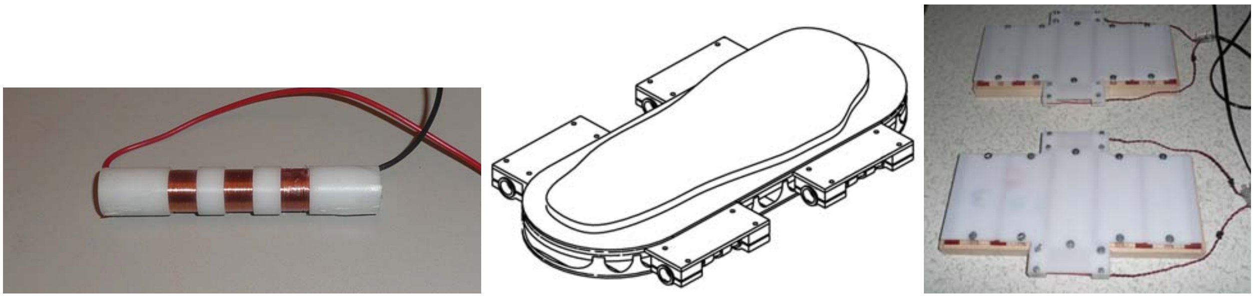


**Figure 13. Haptuator and "vibrofoot" design. Each vibrofoot has 2 haptuators for the stimulation of the sole.**

The preliminary results suggest that some vibrotactile patterns have the ability to produce a stronger self-motion sensation than others. These patterns could be good candidates to produce self-motion sensation in immersive room at a very low cost.

### 4.3 Visual+Audio cues (AAU+INRIA): Perception of bumps and holes with camera motions and footstep sounds

An experiment has also been conducted which goal was to investigate the role of sound and vision in the recognition of different surface profiles of bumps and holes in a walking scenario. Fifteen subjects participated to two within-subjects experiments where they were asked to interact with a desktop system simulating bumps, holes and flat surfaces by means of audio, visual and audio-visual cues.

The visual techniques used to simulate the act of walking over bumps and holes were the same proposed in (Marchal et al. 2010) and described in section 3: a straightforward modification of the cameras height (H), a modification of the cameras navigation velocity (V), a modification of the cameras orientation (O), and the combination of the three effects (HOV).

The technique adopted to render bumps and holes at auditory level has been the placement of footsteps sounds at different temporal intervals, as described in section 2 and displayed in Figure 14.

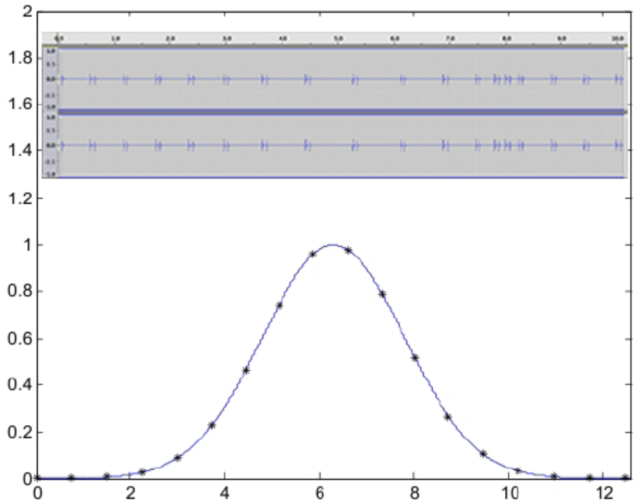


**Figure 14. Gaussian bump simulation with the indication of the points at which the footstep sounds occur, and stereo waveform of the corresponding sound file (above).**

Results of the first experiment could show that participants are able to successfully identify the surface profiles provided through all the proposed audio-visual techniques with very high success rates. The addition of audio stimuli did not produce higher percentages for the recognition of the surfaces rather than the visual only modality which is already very high and close to 100%.

In addition, the role of dominance between audio and visual modalities has been investigated by means of a second experiment in which conflicting audio-visual stimuli were presented. Results show clearly that in presence of audio-visual conflicts audio is dominated by vision when H and O effects are presented. Conversely, vision is dominated by audio when V and HOV effects are presented. In particular the highest role of dominance has been found for audio stimuli respect visual stimuli provided by means of the Velocity effect.

Last, a subjective questionnaire revealed, for the criteria investigated, a clear and significant preference for the bimodal stimuli respect to the stimuli presented in the single modalities.

Details about this experiment can be found in additional material (Turchet et al., 2010) which is a paper accepted at ACM VRST 2010.

## 4.4 Audio+Haptic cues (AAU+UPMC): Perception of different types of ground with sounds of footstep and haptic shoes

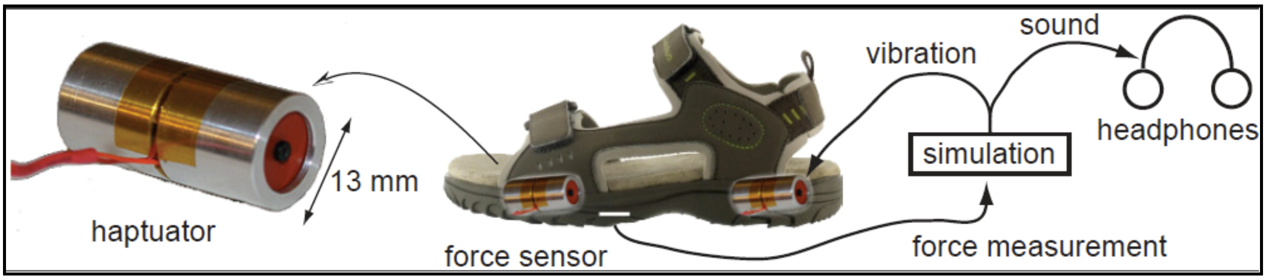



**Figure 15. Experimental apparatus.**

We have conducted three experiments whose role was to investigate the role of the auditory and haptic modalities and their combination in the recognition of synthetic walking sounds and haptic stimuli. The description of how the stimuli were created can be found in deliverable 4.2.

In the first experiment, subjects were sitting on a chair, and exposed to auditory, haptic and a combination of auditory and haptic stimuli. Such stimuli were provided by using headphones and a pair of shoes enhanced with actuators, as shown in Figure. Subjects were asked to recognize the surface they were exposed to, by choosing from a predefined list. Results show that subjects are better at recognizing stimuli by using the auditory modality rather than the haptic modality. The combination of auditory and haptic stimuli did not significantly enhance the recognition.

In a follow up experiments, subjects were asked to perform the same task, but this time while walking on a laboratory wearing the shoes enhanced with sensors and actuators (Figure 15). Results are similar to those obtained while sitting on a chair. Finally, we investigated what happens when conflicting stimuli are provided. Results show that the auditory modality is dominant on the haptic one.

Detailed results can be found in (Nordahl et al. 2010), (Serafin et al, 2010) and (Turchet et al, 2010).

## 4.5 Audio+Haptic cues (UNIVR+INRIA+UPMC): Illusory vibro-tactile changes induced by variable acoustic energy in the low-frequency

Making use of the UNIVR augmented footwear system (see Deliverable 4.2), an experiment was set up investigating the influence of low-frequency auditory cues on the perception of underfoot vibration during a walking task. Results show that vibrotactile perception is influenced by such cues.

For each channel (i.e. left and right shoe), an audio-haptic signal was routed to three paths: two audio paths going to the speakers, and one haptic path going to two vibrotactile transducers (haptuators) embedded in the respective sandal. Concerning the audio path, the signal was split in two frequency bands: the upper band was routed to a mini-speaker mounted on the sandal, while the other band was sent to four broadband loudspeakers located at the experiment room corners. The cross-over frequency was chosen to take advantage of the precedence effect: thanks to this effect, the user heard an ecologically consistent sound of footsteps coming exclusively from the feet while walking with the augmented sandals. Finally, in order to enhance the sense of presence, environmental sounds of a forest (representing wind in the trees, birds singing and a river flowing) were superimposed to the auditory stimuli at foot level.

Subjects were asked to wear the augmented sandals and to walk with a regular pace along a predefined path. Starting from halfway, the intensity of the low frequency signal at the loudpseakers could be changed. Before the experiment, subjects had been informed that a change in the intensity of the feedback could happen halfway during each take, however they were not aware that only the audio feedback was altered. Overall the experiment lasted about 45 minutes and consisted of twelve experimental configurations corresponding to several combinations of low frequency levels: a set of six "increments" (namely, three unvaried conditions plus three increases) plus a set of six "decrements" (again, three unvaried conditions plus three decreases). In detail, every take consisted of a pair of low frequency levels: one for the first half of the path and another one for the second part. The level pairs used in the experiment are shown below:

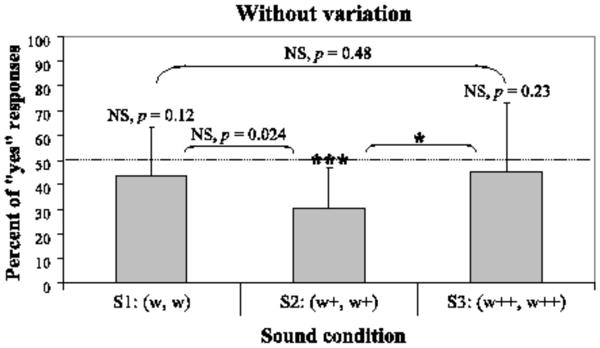
- without-variation - S1: (w, w), S2: (w+, w+), S3: (w++, w++)
- with-variation - S4: (w, w+), S5: (w, w++), S6: (w+, w++)

Note that the unvaried conditions S1, S2 and S3 are the same for both increments and decrements, while the varied conditions S4, S5 and S6 are in reverse order for increments and decrements.

Each condition was repeated four times, for a total of 48 trials. Decrements and increments were presented separately, that is, half subjects started with a randomized sequence of 24 "decrements" (i.e., twelve decrements and twelve no-variation trials) and half with a randomized sequence of 24 "increments" (i.e., twelve increments and twelve no-variation trials). At the end of each take, subjects had to write down whether they had felt any change in the vibrotactile feedback under their feet (answer: yes/no), and the corresponding confidence rating (from 1 to 7; 1: "absolutely not confident", 4: "moderately confident", 7: "very confident").

For each participant, the percentages of "yes" responses were calculated for the twelve experimental conditions. The difference from random percentage (50%) was tested using one-proportion (two-tailed) z-tests, and we used two-proportion (two-tailed) z-tests in order to check the differences between the experimental conditions. An alpha level of 0.05 was adopted.

A first global analysis considered the percentages of "yes" responses in the stimulus conditions "without-variation vs. with-variation". Results confirm that a cross-modal effect is present, and manifests itself as an audio-tactile illusion where audio low frequency influences the vibrotactile perception. The significant differences from random (50%) for the two conditions without-variation and with-variation can be interpreted like a double proof of such audio-tactile illusion. In other words, we have a cause/effect relationship, where the cause is the intensity variation of the low frequency, and the effect is the illusion: when the cause is present the effect is present, furthermore when the cause is absent the effect is absent.



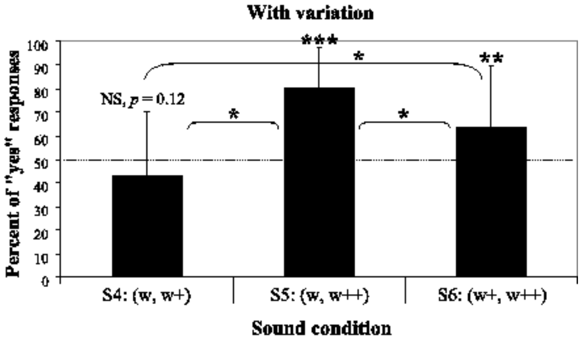



**Figure 16. (Left) Mean percentage of "yes" responses (bars represent std) for the without variation condition as a function of the sound configurations S1: (w,w), S2: (w+,w+), S3: (w++,w++). The difference from random (line at 50%) was tested using one-proportion (two-tailed) z-tests. The differences between the three sound conditions were tested with two-proportion z-tests (two-tailed and Bonferroni-adjusted alpha-level with p = 0:05=3 = 0:0167). (Right) Mean percentage of "yes" responses (bars represent std) for the with variation condition as a function of the sound con_gurations S4: (w,w+), S5: (w,w++), S6: (w+,w++). The difference from random (line at 50%) was tested using one-proportion (two-tailed) z-tests. The differences between the three sound conditions were tested with two-proportion z-tests (two-tailed and Bonferroni-adjusted alpha-level with p = 0:05=3 = 0:0167). Legenda: *: p<0:05, **: p<0:01, ***: p<0:001, NS: not significant. (Papetti et al., 2010b)**

In a detailed analysis, we considered the percentages of "yes" responses for the two stimulus conditions "without-variation vs with-variation" as a function of the sound configurations. The results are presented in Figure 16. For the without-variation condition the percentage of "yes" responses was significantly different from random in the S2 condition, but not in the S1 and S3 conditions. For the with-variation condition the percentage of "yes" responses was significantly different from random in the S5 and S6 conditions, but not in the S4 condition. Furthermore there is an optimal association (sweet spot) for the audio-tactile illusion. In this regard, it is expected that the largest low frequency variation (amounting to 12 dB) – represented by S5: (w,w++) – corresponds to a stronger illusion. On the other hand, it is found that the same relative low frequency variation (6 dB) starting from different absolute levels – namely S4: (w, w+) and S6: (w+, w++) – result in considerably different effects. In particular, a sweet spot is found for higher and more clearly perceivable absolute LFS levels. Also, a sweet spot for the without variation condition is represented by the S2: (w+, w+) condition: it is likely that a clearly perceivable low frequency level facilitated the participants to correctly feel the constancy of vibrotactile feedback.

A more detailed exposition of the experimental methodology is included as part of the companion material to this deliverable, in the form of a manuscript in preparation: (Papetti et al., 2010b).

# 5. Study of ground affordances

The fourth and last step of the work done in WP5 concerns the study of ground affordances in virtual reality. This work has been carried out by INRIA to extend the views and approaches of the NIW project when analyzing perception of virtual grounds. This section describes the main results obtained in this area.

The concept of affordance, introduced by the psychologist James Gibson, can be defined as the functional utility of an object. Indeed, in Gibson's *Ecological* approach to perception and action, the perception is viewed as the active pickup of information specifying affordances, that is, the action possibilities offered by the environment. In other words, the affordance can be defined as the functional utility of an object, a surface or an event for an animal with given physical characteristics (height, weight) and some action capabilities (effectivities) defined according to the species and ontogenetic development.

The purpose of our study was to evaluate the perception of *ground affordances* in virtual environments. In order to test this perception, we considered the affordances for standing on a virtual slanted surface. The participants were thus asked to judge whether a virtual slanted surface supported upright stance (Figure 17).

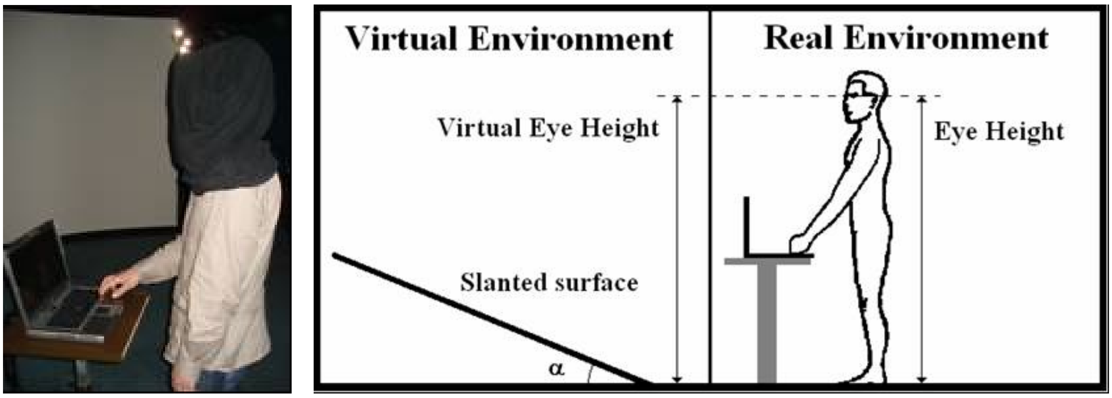



**Figure 17. Experimental apparatus used to study ground affordances.**

Different dimensions were considered for this perception such as the properties of the virtual environment. This dimension was investigated by manipulating the texture of the slanted surface (Wooden texture vs. Ice texture) as displayed in Figure 18.

**Figure 18. Virtual environment made up of a room with a wooden slanted surface. Left: the participant's view. Right: a side view.**

Our results (Figure 19) showed that the perceptual boundary with the Ice texture (22.13°) was significantly lower than with the Wooden texture (27.60°). This result revealed that the virtual information about friction was detected and used in VE. Thus, participants were able to differentiate visually a low-friction texture (Ice) from a high-friction texture (Wooden). In other words, this result indicated that the texture of the slanted surface was involved in perceiving affordances for standing on this surface in virtual reality.

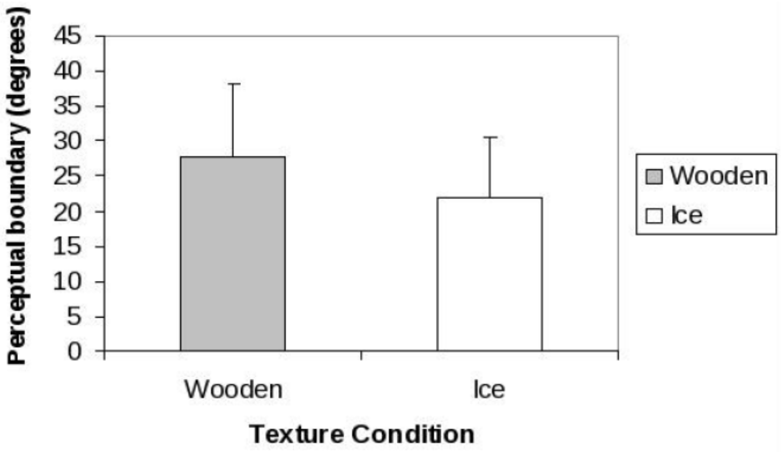



**Figure 19. Perceptual boundary (or critical angle in degrees for standing on the slanted surface) as a function of the texture condition (Wooden and Ice).**

Taken together, our results reveal that perception of affordances for standing on a slanted surface in virtual reality is possible and comparable to previous studies conducted in real environments. Interestingly, it seems that virtual information about friction can be detected and used for perceiving affordances in VE. Regarding the practical implications of our study, the results suggest that people with motor impairments or balance disorders might improve their postural ability with specific activities in VR where they are confronted to different affordances. On the other hand, other practical implications would be in the context of urban projects, where the immersion in the 3D representations of buildings would allow to locate the uncomfortable affordances. The results observed in the present work call for additional investigations devoted to evaluate the perception of different affordances in VR (walking up slopes, stair climbing, gap crossing, and object reaching). It would be also interesting to conduct these investigations by considering different perceptual modalities (vision, haptic and audition).

Details about this experiment can be found in additional materials (Regia-Corte et al., 2010a) which is a paper published at IEEE VR 2010 conference, and (Regia-Corte et al., 2010b) which is a paper submitted at Presence journal.

# 6. Conclusion

This document has surveyed the numerous studies achieved in the frame of work-package N°5 of NIW European Project. The method that we have adopted was iterative and progressive, from low-level evaluations of technological developments, to high-level psychological studies about ground perception[1].

First, we have studied and evaluated individually the technologies developed in the project, i.e., the uni-modal ground cues (visual, haptic, and auditory) developed by the five partners of the project. Visual cues of camera motions were first shown to enhance the perception of walking distance in virtual environments. Sounds of footsteps were shown to enable the perception of walking over bumps and holes when playing with their temporal occurrences. Physical sounds of footsteps or contacts with grounds can also efficiently convey information about the materials of virtual grounds. Vibrations embedded in shoes or provided by means of haptic tiles can also inform about ground materials and, sometimes, can also generate sensory illusions of compliance or motion.

Second, we have developed and studied pseudo-haptic ground cues, which involves visual feedback to distort the perception of ground properties when walking in virtual environments. Our method consists in modifying the motion of the virtual subjective camera (as function of the variations in the height of the ground) when the user is walking on a flat physical environment and wearing an Head-Mounted-Display. Results of two experiments could show that such pseudo-haptic effects are very efficient for the simulation of bumps and holes located on the ground. Interestingly, a strong “orientation-height illusion” was observed, as changes in viewing orientation could produce perception of height changes although camera’s height remained strictly the same in this case.

Third, we have studied the subsequent multi-modal combinations of sensory cues (visual+haptic, visual+auditory, haptic+auditory). This led to an intense collaborative activity, with a variety of studied combinations. Haptic and visual cues were first combined in “Haptic Motion” to enhance sensation of self-motion in virtual worlds. Visual camera motions and sounds of footsteps were associated to enhance subjective perception of bumps and holes. The joint use of auditory and tactile/vibratory feedback of contact with virtual grounds was also studied. All these combinations were used to test consistent associations but also conflicting cases which enable to reveal the potential dominance of one modality cue versus another one for a specific perception.

Last, we have initiated a complementary high-level study of perception of affordances of virtual grounds. In order to test this perception, we considered the affordances for standing on a virtual slanted surface. The participants were asked to judge whether a virtual slanted surface supported upright stance. Taken together, our results revealed that perception of affordances for standing on a slanted surface in virtual reality is possible, and comparable to previous studies conducted in real environments. Interestingly, it seems that virtual information about friction can be detected and used for perceiving ground affordances in VE. The study of ground affordances seems to be a promising psychological approach for the design and evaluation of ground cues in virtual reality.

[1] All the results presented in the document are complemented by additional materials mentioned in the Annex list given hereafter.

# 7. Annex and additional materials

## *7.1 Affective cues (KTH+UNIVR): Expressive sonification of footstep sounds*

This research came as an additional, instructive task thanks to the notable former experience accumulated by Roberto Bresin and collaborators at KTH in the evaluation of affective cues, along with their links with ecological perception. In addition to its innovative value, the related experiment has represented an excellent early testbed for the audio-haptic shoes, prototyped just a couple of weeks before the collaboration with the KTH took place. Results have been published in (Bresin et al., 2010).

We asked subjects to walk (using the sensored-shoes) with four different emotional intentions (happy, sad, aggressive, tender) and for each emotion we manipulated the ground texture sound four times (wood panels, linoleum, muddy ground, and iced snow).

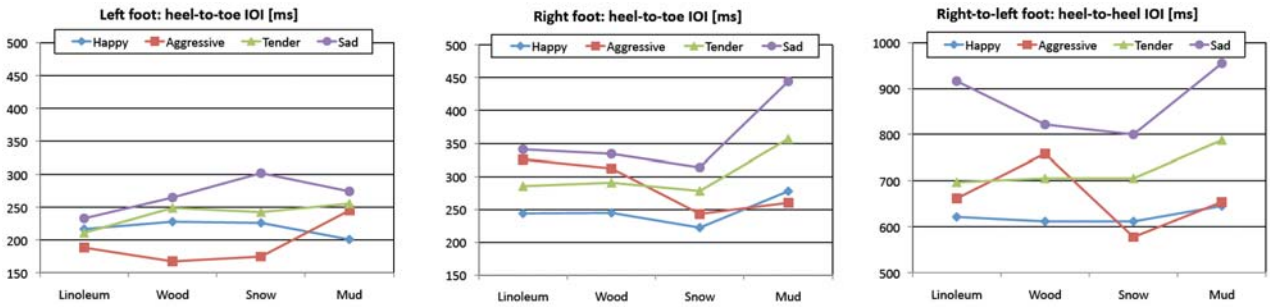



**Figure 20. Preliminary results show that walkers used a more active walking style (faster pace) when the sound of the walking surface was characterized by an higher spectral centroid (e.g. iced snow), and a less active style (slower pace) when the spectral centroid was low (e.g. muddy ground). Harder texture sounds lead to more aggressive walking patterns while softer ones to more tender and sad walking styles.**

In general it has been observed the same tendency as in music performance, sad walking was slower than tender and happy walking. Aggressive walking had a more varied speed, and this could reflect previous results in music performance where tempo was not an important parameter for the communication of anger. Results show that walkers used a more active walking style (faster pace) when the sound of the walking surface was characterized by an higher spectral centroid (e.g. iced snow), and a less active style (slower pace) when the spectral centroid was low (e.g. muddy ground). Harder texture sounds lead to more aggressive walking patterns while softer ones to more tender and sad walking styles. It can be noticed that the average value of heel-to-toe IOI for the right foot was larger than the corresponding one for the left foot, and that it had a trend similar to that of heet-to-heel IOI. This could suggest that subjects control the walking speed with the right foot.

Even if not statistically significant, it has been found that walking patterns can be influenced by the sound of the ground. In particular there are sounds that make people walk faster or slower independently from the emotional intention of the person. These results could be taken into account when designing the sonification of footstep sounds in virtual reality environments, such as new interactive floors where the sound feedback of footstep sounds can influence the behavior of users, or in rehabilitation and therapy applications when the control of the walking style of a client is a desired goal. For example it could be that subjects can be induced to walk with a faster or slower pace depending on the sound feedback: walking speed is often slower in persons with stroke and it could be modulated using sound as an alternative for example to methods using visual feedback

## 7.2 References and additional materials

All documents listed hereafter are available on-line at www.niwproject.eu

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