Applied Acoustics 74 (2013) 566–574

Contents lists available at SciVerse ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Investigating the amplitude of interactive footstep sounds and soundscape reproduction

Luca Turchet *, Stefania Serafin

Department of Architecture, Design and Media Technology Aalborg University Copenhagen, A.C. Meyers Vænge 15, DK-2450 Copenahgen SV, Denmark

ARTICLE INFO

Article history:
Received 24 March 2012
Received in revised form 25 September 2012
Accepted 9 October 2012
Available online 5 December 2012

Keywords:
Amplitude
Footsteps
Soundscapes

ABSTRACT

In this paper, we study the perception of amplitude of soundscapes and interactively generated footstep sounds provided both through headphones and a surround sound system. In particular, we investigate whether there exists a value for the amplitude of soundscapes and footstep sounds which is considered appropriate for different subjects while navigating in the acoustically-simulated environments. In order to answer such question, several experiments are run. Results show that subjects overall choose higher amplitudes when using sound delivery through headphones rather than speakers. The addition of soundscapes does not significantly affect the selected amplitude of footstep sounds. Similarly, the perception of the soundscapes amplitude is not significantly affected by the selected amplitude of footstep sounds.

1. Introduction

One issue when designing interactive sound rendering for virtual environments is how to choose the amplitude at which the sounds are delivered. In movies and computer games, sounds are usually enhanced in amplitude. This is achieved in order to capture the user's attention [1]. However, to our knowledge a formal evaluation of the amplitude of sound rendering for virtual environments has not yet been performed. Most of previous research in evaluating sounds for virtual reality has been focused on sound delivery methods, or the role of sound to enhance presence and complement the quality of the visual feedback. Some studies have also investigated the role of soundscape in enhancing the sense of presence [2]. These studies, however, have looked at the content of the soundscapes, neglecting their delivery amplitude.

On the one hand, research on real soundscapes started with Schafer in late sixties [3] and continued by focusing mostly on musical applications [4,5]. On the other hand, studies of the human perception of locomotion sounds on real surfaces were conducted, revealing that the gender and the posture of a walker can be identified using the acoustic information alone [6,7]. However, the relative combination of soundscapes and footstep sounds is still an unexplored topic. One exception is the work of Nordahl, who investigated the role of the combination of footstep sounds and soundscape rendering in order to create a sense of presence and enhance the amount of motion of subjects in a photorealistic virtual environment [8].

In previous research, we proposed a sound synthesis engine able to simulate footstep sounds on aggregate and solid surfaces [9]. Such engine was utilized to run several experiments investigating the ability of subjects to recognize simulated surfaces, together with the role of context in the recognition of walking sounds [10]. In that particular case, the context was represented by the soundscape which was rendered together with the footstep sounds. In those situations the amplitude of footstep sounds and soundscape was selected empirically by the experimenter.

In this study, we are interested in investigating the user's perception of the amplitude of footstep sounds generated in real-time when physically walking in a virtual reality setup which will be described in the following of this paper. We examine the evaluations of amplitudes of the simulated footstep sounds and of the soundscapes, as well as of their combination. Our research questions are manifold. First of all we are interested in measuring eventual differences in the evaluations of the amplitudes of footstep sounds and soundscapes when the sounds were provided by means of headphones or using a surround system composed by loudspeakers. Secondly, we are interested in assessing the presence of differences between males' and females' evaluations of amplitude, especially for the footstep sounds. In addition, we want to study the relationship between the amplitude of the footstep sounds and the environmental sounds. Furthermore, we are interested in measuring eventual differences in the amplitude evaluations of two different delivery methods proposed for the diffusion of the footstep sounds by means of loudspeakers.

We believe that the amplitudes of both footstep sounds and soundscapes constitute an important element when creating interactive audio rendering for virtual environments, which until now

* Corresponding author.
E-mail address: tur@create.aau.dk (L. Turchet).

0003-682X/$ - see front matter
http://dx.doi.org/10.1016/j.apacoust.2012.10.010

has been neglected in the community working on sound rendering for virtual environments.

2. System architecture

The system adopted for the experiments consisted of a motion capture system (Naturalpoint Optitrack), two soundcards (RME FireFace 800), a pair of sandals with pressure sensors embedded in, and two computers. Concerning the delivery of the sound two approaches were used: a pair of headphones (Sennheiser HD 600) and a surround sound system composed by 16 loudspeakers (Dynaudio BM5A). Fig. 1 shows a schematic representation of the overall architecture developed.

The system was placed in an acoustically isolated laboratory which consisted of a control room and an experiment room. The control room was used by the experimenters providing the stimuli and collecting the experimental results. It hosted two desktop computers: the first computer ran the motion capture software while the second ran the sound synthesis engine (see Section 2.1). The two computers were connected through an ethernet cable and communicated by means of the UDP protocol. The data relative to the motion capture system were sent from the first to the second computer, which processed the data in order to control the sound engine.

The experiment room (5.45 m large, 5.55 m long, and 2.85 m high) was the space where the setup was installed and where the experiments were performed. The user's locomotion was tracked by a motion capture system, composed by 16 infrared cameras. The cameras were placed in a configuration optimized for the tracking of the head position. In order to achieve this goal, markers were placed on the top of the head using a bicycle helmet. The area fully seen by the cameras delimited the zone available for the users to walk. It consisted of a 2.50 × 2.60 m rectangle, whose perimeter was indicated on the floor by means of scotch tape strips (see Fig. 2).

Users were also tracked by using two pressure sensors embedded in the sole of a pair of light-weight sandals, whose aim was to detect the pressure force of the feet during the locomotion. The two sensors were placed in correspondence to the heel and toe respectively in each shoe. The analog values of each of these sensors were digitalized by means of an Arduino Diecimila board and were used to drive the footstep sounds synthesis engine.

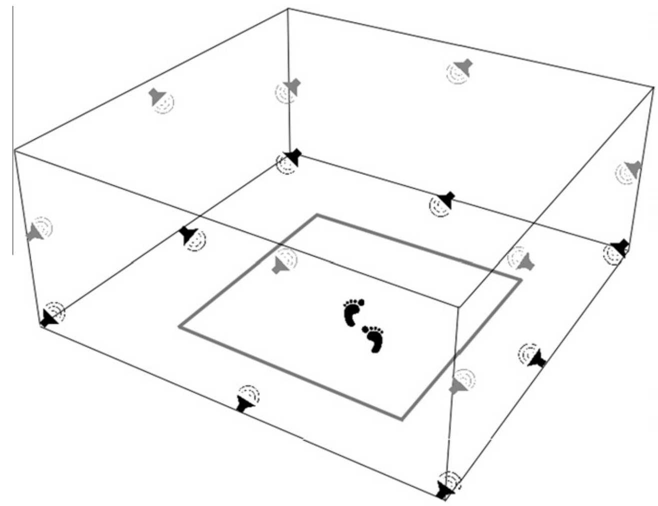

Fig. 2. Loudspeakers configuration (the 8 loudspeakers used for the footstep sounds diffusion are indicated in black). The walking area is indicated by the gray rectangle on the floor.

In addition, users were also asked to wear a belt, on top of which was attached a knob used to adjust the amplitude of the sounds provided during the experiments.

Concerning the surround sound system, the configuration of the 16 loudspeakers is illustrated in Fig. 2. Eight loudspeakers were placed on the ground at the vertices and at the middle point of the sides of the rectangular floor. Four loudspeakers were placed in correspondence to the vertices of the rectangle at the height of 1.40 m, while other four were placed in correspondence to middle points at the height of 2.40 m.

2.1. Sounds synthesis engine

In previous research, we proposed a sound synthesis engine, based on physical models, able to simulate footstep sounds on

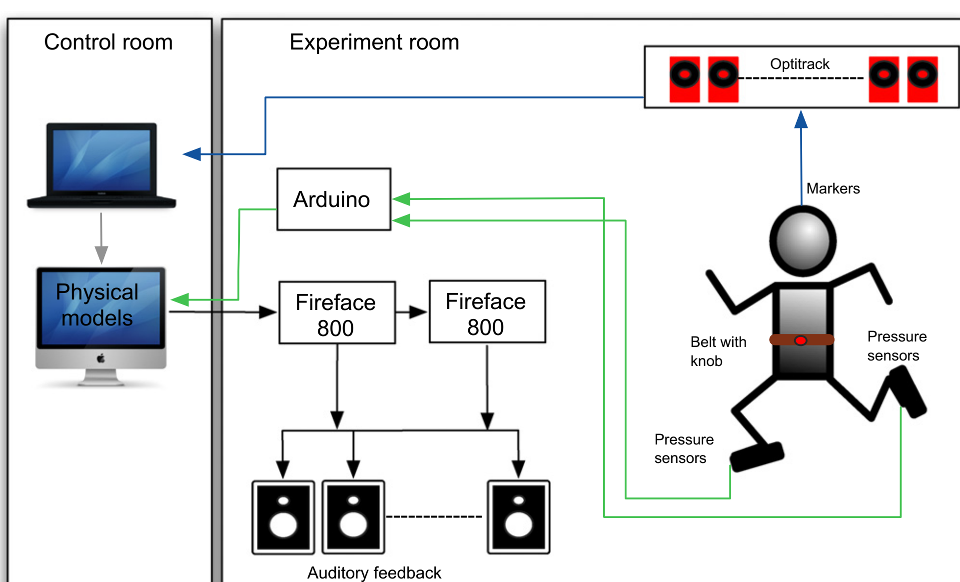

Fig. 1. A block diagram of the architecture developed for the experiments involving the loudspeakers.

aggregate and solid surfaces [9,11]. In the proposed experiments, the footstep sounds synthesis was driven interactively during the locomotion of the subject wearing the shoes. The description of the control algorithms based on the analysis of the values of the pressure sensors can be found in [12].

For the purpose of the experiments, the engine was set in order to synthesize footstep sounds on seven surfaces materials: gravel, sand, deep snow, dry leaves, forest floor, wood and metal. The footstep sounds used in these experiments were designed in order not to provide any specific clue about the gender of the walker, i.e. trying to simulate a sound which could generally be accepted as genderless. This was reached modeling the contribute of a type of shoe which could fit for both males and females.

In addition to the footstep sounds synthesis, the soundscapes of the following seven environments were created for the experiments: a courtyard of a farm in the countryside during summer; a beach and seaside during summer; a ski slope; a park during fall; a forest; a house interior; and a submarine.

Such soundscapes were chosen in order to coherently fit with the synthesized footstep sounds. They were designed according to the indications given by subjects' answers to a questionnaire. Precisely, 10 subjects, chosen among those not performing the experiments, were asked to imagine which sounds could occur in the above mentioned environments. Subjects were asked the following question: "Imagine that you are right now in a forest: which sounds do you think you would hear?". In this particular environment, subjects indicated sounds like birds chirping, wind through the trees, sounds of different animals moving. Among the answers provided, we chose those which were stated by more than one subject, and collected a corresponding sound material using appropriate recordings of real sounds. Such sounds were chosen among those available both on the Hollywood Edge sound effects library and on the Freesound.org website. The chosen sounds were opportunely edited and assembled using the sound editor Adobe Audition 3. Soundscapes were designed with the goal of providing a clear idea of the designed environment within the first seconds of listening.

2.2. Sound delivery methods

Sounds were delivered to the users in two ways according to the provided experimental condition: by means of headphones and by means of a surround system composed by sixteen loudspeakers. Concerning the loudspeakers diffusion, the soundscapes were provided using all the loudspeakers, while the footstep sounds were delivered using only the eight loudspeakers placed on the ground. Two different types of approaches for the delivery of the footstep sounds through the loudspeakers were implemented: static and dynamic diffusion.

For static diffusion, we intend that the footstep sounds, generated interactively during the locomotion of the user wearing the shoes, were diffused using the same amplitude for each loudspeaker. Conversely, during the dynamic diffusion, the user position was tracked by the motion capture system and it was used to diffuse the footstep sounds according to a sound diffusion algorithm based on ambisonics. Specifically, to achieve the dynamism we used the ambisonic tools for Max/MSP which allows to move virtual sound sources along trajectories defined on a bidimensional and tridimensional space [13]. The control parameters of such algorithm were set in order to place under the user's feet the virtual sound source containing the footstep sounds. In this way the sound followed the user trajectories during his/her locomotion, and therefore the eight loudspeakers delivered the footstep sounds with different amplitudes. As an example, in reference to Fig. 2, when the user position was in one corner, the effect resulting from the dynamic diffusion was that the sound was mostly delivered through the loudspeakers near to that corner, while the loudspeakers placed on the opposite sides did not deliver any sound.

In more detail, the footstep sounds' amplitudes were measured by means of a SPL meter (A-weighted) in order to assess the differences between the two delivery methods. As regards the delivery by means of headphones, the measurements were conducted placing the microphone of the SPL meter inside one of the two headphones. For this purpose the microphone of the SPL meter was inserted in a hole, having its same diameter, created in a piece of hardwood which was subsequently sealed against one of the two headphones. Concerning the static diffusion with the surround sound system, the sounds measured in the center of the walking area were on average 2 dB (A) higher than those measured in the corners. Conversely, for the dynamic diffusion, the sounds measured in the center of the walking area were on average 6 dB (A) lower than those measured in the corners. For the purpose of the experiments, the amplitudes of both the static and dynamic diffusion were therefore set at an equal level which was found considering the average amplitude value obtained while randomly walking inside the area for one minute (see the third column of Table 6).

As concerns the soundscapes diffusion, the environmental sounds were delivered statically; no moving sound sources along tridimensional trajectories were involved. Finally, in presence of the dynamic diffusion, the delay due to the motion capture was negligible for the purposes of the experiments.

3. Experiments

We conducted two sets of within-subjects experiments, each composed by four experiments testing as many experimental conditions. In the first set of experiments, sounds were provided through headphones, while in the second it was through the surround sound system. In both the sets of experiments, participants were required to wear the augmented shoes and the belt with the knob described in Section 2. In addition, during the second set of experiments, they were also asked to wear a helmet with the motion capture markers on top of it. The task consisted of freely walking inside the walking area, which was indicated on the floor by means of scotch tape strips. While walking participants were asked to use the knob in order to adjust the amplitude of the sounds they were receiving to the extent they felt appropriate for that sound. The sounds to be adjusted were provided according to four experimental conditions:

Condition 1. Amplitude adjustment of footstep sounds (experiments 1 and 5).

Condition 2. Amplitude adjustment of soundscapes (experiments 2 and 6).

Condition 3. Amplitude adjustment of footstep sounds in presence of soundscapes with fixed amplitude (experiments 3 and 7).

Condition 4. Amplitude adjustment of soundscapes in presence of footstep sounds with fixed amplitude (experiments 4 and 8).

The experiments in Conditions 1–4, were run in two different days by the same group of participants. In the Conditions 3 and 4, the footstep sounds were coherent with the soundscapes (e.g. footsteps on sand in presence of the beach soundscape). In Condition 2, where the soundscapes were provided alone, participants had to walk but they were not producing the footstep sounds. Participants were allowed to walk and listen to the sounds as much as

Table 1
Participants anthropomorphic data.

Group	Males			Females		
	Height (m)	Weight (kg)	Shoes (EUR)	Height (m)	Weight (kg)	Shoes (EUR)
1	181.3	79.1	44.0	166.6	61.4	38.2
2	181.4	79.9	44.1	161.7	59.4	38.1

they wanted before giving an answer. Participants were informed about the type of surface or soundscape they would have listened to before starting each trial.

Each experiment was divided in two subparts: amplitude adjustment starting from a minimum value and from a maximum value. For each experiment the minimum and maximum amplitudes were set to −24 dB and +12 dB from a reference value for each surface and soundscape. The range of variation of the knob was mapped into the range [−24, +12] dB according to the logarithmic scale.

The reference values were chosen in Conditions 1 and 2 by means of a pilot experiment run with three males, who were asked to set the appropriate amplitudes both in the case of headphones and loudspeakers. For Conditions 3 and 4, the reference values of each surface and soundscape consisted of the amplitudes found as result of the experiments in Conditions 1 and 2 (using the average between males and females evaluations). All the reference values are indicated in the tables illustrating the results for each experiment (see Sections 4 and 5).

In the four experiments conducted using the headphones, participants were exposed to 14 trials, 7 starting from the minimum amplitude and 7 starting from the maximum amplitude. During the experiments conducted using the loudspeakers, in Conditions 1, 3 and 4 participants were exposed to 28 trials (14 starting from the minimum amplitude and 14 starting from the maximum amplitude), while 14 trials in Condition 2 (7 starting from the minimum amplitude and 7 starting from the maximum amplitude). In all the experiments, the surfaces materials and the soundscapes were presented in randomized order.

3.1. Population

40 Participants were divided in two different groups ($n = 20$) to perform the two sets of experiments. The first group used the headphones; it was composed by 10 males, aged between 22 and 37 ($\mu = 28.1$, $\sigma = 4.9$), and 10 females, aged between 21 and 37 ($\mu = 25.9$, $\sigma = 4.6$). The second group used the loudspeakers; it was composed by 10 males, aged between 20 and 37 ($\mu = 27.0$, $\sigma = 5.6$), and 10 females, aged between 20 and 37 ($\mu = 23.7$, $\sigma = 5.1$). All participants reported normal hearing conditions.

Three anthropomorphic measures were collected from participants in order to assess the biological differences between the males and females involved in the experiments. Table 1 shows the averaged data for height (m), weight (kg) and shoe size (EUR). A two-tail independent sample *t*-test was performed between males and females on the three anthropomorphic data, both for group one and two. Statistical significance was found for all the three measures in both the groups ($p < 0.05$), indicating that the males were both heavier and taller than the females, and also wore significantly bigger shoes.

4. Results: case with headphones

Results concerning the four experimental conditions in which the sounds were provided through headphones are illustrated in Tables 2–5. In those tables, the first column indicates the provided stimulus, and the second column indicates for each stimulus the reference value (in dB) of the amplitude of the footstep sounds chosen during the pilot experiment. Columns 3, 4 and 5 show the average amplitudes evaluated by males (M), females (F), and both of them together (M&F) respectively. Column 6 indicates the starting point of the amplitude value in the two sub-experiments (from minimum and from maximum, i.e. at −24 dB and +12 dB from the reference value respectively). Columns 7 and 8, and 9 and 10, for males and females respectively, indicate the mean and the standard deviation (in dB) of the values chosen by participants in the range of variation (i.e. [−24, 12] dB). This structure is common to all the tables showing the results of the eight experiments. Several repeated measures ANOVA and *t*-test analyses were performed in order to assess if the differences found in the results were significant (*p*-value was set at a significant $p < 0.05$).

Results of experiment 1 (amplitude adjustment of footstep sounds without soundscapes) are shown in Table 2. The first noticeable element emerging from the table is that the evaluations of the amplitudes are higher when the adjustment was performed starting from the maximum value rather than the minimum (see columns 7 and 9). This aspect is common to males and females and is found in all the eight experiments. Concerning the differences between males and females, it is possible to notice that females gave rise to higher evaluations in 6 out of 7 cases (see columns 3 and 4). Specifically, females evaluations were higher in 6 cases for the subexperiment starting from minimum, while in only 2 cases for the subexperiment starting from maximum. However, an in-depth analysis using ANOVA shows that all these differences are not statistically significant, both considering the effect of the different subexperiments together and separately.

Results of experiment 2 (amplitude adjustment of soundscapes without footstep sounds) are shown in Table 3. Males and females gave rise to similar evaluations (all the differences are not statistically significant). Considering the starting point (maximum or minimum amplitude), females evaluations were higher in 5 cases for the subexperiment starting from minimum, while in 3 cases for the subexperiment starting from maximum (but the effect of each subexperiment does not produce significant differences between males and females).

Results of experiment 3 (amplitude adjustment of footstep sounds in presence of soundscapes with fixed amplitude) are shown in Table 4. As mentioned in Section 3, for this experiment the amplitudes of soundscapes were set to the values found as result of experiment 2. Concerning the differences between males and females, it is possible to notice a trend similar to the one of experiment 1. Females gave rise to slightly higher evaluations, but a separate analysis for each subexperiment shows that females evaluations were always higher for the subexperiment starting from minimum, while in only three cases for the subexperiment starting from maximum. However, the ANOVA analysis shows that all these differences are not statistically significant both considering the subexperiments together and separately.

In addition, from a comparison with experiment 1, it is possible to notice that in five cases the average amplitudes are lower than the reference values (see column 2 and 5). Nevertheless, an in-depth analysis conducted by means of a *t*-test shows that these differences are not statistically significant.

Table 2
Results of experiment 1: amplitude adjustment of footstep sounds without soundscapes (using headphones).

Surface type	Ref. value	Avg. values			Start. point	Males		Females	
		M	F	M&F		μ	σ	μ	σ
Gravel	66.0	59.8	59.1	59.5	Min.	−11.2	9.0	−10.0	5.8
					Max.	−1.0	7.1	−3.6	3.2
Sand	51.5	49.7	50.6	50.1	Min.	−6.5	5.8	−2.4	8.4
					Max.	2.9	4.0	0.7	5.2
Deep Snow	66.5	55.5	56.9	56.2	Min.	−14.9	9.7	−12.0	7.5
					Max.	−6.9	8.5	−7.1	4.9
Dry Leaves	54.1	53.2	53.7	53.4	Min.	−6.1	9.0	−2.7	7.0
					Max.	4.4	5.1	2.0	3.4
Forest Floor	61.7	55.5	56.1	55.8	Min.	−10.0	7.7	−10.0	6.9
					Max.	−2.2	6.0	−1.1	4.4
Wood	70.6	58.7	60.5	59.6	Min.	−16.1	6.2	−13.9	5.0
					Max.	−7.6	7.0	−6.2	5.0
Metal	73.2	61.6	63.3	62.4	Min.	−17.3	7.2	−12.4	6.2
					Max.	−5.8	7.9	−7.3	6.6

Table 3
Results of experiment 2: amplitude adjustment of soundscapes without footstep sounds (using headphones).

Sound-scape	Ref. value	Avg. values			Start. point	Males		Females	
		M	F	M&F		μ	σ	μ	σ
Courtyard in summer	65.8	61.1	61.3	61.2	Min.	−8.9	8.4	−7.2	6.8
					Max.	−0.3	4.8	−1.5	4.4
Beach	66.8	56.5	56.9	56.7	Min.	−12.3	6.1	−11.6	4.2
					Max.	−8.1	7.2	−8.0	4.4
Ski slope	70.0	64.6	62.9	63.7	Min.	−8.0	8.7	−9.0	6.4
					Max.	−2.7	4.1	−5.0	5.7
Park in autumn	57.2	53.3	52.3	52.8	Min.	−7.4	7.0	−6.9	4.8
					Max.	−0.3	5.3	−2.6	4.7
Forest	63.1	58.3	59.3	58.8	Min.	−8.4	7.1	−7.2	5.5
					Max.	−1.1	6.8	−0.3	5.3
House	60.5	52.9	55.5	54.2	Min.	−11.1	5.7	−6.8	5.8
					Max.	−3.9	6.8	−3.0	9.7
Submarine	75.2	68.0	66.2	67.1	Min.	−8.8	9.9	−10.8	6.7
					Max.	−5.4	6.9	−7.0	7.8

Table 4
Results of experiment 3: amplitude adjustment of footstep sounds in presence of soundscapes with fixed amplitude (using headphones).

Surface type	Ref. value	Avg. values			Start. point	Males		Females	
		M	F	M&F		μ	σ	μ	σ
Gravel	59.5	57.6	58.0	57.8	Min.	−5.0	4.1	−2.2	4.6
					Max.	1.3	3.6	−0.7	3.5
Sand	50.1	50.9	53.0	51.9	Min.	−1.1	3.8	1.6	5.5
					Max.	2.8	3.1	4.1	4.3
Deep Snow	56.2	55.3	55.5	55.4	Min.	−3.3	3.5	−1.4	4.4
					Max.	1.6	3.3	0.1	5.7
Dry Leaves	53.4	54.3	54.4	54.4	Min.	−2.3	4.6	0.1	5.4
					Max.	4.2	3.5	1.9	3.0
Forest Floor	55.8	53.1	53.9	53.5	Min.	−5.3	3.1	−3.5	3.5
					Max.	0.1	3.8	0.0	6.7
Wood	59.6	53.2	55.3	54.2	Min.	−8.9	3.3	−5.6	4.0
					Max.	−3.8	5.7	−2.8	4.8
Metal	62.4	60.7	62.4	61.5	Min.	−4.1	4.1	−1.3	4.1
					Max.	0.8	5.7	1.3	6.5

Results of experiment 4 (amplitude adjustment of soundscapes in presence of footstep sounds with fixed amplitude) are shown in Table 5. As mentioned in Section 3, for this experiment the footsteps amplitudes were set to the values found as result of experiment 1. Males gave rise to higher evaluations in all the cases, although the ANOVA analysis shows that all these differences are not statistically significant, both considering the subexperiments together and separately. Comparing the results with those of experiment 2, it is possible to notice that the average values are very similar between the two experiments.

5. Results: case loudspeakers

Results of experiment 5 (amplitude adjustment of footstep sounds without soundscapes) are shown in Table 6. The first

Table 5
Results of experiment 4: amplitude adjustment of soundscapes in presence of footstep sounds with fixed amplitude (using headphones).

Sound-scape	Ref. value	Avg. values			Start. point	Males		Females	
		M	F	M&F		μ	σ	μ	σ
Courtyard in summer	61.2	63.3	62.1	62.7	Min.	0.4	7.5	−0.8	2.9
					Max.	3.9	5.9	2.8	5.2
Beach	56.7	55.6	52.8	54.2	Min.	−2.5	5.4	−5.4	1.7
					Max.	0.4	6.2	−2.1	4.4
Ski slope	63.7	63.1	63.0	63.0	Min.	−1.3	5.5	−0.9	3.0
					Max.	0.2	5.0	−0.3	5.4
Park in autumn	52.8	52.9	51.2	52.0	Min.	−0.7	5.7	−3.6	5.1
					Max.	0.9	4.8	0.5	4.7
Forest	58.8	60.1	57.4	58.8	Min.	−0.7	6.6	−3.6	4.0
					Max.	3.4	3.1	0.9	4.9
House	54.2	54.7	53.5	54.1	Min.	−1.4	6.5	−2.7	5.0
					Max.	2.5	3.9	1.4	4.4
Submarine	67.1	68.5	65.9	67.2	Min.	0.0	7.0	−2.8	3.7
					Max.	2.8	5.2	0.6	5.6

Table 6
Results of experiment 5: amplitude adjustment of footstep sounds without soundscapes (using loudspeakers).

Surface type	Diffusion type	Ref. value	Avg. values			Start. point	Males		Females	
			M	F	M&F		μ	σ	μ	σ
Gravel	Static	55.9	53.4	52.5	53.0	Min.	−7.2	2.4	−6.8	3.8
						Max.	2.4	3.5	0.1	4.5
	Dynamic	55.9	54.1	50.8	52.4	Min.	−4.9	4.3	−8.4	2.9
						Max.	1.3	2.7	−1.7	3.8
Sand	Static	46.5	44.8	44.7	44.7	Min.	−4.5	5.6	−4.5	4.9
						Max.	1.2	5.4	0.9	4.9
	Dynamic	46.5	44.8	44.4	44.6	Min.	−4.4	4.3	−4.0	4.8
						Max.	1.0	5.2	0.0	5.0
Deep snow	Static	51.5	48.3	47.8	48.1	Min.	−5.5	4.1	−6.0	3.5
						Max.	−0.6	5.5	−1.2	5.6
	Dynamic	51.5	49.4	47.8	48.6	Min.	−4.2	4.8	−6.6	3.7
						Max.	0.1	4.9	−0.6	6.4
Dry leaves	Static	47.0	49.3	47.6	48.4	Min.	−3.2	4.1	−2.1	2.9
						Max.	7.9	2.8	3.4	3.5
	Dynamic	47.0.	50.8	48.1	49.5	Min.	−0.4	3.2	−1.1	2.3
						Max.	8.2	3.7	3.5	3.1
Forest floor	Static	51.4	49.3	48.2	48.8	Min.	−5.3	2.5	−5.6	3.9
						Max.	1.2	6.7	−0.6	4.5
	Dynamic	51.4	49.2	48.1	48.6	Min.	−6.1	3.0	−7.2	4.3
						Max.	1.8	5.5	0.7	4.9
Wood	Static	59.5	55.6	54.4	55.0	Min.	−5.9	5.9	−7.7	4.0
						Max.	−1.6	4.9	−2.4	3.4
	Dynamic	59.5	55.9	54.9	55.4	Min.	−5.2	4.3	−6.5	2.4
						Max.	−1.8	3.8	−2.5	3.6
Metal	Static	55.1	54.0	53.9	54.0	Min.	−4.5	4.6	−2.6	4.4
						Max.	2.4	5.1	0.4	3.9
	Dynamic	55.1	54.2	54.2	54.2	Min.	−4.7	3.1	−4.6	3.8
						Max.	3.0	4.5	3.1	4.8

noticeable element emerging from the table is that despite the fact that different delivery methods were used, participants produced very similar evaluations of the footstep sounds amplitudes. On average males gave rise to higher evaluations than females, although the ANOVA analysis conducted for the static and dynamic cases separately, did not reveal statistically significance, both considering the effect of the subexperiments together and separately. Considering instead a comparison at stimulus level, significance was found for gravel ($p < 0.03$) and dry leaves ($p < 0.02$) at dynamic level.

Results of experiment 6 (amplitude adjustment of soundscapes without footstep sounds), are shown in Table 7. Males gave rise to significantly higher evaluations ($p < 0.02$ considering the effect of the subexperiments together, and $p < 0.02$ and $p < 0.04$ considering the effect of the subexperiments separately). In addition, significance was found at stimulus level for the soundscapes courtyard in summer ($p < 0.02$), ski slope ($p < 0.009$) and forest ($p < 0.005$).

Results of experiment 7 (amplitude adjustment of footstep sounds in presence of soundscapes with fixed amplitude), are shown in Table 8. For this experiment, the soundscapes amplitudes were set to the values found as result of experiment 6. It is possible to notice a trend similar to the one of experiment 5. First of all, the footstep sounds amplitudes were evaluated similarly in the two proposed delivery methods. Secondly, males gave rise to higher

Table 7
Results of experiment 6: amplitude adjustment of soundscapes without footstep sounds (using loudspeakers).

Sound-scape	Ref. value	Avg. values			Start. point	Males		Females	
		M	F	M&F		μ	σ	μ	σ
Courtyard in summer	57.9	56.5	52.7	54.6	Min.	−3.0	3.9	−7.6	3.2
					Max.	0.3	4.4	−2.6	2.9
Beach	58.6	58.2	54.2	56.2	Min.	−0.7	6.4	−6.2	3.9
					Max.	0.0	7.3	−2.5	5.1
Ski slope	61.6	61.4	57.1	59.3	Min.	−2.5	4.4	−6.1	3.2
					Max.	2.2	4.2	−2.7	2.6
Park in autumn	50.0	49.7	45.6	47.7	Min.	−1.6	6.7	−6.2	4.3
					Max.	1.1	4.2	−2.4	3.8
Forest	57.9	58.1	52.1	55.1	Min.	−0.2	5.7	−7.0	3.3
					Max.	0.7	3.8	−4.3	4.0
House	51.9	51.4	48.4	49.9	Min.	−2.1	5.9	−6.6	3.8
					Max.	1.2	4.4	−0.3	3.5
Submarine	64.1	62.9	58.6	60.8	Min.	−1.5	7.2	−6.6	3.9
					Max.	−0.7	7.3	−4.2	3.9

Table 8
Results of experiment 7: amplitude adjustment of footstep sounds in presence of soundscapes with fixed amplitude (with loudspeakers).

Surface type	Diffusion type	Ref. value	Avg. values			Start. point	Males		Females	
			M	F	M&F		μ	σ	μ	σ
Gravel	Static	53.0	50.6	46.9	48.7	Min.	−3.9	5.2	−9.8	6.7
						Max.	−0.6	5.8	−2.3	3.7
	Dynamic	52.4	49.6	46.5	48.1	Min.	−4.2	4.1	−9.5	5.4
						Max.	−1.1	4.6	−2.2	4.7
Sand	Static	44.7	49.6	46.1	47.9	Min.	5.3	2.8	0.3	5.4
						Max.	4.6	4.3	2.5	3.6
	Dynamic	44.6	47.8	44.7	46.3	Min.	2.4	3.7	−2.0	5.8
						Max.	4.0	3.6	2.3	5.9
Deep snow	Static	48.1	49.6	46.6	48.1	Min.	1.6	4.1	−2.4	5.4
						Max.	1.5	3.7	−0.3	4.4
	Dynamic	48.6	50.1	46.6	48.4	Min.	0.8	3.0	−4.2	5.4
						Max.	2.4	3.2	0.4	5.6
Dry leaves	Static	48.4	50.9	46.8	48.9	Min.	1.2	3.9	−3.3	6.2
						Max.	3.8	3.6	0.3	3.5
	Dynamic	49.5	51.1	47.5	49.3	Min.	−0.8	3.9	−3.6	5.6
						Max.	4.1	4.5	−0.2	5.6
Forest floor	Static	48.8	49.2	47.8	48.5	Min.	−0.1	3.4	−2.4	4.8
						Max.	1.0	3.4	0.6	4.2
	Dynamic	48.6	49.8	47.1	48.4	Min.	0.2	3.5	−3.0	6.2
						Max.	2.2	3.1	0.1	4.5
Wood	Static	55.0	49.9	47.2	48.6	Min.	−6.1	5.0	−9.0	7.0
						Max.	−4.0	3.1	−6.3	4.1
	Dynamic	55.4	49.8	48.1	50.0	Min.	−8.2	4.8	−11.7	7.9
						Max.	−2.9	2.6	−6.9	4.9
Metal	Static	54.0	54.9	53.3	54.1	Min.	0.3	3.6	−1.2	3.9
						Max.	1.5	2.8	0.0	3.9
	Dynamic	54.2	53.9	52.8	53.4	Min.	−0.9	2.9	−2.4	6.3
						Max.	0.4	3.2	−0.1	3.2

evaluations, although the ANOVA analysis conducted for the static and dynamic cases separately did not reveal statistical significance, both considering the effect of the subexperiments together and separately. Considering the comparison at stimulus level, significance was found only for dry leaves ($p < 0.02$) at static level. In addition, from a comparison with Table 6 it is possible to notice that the evaluations are on average very similar to those obtained in experiment 5.

Results of experiment 8 (amplitude adjustment of soundscapes in presence of footstep sounds with fixed amplitude) are shown in Table 9. For this experiment, the footsteps amplitudes were set to the values found as a result of experiment 5. Males gave rise to slightly higher evaluations in all the stimuli (both using the static and dynamic diffusion for the footstep sounds), although the ANOVA analysis shows that all these differences are not statistically significant both considering the subexperiments together and separately. Considering the comparison at stimulus level, significance was found only for the soundscapes park in autumn ($p < 0.05$) and house ($p < 0.05$) at static level. Comparing the results with those of experiment 6, it is possible to notice that the average values are very similar between the two experiments. Finally, the evaluations of the soundscapes amplitudes are similar in presence of the two delivery methods of the footstep sounds.

Table 9
Results of experiment 8: amplitude adjustment of soundscapes in presence of footstep sounds with fixed amplitude (using loudspeakers).

Soundscape	Diffusion type	Ref. value	Avg. values			Start. point	Males		Females	
			M	F	M&F		μ	σ	μ	σ
Courtyard in summer	Static	54.6	59.7	54.7	57.2	Min.	4.8	5.0	−1.3	9.3
						Max.	5.5	3.0	1.6	5.6
	Dynamic	54.6	59.6	55.6	57.6	Min.	5.3	3.8	1.3	7.4
						Max.	4.7	2.5	0.7	6.6
Beach	Static	56.2	54.5	53.9	54.2	Min.	−1.2	3.0	−2.5	7.4
						Max.	5.5	3.8	−1.8	5.1
	Dynamic	56.2	56.1	53.5	54.8	Min.	−0.5	2.9	−3.8	7.4
						Max.	0.3	3.4	−1.5	7.0
Ski slope	Static	59.3	60.2	59.2	59.7	Min.	1.1	2.9	−0.1	5.8
						Max.	−2.0	1.5	0.1	6.8
	Dynamic	59.3	61.1	59.4	60.2	Min.	2.6	3.6	−0.2	6.0
						Max.	1.0	2.9	0.5	6.4
Park in autumn	Static	47.7	52.4	48.7	50.6	Min.	5.4	3.1	0.9	4.6
						Max.	0.7	2.5	1.1	5.0
	Dynamic	47.7	51.5	49.1	50.3	Min.	3.3	3.0	0.9	5.6
						Max.	4.2	3.2	1.9	3.9
Forest	Static	55.1	57.0	54.8	55.9	Min.	1.7	4.0	−0.6	4.9
						Max.	4.1	6.3	0.0	6.9
	Dynamic	55.1	58.5	56.7	57.6	Min.	3.3	6.5	1.4	7.6
						Max.	3.5	4.2	1.8	6.2
House	Static	49.9	54.6	49.0	51.8	Min.	4.9	3.4	−1.4	6.6
						Max.	2.2	3.7	−0.2	7.3
	Dynamic	49.9	54.7	48.2	51.4	Min.	3.8	6.5	−1.3	8.7
						Max.	5.7	4.0	−2.0	9.9
Submarine	Static	60.8	62.0	58.2	60.1	Min.	2.1	3.6	−2.9	7.3
						Max.	4.5	4.6	−2.0	6.8
	Dynamic	60.8	62.3	57.5	59.9	Min.	2.5	6.2	−3.0	8.3
						Max.	0.5	3.4	−3.5	8.0

Table 10
Gender judgements of the footstep sounds in Condition 1 for both loudspeakers and headphones, for each surface.

Surface	Group 1 (Headphones)						Group 2 (Loudspeakers)					
	Males			Females			Males			Females		
	% M	% F	% M&F	% M	% F	% M&F	% M	% F	% M&F	% M	% F	% M&F
Gravel	50		50	20	20	60	50		50	30	20	50
Sand	50		50	20	20	60	50		50	30	20	50
Deep snow	50		50	20	20	60	50		50	30	20	50
Dry leaves	50		50	20	20	60	50		50	30	20	50
Forest floor	50		50	20	20	60	50		50	30	20	50
Wood	20	30	50	20	20	60	30	20	50	10	40	50
Metal	20	30	50	20	20	60	30	20	50	10	40	50

6. Discussion

The first noticeable element emerging from a comparison between the two sets of experiments is that the use of headphones gave rise to evaluations always higher than those obtained using the surround system. The experiments confirm a tendency which already appeared in the pilot experiment. On average, the difference between the two systems is about 6 dB for the footstep sounds and about 3 dB for the soundscapes. In addition, a *t*-test revealed that such differences are significant only for the footstep sounds ($p < 0.006$ and $p < 0.002$, comparing Conditions 1 and 3 in the two sets of experiments), while no significance was found for the soundscapes. Nevertheless, it is more realistic to think that the values found for the loudspeakers case are those closer to the amplitudes of the footsteps produced in real life (even if a more detailed study should be conducted in order to measure the amplitudes for each surfaces). The same holds for the soundscapes amplitudes.

Another element emerging from the results is that the evaluations of the amplitudes were higher when the adjustment was performed starting from the maximum value rather than the minimum. This aspect was common to males and females and it was found in all eight conditions. Concerning the differences between males and females evaluations, in the headphones case no significant differences were found in all the experimental conditions. Instead, in the loudspeakers case, a small tendency of males in producing higher evaluation was found, even if significance was measured only in few cases at stimulus level. Therefore, it is not possible to claim that in general males evaluations are higher than those of females, neither for footstep sounds or for soundscapes, even if further experiments could investigate deeper into this tendency.

In particular, as mentioned in Section 2.1, the footstep sounds were designed in order to not provide any specific clue about the gender of the walker. The perception of the gender of the footstep sounds was investigated at the end of Condition 1 (i.e., the case of footstep sounds without soundscapes, using both headphones and loudspeakers). For each surface, participants were asked to express a judgement on the maleness or femaleness of footstep sounds they produced. As Table 10 shows, participants did not have a strong preference for the gender of the simulated footstep sounds. Mainly participants judged the sounds they were producing as genderless; when providing an answer coherent with their gender, participants reported that this choice was taken because they listened to themselves walking.

In addition, a difference between males and females was noticed considering the times taken to complete the experiments. In particular, for each experiment females took less time rather than males to take their decisions (on average about 1 min) and these differences resulted as significant using a *t*-test ($p < 0.009$ for the case of headphones and $p < 0.05$ for the case of loudspeakers).

As regards the relationship between footstep sounds and soundscapes, from a comparison between Conditions 1 and 3, it appears that the presence or the absence of soundscapes does not influence the evaluations of the footstep sounds amplitudes. Similarly, comparing Conditions 2 and 4, it can be noticed that the presence or the absence of footstep sounds does not influence the evaluations of the soundscapes amplitude.

Furthermore, the footstep sounds amplitudes were evaluated similarly in the two proposed delivery methods (static and dynamic diffusion), despite their different behavior.

7. Conclusion and future work

In this paper, we designed an experiment whose role was to assess the amplitude perception of footstep sounds when rendered both alone and together with a soundscape. The main goal of this experiment was to assess whether subjects were consistent in their choice of amplitudes. This was performed in order to provide guidelines to designers of interactive soundscapes on how to set the amplitude of the rendered environments.

Results show that subjects are quite consistent in their choice of amplitude, both for footstep sounds and for soundscape. Moreover, the combination of footstep sounds and soundscape does not significantly increase the selected amplitudes.

The results presented in this paper are important in order to provide guidelines to designers of interactive systems concerning the appropriateness of amplitude values which should be chosen when producing soundscapes. Moreover, the differences noticed between choices performed by male and female subjects are interesting and require further investigation.

Acknowledgment

The research leading to these results has received funding from the European Community's Seventh Framework Programme under FET-Open grant agreement 222107 NIW – Natural Interactive Walking.

References

[1] Sonnenschein D. Sound design: the expressive power of music, voice, and sound effects in cinema; 2001.
[2] Turner P, McGregor I, Turner S, Carroll F. Evaluating soundscapes as a means of creating a sense of place. In: Proceedings of international conference on auditory display. 2003. p. 148–51.
[3] R.M. Schafer, The tuning of the world; 1977.
[4] Truax B. Soundscape, acoustic communication and environmental sound composition. Contemp Music Rev 1996;15:49–65.
[5] Eckel G. Immersive audio-augmented environments: the listen project. In: Proceedings fifth international conference on information visualisation, vol. 128; 2001. p. 571–3.
[6] Li XF, Logan RJ, Pastore RE. Perception of acoustic source characteristics: walking sounds. J Acoust Soc Am 1991;90:3036–49.
[7] Pastore R, Flint J, Gaston J, Solomon M. Auditory event perception: the source–perception loop for posture in human gait. Attention Percept Psychophys 2008;70:13–29.
[8] Nordahl R. Evaluating environmental sounds from a presence perspective for virtual reality applications. Eurasip J Audio Speech Music Process 2010;1:426937.
[9] Turchet L, Serafin S, Dimitrov S, Nordahl R. Physically based sound synthesis and control of footsteps sounds. In: Proceedings of digital audio effects conference. 2010. p. 161–8.
[10] Turchet L, Serafin S, Nordahl R. Examining the role of context in the recognition of walking sounds. In: Proceedings of sound and music computing conference. 2010.
[11] Nordahl R, Serafin S, Turchet L. Sound synthesis and evaluation of interactive footsteps for virtual reality applications. In: Proceedings of the IEEE virtual reality conference. 2010. p. 147–53.
[12] Turchet L, Nordahl R, Berrezag A, Dimitrov S, Hayward V, Serafin S. Audio-haptic physically based simulation of walking on different grounds. In: Proceedings of IEEE international workshop on multimedia signal processing. IEEE Press; 2010. p. 269–73.
[13] J. Schacher, M. Neukom, Ambisonics spatialization tools for max/MSP. In: Proceedings of the international computer music conference. 2006.