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The impact of sound in people's behaviour in outdoor settings: A study using virtual reality and eye-tracking

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ABSTRACT

This paper presents an analysis of space perception and how visual cues, such as landmarks and sound, are perceived and impact people's behaviour while exploring a given outdoor space. The primary goal of the research is to investigate how auditory sensations and visual stimuli influence people's behaviour in outdoor built environments. Our technique compares people's perception of the built environment in different conditions: the real world and a replicated virtual world. As a case study, a university campus was used, and four experimental conditions were designed. The study followed a between-subjects design, and the data collection included gaze data acquired from an eye-tracking device as well as self-reports. The study concludes that sound influences human behaviour in such settings. More specifically conclusions are that: i) human behaviour in virtual replications of the real space, including both visual and sound stimuli, is tendentially more similar to human behaviour in the real world than in simulations omitting sound; and ii) there is a difference in human behaviour when people explore the same virtually replicated outdoor space, by varying the presence of sound. This study is particularly useful for researchers working on the comparison between human behaviour in virtual and real environments, related to visual and sound stimuli.

1. Introduction

In the topic of environmental perception, we analyse how the outside world is apprehended by individuals and then translated into actions upon that world (Jones and Gomez, 2010). The built environment influences people's behaviour in numerous ways. The research described in this paper focuses on how auditory senses and visual elements influence people's behaviour in an outdoor built environment.

This study follows our team's prior research on space perception via analysis of real environments and virtual reality settings that simulate real spaces (Dias et al., 2014; Eloy et al., 2015; Ourique et al., 2017). This paper arises from a sequence of studies that aim at assessing the influence of sound in the spatial perception of people exploring outdoor environments. In Eloy et al. (2015), we showed that the presence of landmarks can be objectively identified and assessed by collecting data with GPS and eye-tracking devices, from people's movement while walking in a real space, in a simple space exploration task. In Ourique et al. (2017) we compared people's movement in the real world with their movement in a replicated virtual world and concluded that: i) the level of visual importance of landmarks can be captured by eye tracking data; ii) our virtual environment setup is able to simulate the real world, when performing experiments on spatial perception.

People's experience of space relies on a representation of the environment generated through a conjugation of our senses, that is compiled by our central nervous system (Loomis, 2003). This representation informs our decisions on space use and therefore, by studying our senses we can aim at predicting how people perceive and make use of space. One of the main senses that influences our decisions is vision. Besides vision also sounds have a profound influence on people perception of the environment.

To study the effects of different environmental variables in human behaviour, several authors have used virtual environments that enable the simulation and the manipulation of reality through the creation of alternative environments. Showing that the behaviour of people is similar in real, and simulated environments opens up the possibility to use virtual environments for environment behaviour research (Kort et al., 2003). By testing three environmental-simulation display formats Higuera-Trujillo, Maldonado and Millán have shown that "360° panoramas offer the closest to reality results according to the participants' psychological responses, and virtual reality according to the

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physiological responses" (2017). Chamilothori et al. (2019) present how using photometrically accurate lighting simulations in virtual reality, is a successful alternative method to study the perception of daylit interior spaces.

Existing studies suggest that the perceiving of auditory and visual information of an environment is an interconnected process. Studies like the ones reported by Rohrmann and Bishop research found that providing sound in an environmental simulation "is important in enhancing perceived realism (and also fosters attention and recognition)" (2002, p. 328), A similar study, by Brinkman et al. (2015) observed that adding sound to a visual virtual world had a significant effect on people's experience. Morinaga et al. (2003) refers that visual information has greater effects on the impression related to pleasant factor than auditory information. For Fastl (2004) the addition of visual input, as images of greenery, reduces the perceived loudness of noisy soundscapes. Also, Kınayoğlu states that sound can transform the emotion or mood associated with a place (Kınayoğlu, 2009). Pedersen and Larsman (2008) concluded that noise annoyance is positively correlated to the visual presence of the sound noise (in this case wind turbines) and that the association between noise exposure and response should be assessed as being different in different types of landscapes. Another perspective is the one of Carles et al. (1999) which showed that aesthetically unpleasant sounds such as traffic noise negatively influenced the overall pleasantness of spaces.

Another aspect that is fundamental in our study is the notion and study of landmarks. Landmarks are differentiated parts of environments that by being distinct and memorable help people to comprehend environments (Lynch, 1960). Landmarks and their importance on users' navigation have long been shown in literature (Michon and Denis, 2001; Loomis, 2003; Liu, 2010; Bruns and Chamberlain, 2019). In order to evaluate the importance of landmarks several methodologies and tools have been used as, space syntax (e.g. (Montello, 2007)), biometric sensors analysis (e.g. (Leite et al., 2019)), eye tracking analysis (e.g. (Andersen et al., 2012)), and virtual reality (VR) simulations (e.g. (Waller et al., 2004; Bruns and Chamberlain, 2019)). In this study we use eye tracking to acquire and study gaze data. According to Shiferaw et al. (2019) "gaze control primarily refers to the overt (i.e. involving eye movement) shift of spatial attention".

In this paper, we raise three new hypotheses following our previous research:

Hypothesis 1. The correlation between people's preferred spaces in both real and virtual spaces with sound, is higher than the correlation between people's preferred spaces in both real and virtual spaces without sound.

Hypothesis 2. The presence of landmarks objectively assessed by analysing gaze data acquired from an eye-tracking device, has a higher correlation when comparing real space with virtual space with sound, than when comparing real space with virtual space without sound.

Hypothesis 3. The presence of "audible noisy" landmarks objectively assessed by analysing gaze data acquired from an eye-tracking device, has a low correlation when comparing virtual space with sound with virtual space without sound.

This paper is divided in four sections. In section 2 our research methodology is explained as well as the used experimental settings. In this section, we also describe how experiments in both real and virtual spaces were designed to observe the way people move. Section 3 presents our obtained results and, in section 4, we discuss those results in line with the hypothesis raised for the research, taking conclusions and highlighting the limitations of the study and topics of further research.

2. Experimental methodology

2.1. Experimental conditions

The methodology used in this study encompasses the analysis of four experimental conditions, using the same physical territory, namely, the exterior area of Iscte's University Campus, as shown in Fig. 1. The four conditions are: i) Condition 1 – computer assisted automatic space analysis performed by the following tools: space syntax DepthmapX[1] and Space Syntax Toolkit for QGIS[2]; ii) Condition 2 - real space (RE) analysed by direct observation of people, with data collection; iii) Condition 3 - virtual space without sound (VRWS) analysed in a semi-immersive virtual environment by direct observation of people, with data collection; iv) Condition 4 - virtual space with environmental sound (VRS) analysed in a semi-immersive virtual environment by direct observation of people, with data collection.

In condition 1, we used Space Syntax analysis methodologies and have performed a Visibility Graph Analysis (VGA) and a Segments Analysis. Space Syntax theories state that patterns of human behaviour in space can be recognized and measured through variables such as Integration, Choice, and Depth (Hillier and Hanson, 1984). This analysis aimed at obtaining standard integration, control, depth, and intelligibility measures which help to identify the potential behaviours of movement of users of such area. With Integration one can measure how close an origin space is to all other spaces. Control "measures what degree of choice each space represents for its immediate neighbours as a space to move" while Depth measures how much "it is necessary to go through intervening spaces to get from one space to another".[3] Depth is analysed as Total Depth, meaning the sum of the topological depth from any a node to all the others, and Mean Depth (Hillier and Hanson, 1984). Mean Depth is equivalent to Total Depth "relativised to the number of axial lines or nodes of the system and represents the average number of steps needed to reach any of the axial lines or nodes in the system" (van Nes and Yamu, 2021, p. 47). Intelligibility measures how well a space can be read within the system, in other words, a system with high intelligibility', implies that the whole can be read from the parts. With this analysis, we obtained NACH (normalised angular choice) and NAIN (normalised angular integration[4] (Hillier et al., 2012) that help us to identify the most integrated space in the campus according to space syntax analysis that has been used as the location to start the experimentation of conditions 2, 3 and 4 (staring point (S) can be seen in Fig. 1). The study of condition 1 was published in (Eloy et al., 2015).

Condition 2 consisted of an analysis of how people walk in the real space (Figs. 2 and 3). The experiment was performed in the campus area, exactly in the same location that was subject to space syntax analysis in condition 1 (Fig. 1).

For condition 3, a virtual model of the Iscte's campus was modelled and experiment participants were allowed to navigate through it, in a semi-immersive virtual environment where the visual stimuli were the

[1] https://www.spacesyntax.online/software-and-manuals/depthmap/, last seen in 13/02/2022.

[2] https://www.spacesyntax.online/software-and-manuals/space-syntax-toolkit-2/, last seen in 13/02/2022.

[3] Definitions from the Space Syntax online Glossary available at https://www.spacesyntax.online/glossary/.

[4] NACH (normalised angular choice) and NAIN (normalised angular integration) are used in Space Syntax analysis methodology and derive from the measures of choice and integration. Choice measures how likely an axial line or a street segment it is to be passed through on all shortest routes from all spaces to all other spaces in the entire system (Hillier et al., 1987), and integration measures how close the origin space is to all other spaces. Normalised angular choice divides total choice by total depth for each segment in the system, therefore adjusting choice values according to the depth of each segment in the system. Normalised angular integration normalise angular total depth by comparing the system to the urban average (Hillier et al., 2012).

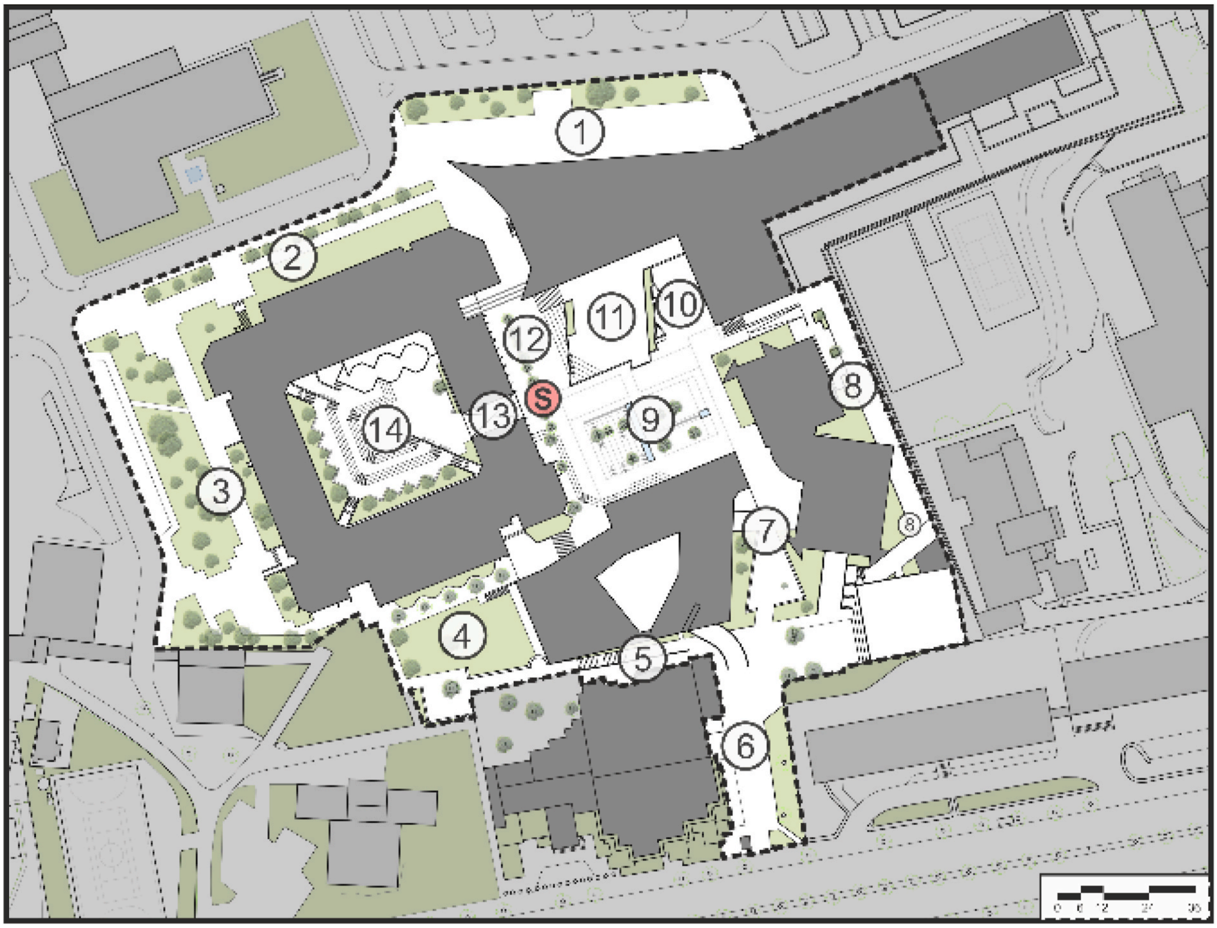

Fig. 1. Main areas of the Iscte campus and starting point (S). Numbers 1 to 14 identify spaces in the campus.

Fig. 2. Iscte's campus used in the experiment of condition 2.

Fig. 3. Experimental subject in condition 2 using the eye-tracking.

only stimuli enabled (Figs. 4 and 5). Our CAVE-type of device is a semi-immersive Virtual Reality Environment with a projection screen of 4m × 3m, a high-definition (HD 720) stereoscopic Video Projector (Optoma W307USTI Ultra Short Throw) capable of active stereoscopy and Active Shutter 3D Glasses (Optoma ZD301). Our virtual environment setting, features a field of view less than 180° and therefore is defined as semi-immersive, as opposed to the immersive case, where the field of view needs to be a figure between 180° and 360°. Our system provides 3D binaural feedback as well as full body stereoscopic visual feedback, consistent with the user input, which enables the user to feel immersed in the virtual space, also enabling a sense of presence as if he/she is present and can interact with the virtual environment. In fact, high

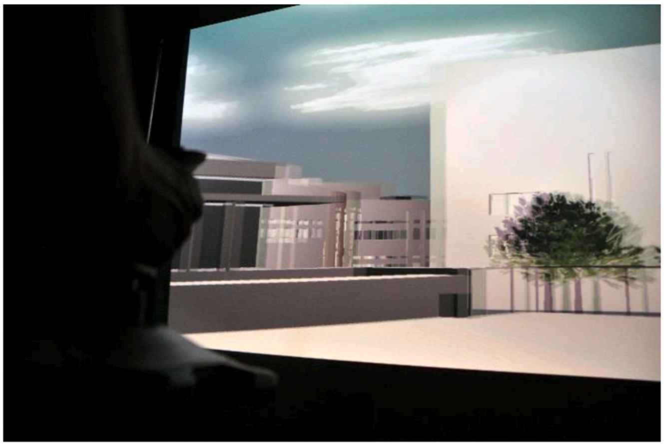

Fig. 4. A snapshot of Iscte's virtual campus visible in the semi-immersive virtual environment used in the experiment of conditions 3 and 4.

Fig. 5. Participant of condition 3 using the instrument for data collection (eye-tracking) as well as the stereoscopic glasses in the semi-immersive virtual environment.

levels of sense of presence were measured by a standard self-report, as it will be detailed in the paper.

The 3D model was produced in Revit and the software CAVE Hollowspace (Soares et al., 2010), fully developed and maintained in-house by our research team, was used for the virtual reality experience. Besides the 3D built structure of the campus, avatars were also included along the virtual campus to better simulate the reality of such place. The position of the avatars is represented in Fig. 6. Participants could navigate through the virtual environment using a joystick (Logitech Extreme 3D Pro) with (Fig. 5). The walking speed for the virtual experience was fixed and defined using the average speed of the participants of condition 2. This value was constant for the whole experiment, so that the subject could only either be standing still or moving in the virtual environment at this fixed speed.

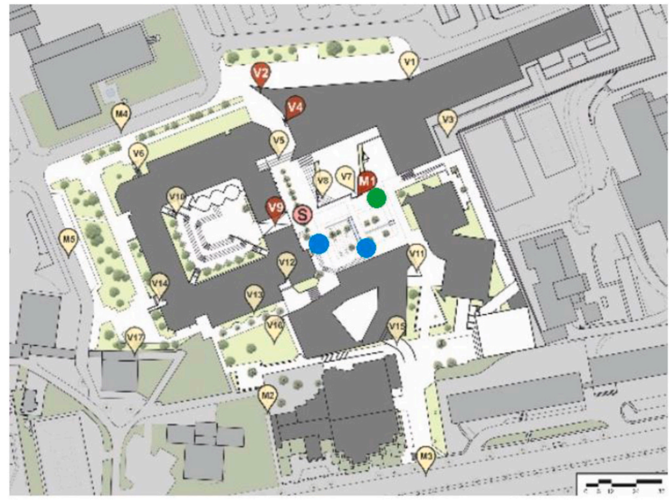

Fig. 6. Full set of identified landmarks (yellow), analysed landmarks (red) starting point (S) of the experiment. and focused sound sources of water (green) and avatars (blue) (in condition 3 silent avatars were position in the blue circles). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Condition 4 consisted of the same virtual model and navigation mode of condition 3, visualized in the same semi-immersive virtual environment, with the difference that environmental sound was added to the experiment. In condition 4 real sounds of the place, previously collected, could be heard. For that purpose, samples of circa 5 min sound were recorded in the real space and then treated and played in the virtual environment, that features 3D binaural simulation of the space, while experiments were being performed. The 3D mapped sounds included: the sound of airplanes (very present along the campus); the sound of water in fountains; and the sound of people chatting at a distance. The sound of a water fountain was positioned in landmark M1 and the sound of people chatting was attached to the avatars whose position is identified in Fig. 6 in space 9, one of them close to V9. Environmental sounds, including passing airplanes, were present in the model. The sound was spatialised in 3D, synthetised as binaural sound and reproduced to the users in the experimental condition 4, by means of a headset.

The metrics studied in conditions 2, 3, and 4 are explained in section 2.5.

Since the aim of this paper is to analyse the influence of sound in people's movement, we will specially focus on the analysis of conditions 2, 3 and 4.

2.2. Experimental settings

The experiments undertaken for conditions 2, 3 and 4 were performed with a between subjects design, where each participant volunteer provided results for only one condition. Subjects freely explored the campus for a period of approximately 10 min for conditions 2 and 3, and for approximately 7 min for condition 4. Since the three studies were based in observing people walking, several decisions were taken in order to define how to perform the experimentations. The prior Space Syntax analysis (condition 1), was used in order to select a location in the Campus to start the experimentation in conditions 2, 3 and 4. To that aim, we selected the place with higher integration value measured in condition 1 as the start location (indicated with an "S" in Fig. 1).

According to Sayed et al. the syntactic measure of integration is "indicative to how many people are likely to be in a space, and is thought to correspond to rates of social encounter and retail activities" (Al_Sayed et al., 2014, p. 15) and therefore, for our case study, refers to the place where social encounters have the potential to be higher. According to the theory, from this place S all possible trajectories could be followed by participants, enabling them to choose freely from a large variety of options.

2.3. Participants

The recruitment of participants considered their eligibility to take part of the experiment if the following criteria was meet: i) participants that didn't have an architecture background, ii) participants that had good prior knowledge of the university campus, iii) participants that didn't have motion constrains, physical disabilities and did not suffer from cardiovascular diseases. We did not control the age of participants and allowed it to vary randomly, whereas we did our best effort to balance the gender in each condition.

The distribution of participants in the three conditions is described in Table 1.

2.4. Experimental protocol

The experimental protocol included two parts: i) a prospecting one during which volunteer participants were survey to check eligibility criteria; ii) and the proper experiment, where participants were asked to explore the prescribed area of the university campus (physical space in condition 2 and virtual environment in condition 3 and 4). All participants engaged in experiments of conditions 2, 3 and 4, received the same instructions to accomplish the campus exploration. Before the experiment started participants were briefed about the task to be performed and the data collection equipment they would carry. Participants were told to freely explore the area the best that they could for 10 min. At the end, they answered self-reporting questionnaires about their experiment. The experimental protocol was approved by the Ethical Committee of ISCTE – Instituto Universitário de Lisboa, prior to the user study.

2.5. Data collection

For conditions 2, 3 and 4, we collected both objective and subjective data from the participants' activities namely, objective gaze data, measuring fixations and saccades generated by participants, while walking along the paths chosen to explore the campus area, and subjective questionnaire data (self-reports) on the topics of their attachment to the space. The measured objective data consisted of the gaze of participants during the entire experiment (described by fixations and saccades).

From a qualitative analysis, twenty-two landmarks were identified in campus, based on special architectonic elements (e.g., prominent doors, unusual shape) and audio sources (e.g., waterfalls), as depicted in Fig. 6. We then conducted an analysis of the university campus by means of Space Syntax (Eloy et al., 2015) as explained in section 2.1. This analysis allowed us to define the landmarks to study by choosing the ones placed in more integrated areas. Based on a VGA analysis we chose the four most integrated landmarks – V2, V4, V9 and M1 – that allowed us to perform the gaze (based in eye-tracking) analysis in conditions 2, 3 and 4 (see Fig. 7).

In the 3 experimental conditions, the raw eye-tracking gaze data was collected with the following means:

- Condition 2 - participants used a head-mounted eye tracker from Ergoneers (Dikablis DHUV3.0 - 0046 model,[5] binocular, with eye cameras tracking frequency of 60 Hz, eye cameras resolution of 648 × 488 pixel, visual camera resolution of 1920 × 1080 pixel @30 fps). A backpack used by participants in condition 2 stored a Surface Pro 2 computer that was collecting the data from the eye tracking device.
- Condition 3 and 4 - participants used the same head-mounted eye tracker. Since participants were standing still in a laboratory, a desktop computer was used to collect the eye tracking data.

In all the three above mentioned conditions, we extracted several primitives for each timestamp from the gaze data, such as X and Y gaze location on each video source, eye saccade movement, fixation state and pupil area (height and width). We used a fixation duration metric, according to the principles of Salvucci and Goldberg (2000). The methodology used to evaluate landmark influence was based on an analysis of events which describe the presence of a landmark on the field video. Fast-head movements and fixations lower than 50 ms were not considered for analysis. For our analysis we used the DLab software of Ergoneers.[6] In an exhaustive manner we scanned all the video of an experiment of each subject to identify the ranges where a given landmark was in the field of view. After marking these ranges, we inspected the position of the eye tracker, and signal a sub-range where the gaze of the user was over each landmark. In this manner we were able to compute the percentages of time the number of fixations and saccades of the user, corresponding to when he/she was actually looking at the landmark, in relation to the wider range where the landmark is in the field of view of the user.

In this study we used the aggregated values of gaze data -"fixations (pauses over informative regions of interest) and saccades (rapid movements between fixations)" (Salvucci and Goldberg, 2000, p. 71). The use of these measures enabled us to focus our analysis on what attracted the most attention from the participants.

The subjective data collected by self-reporting questionnaires, included:

- Questionnaires on space perception regarding Iscte's campus (questionnaire 3 - for conditions 2, 3 and 4, see Table A in supplementary material).
- Questionnaires on the felling of presence (questionnaire 1 and 2 – for condition 3 and 4) following the three questions on presence by SUS (Slater et al., 1994) and the presence questionnaire of Witmer & Singer (Witmer and Singer, 1998).

A summary of our four experimental conditions is presented in Table 2.

3. Results and analysis

The VGA analysis (condition 1) shows that areas 9, 12, 14 and the transition zone between areas 1 and 2 (see Fig. 1) have high values of Integration, Intelligibility and Control and low values of Mean Depth,

Table 1
Distribution of participants.

	Number of participants	Gender		Range of age	Mean age	Standard deviation
		Female	Male			
Condition 2	20	8	12	19–46	24.6	7.2
Condition 3	19	8	11	18–32	22.5	4.7
Condition 4	25	14	11	18–42	20.4	6.1

[5] https://www.ergoneers.com/en/en/hardware/eye-tracking/head-mounted/, last seen in 13/02/2022.
[6] https://www.ergoneers.com/en/data-capture-software-and-analysis-software/d-lab/, last seen in 13/02/2022.

Fig. 7. The four landmarks (M1 photo was taken when the waterfall was off.

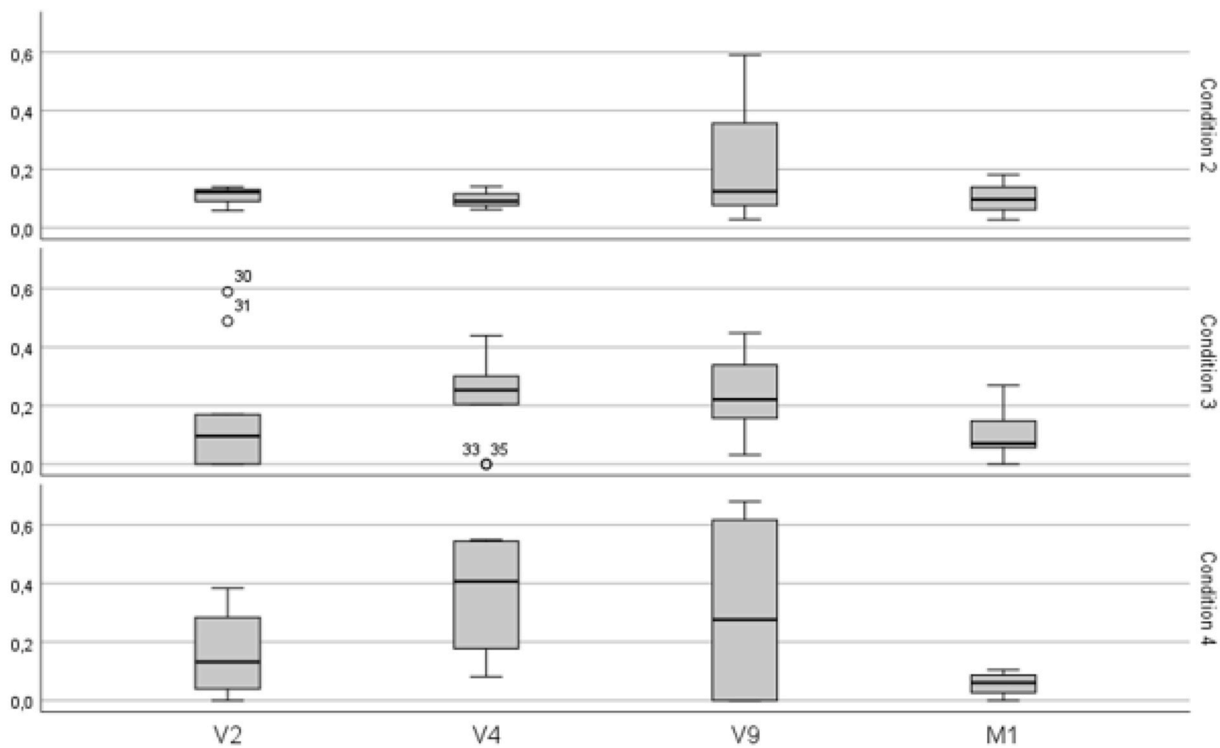

Fig. 8. Box-plot representations of the four landmarks.

indicating that, in the context of the studied area, those areas are very central, easily reachable and are areas where the whole system is visually controlled and easily understood. More peripheral areas like 2, 3, 4 and 5 present the opposite values and constitute areas where users more rarely access and are not part of the regular flow.

3.1. Feeling of presence analysis

From the self-reported questionnaires, we obtained the felling of presence (for condition 3 and 4) in order to assess how similar were the simulations of these two conditions and therefore how able they were to be compared to the real environment (condition 2). Measuring the feeling of presence was important to the study to validate the virtual reality scenarios as being close to reality. For condition 3 the questionnaire on presence had the three questions by (Slater et al., 1994) and 22 questions by (Witmer and Singer, 1998). For condition 4, four questions about audio were added to the previous ones. Participants answered each question using a Likert scale from 1 (totally disagree) to 7 (totally agree) and their answers were summed, providing each participant an index. Thus, for each participant, the ratio between its index and the ideal index (152) allows to obtain the individual feeling of presence. Being 100% the maximum feeling of presence for these questionnaires, participants in condition 3 and condition 4 self-reported high levels of feeling of presence, respectively, 85.8% and 84.1%, computed as the average of each participant feeling of presence multiplied by 100.

3.2. Identification with the campus analysis

From the self-reported spatial preferences done by applying questionnaires, we obtained the level of identification of the participants with Iscte's campus (for conditions 2, 3 and 4).

To measure the level of identification with ISCTE's campus we analysed two questions ("I identify myself with Iscte", "I like ISCTE very much"). Participants answered each question using a Likert scale from 1 (totally disagree) to 7 (totally agree). The analysis of the means revealed a high level of identification with Iscte both in the real, and in the virtual scenarios (Table 3). Furthermore, there were no significant differences in the level of identification between the real experience and the two virtual scenarios. These questions were done in order to assess how

Table 2
Resume of the four experimental conditions.

Conditions	Summary
Condition 1 - Space Syntax analysis	Computer assisted automatic space analysis using space syntax DepthmapX and Space Syntax Toolkit for QGIS software. No observation of people. Analysed metrics: Integration, Intelligibility, Control and Mean Depth.
Condition 2 - Real space (RE)	Participants walk in a real environment. Direct observation of people; n = 20; between subjects design. Analysed metrics: objective data gaze (fixations and saccades); subjective questionnaire data (self-reports) on the topics of their attachment to the space.
Condition 3 - Virtual space without sound (VRWS)	Participants navigate in a semi-immersive virtual environment. Direct observation of people; n = 20; between subjects design. Analysed metrics: gaze (fixations and saccades); self-reports on the topics of attachment to the space and felling of presence.
Condition 4 - Virtual space with environmental sound (VRS)	Participants navigate in a semi-immersive virtual environment. Direct observation of people; n = 20; between subjects design. Analysed metrics: gaze (fixations and saccades); self-reports on the topics of attachment to the space and felling of presence.

Table 3
Level of identification with Iscte's campus. Values vary from 1 (totally disagree) to 7 (totally agree).

	I like ISCTE very much		I strongly identify with ISCTE	
	mean	standard deviation	mean	standard deviation
Condition 2	5.7	3.3	4.6	3.7
Condition 3	5.2	3.3	4.5	3.4
Condition 4	5.7	3.9	4.8	4.2

connected participants were to Iscte and therefore what would be the engagement in responding correctly to the more specific user study questions.

3.3. Green, blue, and less enjoyable areas analysis

From the self-reported spatial preferences done by applying questionnaires, we also obtained: i) the relevance of water and trees to make a space more comfortable (for Condition 3 and 4); ii) a personal assessment on what were the less comfortable spaces and the ones who bothered them the most (for condition 3 and 4) (see Table 4).

For conditions 3 and 4 participants were asked about the relevance of water (e.g., fountains) and trees to make a space more comfortable. Participants answered each question using a Likert scale from 1 (totally disagree) to 7 (totally agree). Participants answered that both elements have a big relevance. The correlation among results of condition 3 and 4 is high (0.96).

Table 4
Relevance of the presence of water elements and trees for the feeling of comfort in outdoor spaces. Values vary from 1 (totally disagree) to 7 (totally agree).

	The existence of water elements makes a space more comfortable		The existence of trees makes a space more comfortable	
	mean	standard deviation	mean	standard deviation
Condition 3	5.4	4.7	5.7	4.4
Condition 4	6.0	3.8	6.0	3.8

In condition 3 and 4 participants were also asked about the areas that were less comfortable spaces and the ones who bothered them the most. Besides identifying the number of the area, participants were also asked to explain the reason of such decision. There are not many results since not all the participants answer these questions and several said that no area was bothering them. Results show therefore very low correlations. Nevertheless, some of the reasons mentioned for not liking an area, are relevant for a qualitative analysis of the results of this study. The reasons for not liking were "without green areas", "too dark", "empty", "segregated", "not looking like the real". Spaces that were considered less comfortable and less enjoyable were, among others 7 and 8 and to a lower level 1, 6 and 13.

3.4. Preferred areas analysis (hypothesis 1)

For proving hypothesis 1, we measured the self-reported spatial preferences in all 3 conditions. In this study the independent variable is the sound and the evaluated dependent variable is the correlation between the preferred areas.

According to our hypothesis 1, condition 2 (real space) and 3 (virtual space without sound) should have a lower correlation than condition 2 (real space) and 4 (virtual space with sound).

From the self-reported spatial preferences done by applying questionnaires, we obtained a personal assessment on what were their preferred areas (for conditions 2, 3 and 4) (see Table 5).

Regarding the preferred areas, participants indicated their three favoured areas, using a scale of more to less, among the 14 exhibited in Fig. 1. We then gave to the 1st preferred a total of three points, to the 2nd preferred a total of two points and to the 3rd preferred a total of one point. By summing all the points each space received, we have identified the preferred areas of the campus (Table 5).

In condition 2, the subjects tended to prefer areas dominated by vegetation (areas 3 and 4) as well as central areas (area 9). In both conditions 3 and 4 subjects preferred the areas that, in the real environment, have the most social life of the campus (areas 9, 11, 14).

Correlations among this data revealed: a strong positive correlation (0.88) between condition 3 (VRWS) and 4 (VRS); a moderate positive correlation (0.50) between condition 2 (RE) and 3 (VRWS); a less moderate positive correlation (0.42) between condition 2 (RE) and 4 (VRS). These results contradict hypothesis 1, $0.42 < 0.5$. The analysis on the three conditions revealed that areas more appreciated in the real environment (condition 2) are not the same as the ones in the virtual environment (condition 3 and 4). Nevertheless, there is a strong positive correlation between areas appreciated in both condition 3 and condition 4 which is coherent with the fact that the same environment is presented in both conditions except for the sound variable. The medium correlation between the conditions Real and Virtual, although all participants showed a high level of identification with the campus, drives us to conduct further studies on this subject in the future.

A preliminary hypothesis for such a correlation, that requires further experimental validation, is that participants of the virtual experiment were first curious and then satisfied by the virtual representation of places they like. For the real experiment, participants might have learned better the campus and discovered places they did not knew well.

3.5. Gaze and landmarks analysis (hypothesis 2 and 3)

Table 6 shows the aggregated fixations and saccades occurred for each landmark per subject, in conditions 2, 3 and 4. In this study the independent variable is the sound and the dependent variable is the correlation of gaze data.

Only seven from the 18 experiments of conditions 2, 13 from the 20 experiments of Condition 3, and 22 from 25 experiments of condition 4 were considered valid for the eye-tracking analysis.

According to hypothesis 2 and 3 the presence of landmarks

Table 5
Preferred areas by the participants.

Areas of preference	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Condition 2	5	18	23	29	0	0	5	1	22	0	7	3	0	4
Condition 3	3	1	6	15	1	3	3	3	35	0	22	3	1	17
Condition 4	4	12	9	8	0	0	8	9	31	3	23	10	8	17
Mean	4.0	10.33	12.67	17.33	0.33	1.0	5.33	4.33	29.33	1.0	17.33	5.33	3.0	12.67
Standard Deviation	1.0	8.62	9.07	10.69	0.58	1.73	2.52	4.16	6.66	1.73	8.96	4.04	4.36	7.5

objectively assessed by using gaze data acquired by an eye-tracking device: hypothesis 2 – has a higher correlation when comparing real space with virtual space with sound, than when comparing real space with virtual space without sound; hypothesis 3 – has a low correlation when comparing virtual space with sound with virtual space without sound.

Regarding the aggregated fixations and saccades (Table 6), V9 is the landmark that in condition 2 and 4 has higher values with V2 being the second one, both in condition 2 and 3. V4 is the landmark with higher percentage in condition 3 and the second with highest values in condition 4. V4 is however the one raking less for condition 2 while M1 is the one raking less for condition 3 and 4.

The landmarks correlations under the considered conditions are presented in Table B in the section Supplementary material.

Table 7 shows the correlations calculated for each landmark and between conditions 2 and 3 (real and virtual without sound), conditions 3 and 4 (virtual without sound and virtual with sound), and conditions 2 and 4 (real and virtual with sound).

Our data analysis enables us to say:

- For M1 there are moderate positive correlation between condition 2 and 4 (N = 4) and a very low positive correlation between condition 2 and 3 (N = 4). Correlation between condition 3 and 4 (N = 11) is low negative, which can be related to the presence of sound which makes the virtual environment different between these two conditions.
- For V9 correlation strong positive between condition 2 and 4 (N = 4) and is low positive between condition 2 and 3 (N = 4) which leads us to conclude that sound had no influence here. Correlation between condition 3 and 4 (N = 10) is low negative pointing to possible influence of sound.
- For V2 and V4 correlations between condition 2 and 4 are low positive and between condition 2 and 3 are moderate negative for V2 and small negative to V4 exhibiting opposite directions.
- For V2 and V4 correlations between condition 3 and 4 are high positive, being higher for V4.

It is important to point out that it is only possible to consider the obtained results as tendencies due to the size of the samples used.

To find out if the differences between conditions 2, 3, and 4 are statistically significant we conducted a one-way ANOVA. Hence, this method provided a statistical test of whether mean values results, of each landmark are equal in conditions 2, 3 and 4 versus there is at least one mean value different for one of the conditions in the experiment. The results are presented in Table 8.

To perform the ANOVA test, previously were analysed the required assumptions: independence of cases; normal distribution and test of homogeneity of variances. The observations are from different individuals in each of the conditions, so observations independence is confirmed; respecting the normal distribution, it should be noted that only landmark V2, in condition 3, escapes the normal distribution condition; finally, the test of homogeneity of variances of each landmark in the three conditions, and only landmark V9 fails homogeneous variances. The assumptions results tests are presented in Table C and Table D, respectively, in the section.

Supplementary material. Regarding this, it is important to note that ANOVA is not robust to violations to the assumption of independence. Therefore, since only one landmark is skipping this assumption, the test was conducted.

As it can be observed in Table 8 for all the landmarks the column values Sig. - the p-values - are all higher than 0.05 (5%), therefore the hypothesis of equal means across the three conditions is not rejected, meaning that there are not statistically significant differences in the means between the three conditions. In fact, given the obtained data, it is not possible to statistically identify differences in the mean values of the landmarks used – V2, V4, V9 and M1. The small size of the collected data may be biasing the results.

3.6. Relation between different obtained data

The four variables used - V2, V4, V9, and M1 landmarks - were selected from the Space Syntax analysis (see 2.1) and therefore had no connection with the participants' measurement of campus.

On the other hand, space preference questions on campus are related to presence of trees, water, and identification with the space, regardless of the chosen landmarks. When choosing the prefeed space participants had a list of all the campus spaces and not only the four landmarks. Furthermore, the ranking of preferred areas results from a construction obtained from the individual rankings of the participants, not an observable dimension of the participants.

But, above all, it can be observed (Fig. 1 and Table 5) that the preferred areas:

- dominated by vegetation (areas 3 and 4), as well as central areas (area 9) - for Condition 2;
- areas with social life (areas 9, 11, 14) - for conditions 3 and 4;

Are distinct from the landmarks observed and measured, and some preferred areas and measured landmarks are even distant from each other.

4. Discussion

Our analysis on the data obtained in the conducted experiments, allowed us to assess the hypothesis raised for this research.

This study assumes that when simulating more senses than just the visual one, a virtual environment is perceived as being closed to the reality. We then raised three hypotheses following this assumption.

Hypothesis 1. The correlation between people's preferred spaces in both real (condition 2) and virtual spaces with sound (condition 4) is higher than the correlation between people's preferred spaces in both real (condition 2) and virtual spaces without sound (condition 3).

Although it would be expected a higher correlation between conditions 2 and 4 regarding the preferred areas than the one between conditions 2 and 3, the difference among them is not statistical significant, regarding the sample. Therefore, hypothesis 1 is not proven.

Questions made to the participants enabled also to identify that the presence of water and of trees is relevant for making a space more comfortable which confirmed the choices of preferred areas. In fact, area 9, one of the preferred ones in conditions 2, 3 and 4, is a central place where water (a cascade and water lines on the floor) plays a relevant

Table 6
Fixations and saccades for each landmark, per subject (condition 2 subjects RE02 to RE10, condition 3 subjects VRWS03 to VRWS19, and condition 4 subjects VRS01 to VRS25). The values shown represent the percentage of time that the participant looked at the landmark when it was on his/her field of view. "-" means that the subject did not pass through the landmarks and "o" means that the subject did not look at the landmark.

Subject/Landmark	V2	V4	V9	M1
	(%)	(%)	(%)	(%)
Condition 2				
RE02	12.22	6.20	59.03	18.15
RE03	32.12	10.69	52.62	–
RE04	–	5.13	4.17	30.43
RE05	30.15	4.95	8.75	–
RE06	5.83	9.09	2.86	2.70
RE08	13.95	14.15	12.44	9.65
RE10	5.84	–	–	8.48
Mean	16.69	8.37	23.31	13.88
Standard deviation	10.66	3.32	23.27	9.64
Confidence interval	0.09	0.03	0.19	0.08
Condition 3				
VRWS03	16.96	35.71	21.74	23.21
VRWS04	o	26.87	22.12	o
VRWS05	9.59	30.12	15.74	3.45
VRWS07	–	29.63	9.24	2.66
VRWS08	–	o	9.43	–
VRWS09	o	25.32	41.97	6.92
VRWS11	–	–	12.25	1.21
VRWS14	58.93	43.95	14.35	14.75
VRWS15	48.89	20.50	44.77	26.97
VRWS16	–	–	12.03	2.94
VRWS17	8.73	o	33.87	7.10
VRWS18	13.64	21.43	3.16	8.02
VRWS19	o	o	33.23	5.68
Mean	26.12	29.19	21.07	9.36
Standard deviation	20.04	7.23	12.59	8.99
Confidence interval	0.16	0.05	0.07	0.05
Condition 4				
VRS01	o	–	21.38	o
VRS02	–	–	64.75	–
VRS03	5.03	–	o	9.24
VRS05	3.19	24.74	–	o
VRS06	3.64	18.35	–	–
VRS07	–	28.07	o	2.06
VRS09	o	55.00	55.32	5.38
VRS11	–	–	58.38	2.03
VRS12	7.97	27.44	o	o
VRS13	59.79	14.48	–	1.94
VRS14	–	–	41.18	1.61
VRS15	–	–	o	13,.64
VRS16	–	–	10.76	o
VRS17	–	o	–	–
VRS18	38.46	8.11	o	10.53
VRS19	33.33	68.75	–	21.79
VRS20	–	–	–	o
VRS21	–	22.06	39.26	6.85
VRS22	–	1.77	30.36	–
VRS23	–	–	o	–
VRS24	18.42	53.98	68.06	6.85
VRS25	12.50	–	–	–
Mean	20.26	29.34	43.27	7.45
Standard deviation	18.50	20.11	18.77	5.91
Confidence interval	0.12	0.12	0.12	0.03

The box-plot representations of the landmarks, Fig. 8, display slight differences in the statistical central measures (average and median) and dispersion measures (standard deviation) of the landmarks, according to conditions 2, 3 and 4.

role. In condition 2, the subjects tended to prefer areas dominated by vegetation (areas 3 and 4) which were not preferred in the virtual environment (maybe because virtual vegetation was not so realistic as the real one, as one participant stated). Also, qualitative answers by participants, as not liking places because they are "too dark", "empty", or "segregated", showed us the relevance of designing good qualified architectural space and the impact that not well qualified spaces have on the wellbeing of who uses them. These results are in line with to the ones found by Montello (2007), that mentions that "greater visual access will decrease mystery and uncertainty" and, "visual access will tend to reduce excess stress", as well as and the ones by Rohrmann and Bishop (2002). Also, this study shows that green and blue areas are perceived as comfortable and satisfactory spaces, as shown in Shoaib et al. (2021) and Skärbäck et al. (2014), adding the fact that such perception is also recognized on university campuses rather than just in residential areas.

Table 7
Correlations between Landmarks in the three conditions (2, 3, and 4).

Condition		V2	V4	V9	M1
2 vs 3	Pearson Correlation	**−0.566**	−0.295	**0.220**	0.076
	Sig. (2-tailed)	0.617	0.570	0.250	0.924
	N	3	6	4	4
2 vs 4	Pearson Correlation	0.368	0.391	**0.750**	**0.558**
	Sig. (2-tailed)	0.632	0.744	0.250	0.442
	N	4	3	4	4
3 vs 4	Pearson Correlation	**0.659**	**0.838**	−0.288	−0.330
	Sig. (2-tailed)	0.542	0.162	0.420	0.321
	N	3	4	10	11

Table 8
ANOVA for results of Table 6 with the tree conditions.

		Sum of Squares	df	Mean Square	F	Sig.
V2	Between groups	0.000	2	0.000	0.005	0.995
	Within groups	0.821	23	0.036		
	Total	0.821	25			
V4	Between groups	0.137	2	0.069	2.357	0.115
	Within groups	0.758	26	0.029		
	Total	0.896	28			
V9	Between groups	0.017	2	0.008	0.170	0.845
	Within groups	1.530	31	0.049		
	Total	1.547	33			
M1	Between groups	0.31	2	0.015	2.468	0.102
	Within groups	0.186	30	0.006		
	Total	0.217	32			

Hypothesis 2. The presence of landmarks objectively assessed by analysing gaze data acquired from an eye-tracking device, has a higher correlation when comparing real space with virtual space with sound (conditions 2 and 4, respectively), than when comparing real space with virtual space without sound (conditions 2 and 3, respectively).

Correlation for M1, the landmark where sound was more evident, between conditions 2 and 4, is higher than the one observed between conditions 2 and 3. Correlation between conditions 3 and 4 ($N = 11$) is a low negative, which can be related to the presence of sound, making the virtual environment different between these two conditions. These results suggests that our analysis shows a tendency to prove hypothesis 2.

V9 in condition 4 is the second landmark where the existence of sound is more audible, since speaking avatars are closer. The correlation between conditions 3 and 4 for V9 ($N = 10$), is a low negative which indicates that indeed, in this case, sound might have influenced the participants.

In the case of V2 and V4 the correlation between conditions 2 and 3 are a moderate negative ($N = 3$) and a low negative ($N = 6$), respectively, pointing opposite choices and therefore a difference between real and virtual environments. But this is not observed in all variables. Nevertheless, this hypothesis is not proven for all the landmarks. Since N is very small for most collected gaze data, our results do not allow to have statistical significant conclusions. Hypothesis 2 is therefore not proven.

Hypothesis 3. The presence of "noisy" landmarks objectively assessed by analysing gaze data acquired from an eye-tracking device, has a low correlation when comparing virtual space with sound with virtual space without sound.

When comparing conditions 3 and 4, the presence of sound in condition 4, gives to the subject an experience closer to the real environment, with the consequent increased perception of the landmarks.

On one side, for V2 and V4, the landmarks where there is no emerging sound, correlation between conditions 3 and 4 are a high positive. On the other side, for M1 and V9, the landmarks where there is emerging sound (avatars speaking and water falling respectively), there is a low negative correlation between conditions 3 and 4, showing that sound may influence people's behaviour. Hypothesis 3 is therefore proven.

Hypotheses 2 and 3 were simultaneously evaluated by comparing the equality of the observed mean values of the landmarks V2, V4, V9 and M1 in the different environments – real, virtual without sound and virtual with sound – with the ANOVA test. No statistically significant differences were observed in the mean values of the landmarks in the three conditions.

These results show that participants perceive a specific virtual environment differently if it has environmental sound or not, following Brinkman et al. (2015) and Serafin et al. (2018). The novelty of our study is the use of the gaze data acquired from an eye-tracking device to prove this relation.

4.1. Limitations of this study

This study has two identified limitations.

The first is the small sample of experimental subjects due to the complexity, duration and costs involved in these experiments. The results obtained by analysing gaze data, showed us that for this type of research, the number of subjects for each conditions needs to be much higher. In fact, in most of the reported cases, the collected data only enabled to acquire a low number of gaze data for each landmark. The high demand of time needed for each data collection on site, prevent us to obtain more subjects that could be incentivized for performing the experiment.

The second limitation is the effect of distance of the subject to the landmarks, when having the landmarks under his/her saccade and fixation ranges. We believe that it might be possible that for landmarks which are closer to the participant, the percentage of fixation and saccades are higher than for landmarks that are more far away. If this is a limitation of the study, it needs to be further tackled in future experiments.

4.2. Future work

Our study focused on the assessment of how environmental conditions, mainly the ones related to the architecture design, influence human behaviour and are perceived as negative or positive. This approach aims at informing how a given built environment design, better fits the users' needs. For future work we want to analyse the paths of participants to assess if audio stimuli has an impact of the path's decisions. This works follows on our previous analysis of space syntax predictions (Ourique et al., 2017).

Following the findings of Carles et al. (1999) that aesthetically unpleasant sounds such as traffic noise, negatively influenced the overall pleasantness of spaces, we plan also, as future work, to identify if the surrounding sound of the campus (i.e. the hard noise of the planes passing by), have an influence on people's perception of the campus space.

5. Conclusions

In this study, we identified how auditory senses and visual elements influence people's behaviour in an outdoor built environment. To this aim, we compared people's perceptions of the built environment in different conditions: the real world and a replicated virtual world.

We raised three hypotheses related to proving that when simulating more senses than just the visual one, a virtual environment experience is perceived closer to reality.

The results of our study have shown that: i) water and trees are relevant for making a space more comfortable; ii) there is a tendency to prove that a virtual simulation of space is close to reality, if its acoustic characteristics are introduced rather than just its visual characteristics: iii) the introduction of sound in a simulated virtual space does not increase users' satisfaction with such space, compared to the same virtual simulation without sound.

Our results are of interest to researchers working on the analysis of the influence of sound on human behaviour in outdoor spaces as well as on comparing human behaviour in virtual and real environments.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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