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Influence of automated façades on the soundscape outside of buildings

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ABSTRACT

As automation is progressively more present in buildings, it is important to understand its impact on people's experience of urban environments. This case study investigated how one automated shading system with motorized venetian blinds affects sound perception of the acoustic environment in the immediate outdoor surroundings of a university campus building in Detmold, Germany. Procedures of ISO 12913 series for soundscape research were followed to conduct acoustic measurements and derive psychoacoustic indicators. Additionally, soundwalks involving 41 participants and a laboratory study using immersive virtual reality (VR) with 34 participants were conducted to assess how individuals perceive the acoustic environment. The results show that the operation of automated blinds increases sound levels above reference thresholds at short distances, and has a consistent effect on the soundscape, shifting it from pleasant and calm to annoying and chaotic. These trends are notable in both on-site and laboratory data. Additionally, when participants evaluated the soundscape in direct visual connection with the operating façade shading system, they perceived the sounds to be less chaotic than when they were not seeing the façade. These findings highlight that automated buildings and façades are active sound sources capable of influencing environmental quality through acoustic and non-acoustic effects; therefore, their influence on the soundscape should be considered within performance assessments, smart/automation policy, and sustainability frameworks.

1. Introduction

As an increasing proportion of the global population lives in cities [1], the urban soundscape is becoming more recognized as an important determinant of health and well-being [2,3]. In this context, soundscape research emphasizes not only the physical properties of acoustic environments, but also the ways in which people experience sound in a specific context. This perspective builds on the pioneering work of Southworth [4] and Schafer [5] among others in the 1960 s and 1970 s, who helped establish the foundations of the soundscape discipline, which shifts the narrative of sound management as a purely physical phenomenon to the experience and perception of sounds in different contexts. Later contributions have further shaped this body of knowledge through interdisciplinary approaches such as spatial, affective and ecological [6–8] and are currently reflected in the definitions and conceptual framework for soundscape research of ISO 12913–1:2014 [9], and its methodology for data collection and analysis [10,11].

At the same time, the building sector is undergoing rapid technological transformation in response to energy and climate targets. In Europe, buildings account for about 40% of energy use and 36% of CO_2 emissions, leading to regulatory measures such as the amended Energy Performance of Buildings Directive [12], accelerating the adoption of Building Automation and Control Systems (BACS) in non-residential buildings. As a result, motorized components are becoming more common in buildings [13,14], and their operational sounds are increasingly present in the built environment. This trend is particularly evident in façade design and operation, where smart and adaptive technologies are promoted as key strategies for improving building energy performance [15]. Automated dynamic façade components, such as motorized external shading systems, can respond to changing outdoor conditions or user preferences and help reduce solar heat gains and energy use, while also improving indoor environmental quality and visual comfort

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[16–18]. Although automated façades have been widely studied from the perspective of thermal comfort, lighting, and energy performance, it has recently been highlighted that their acoustic performance remains largely absent in the literature [19].

The influence of façades on the outdoor environment has been mainly investigated in terms of sound transmission, reflection, and absorption [20–22]. In contrast, the role of façades as active sound sources remains comparatively underexplored [23]. It is therefore necessary to consider more explicitly how façades affect the outdoor acoustic environment and its perception, rather than treating their acoustic consequences as a by-product of design and operation [24,25]. Research on mechanical sounds generated by façade components has focused mainly on air-conditioning systems [26,27], with limited attention given to automated shading technologies.

This study addresses that gap by investigating the effects of automated façade blinds on the soundscape, based on the conceptual framework described in ISO 12913-1:2014 [9], understanding "soundscape" as the way people perceive and experience the acoustic environment in context. The methodologies for data collection and analysis of ISO/TS 12913-2:2018 [10] and ISO/TS 12913-3:2025 [11] were explored through a mixed-method case study combining field measurements, on-site soundwalks, and an immersive virtual reality (VR) laboratory experiment. In line with previous work on façades and soundscape [28], this study analyzes how a façade affects sound perception through two pathways: by altering the sound propagation (acoustic effects), and by modifying contextual conditions such as the visual environment (non-acoustic effects). Accordingly, the study addresses the following research questions: (1) to what extent does the operation of automated façade blinds modify the acoustic environment around a building; (2) how does blinds movement affect soundscape appraisal under different background sound conditions; (3) to what extent does immersive VR reproduce the perceptual trends observed in on-site assessments; (4) how does visual attention to the sound source (the moving blinds) affect soundscape appraisal when compared to looking away from the building.

This paper continues as follows: section 2 presents the methods, including the experimental design, data collection and analysis procedures. Section 3 reports the results, focusing on the impact of the automated blinds on the acoustic environment and on the soundscape. Section 4 discusses the findings and their implications for automation policy and sustainable design. Section 5 concludes by summarizing the key findings and outlining directions for future research.

2. Methodology

2.1. Experimental design

This study was designed as a mixed-method case study to examine how automated façade blinds influence the outdoor soundscape around a building through both acoustic and contextual pathways. The methodological rationale builds on the façade-and-soundscape framework previously proposed [28], which presents a procedure to evaluate façade influence on soundscape. The framework points out two main pathways through which façades affect people's perception of sound: (i) acoustic effects, altering sound propagation (e.g. reflection, absorption, emission, transmission), and (ii) non-acoustic effects, by changing the context (e.g. visual environmental features, smell, temperature), which can affect how sounds are interpreted.

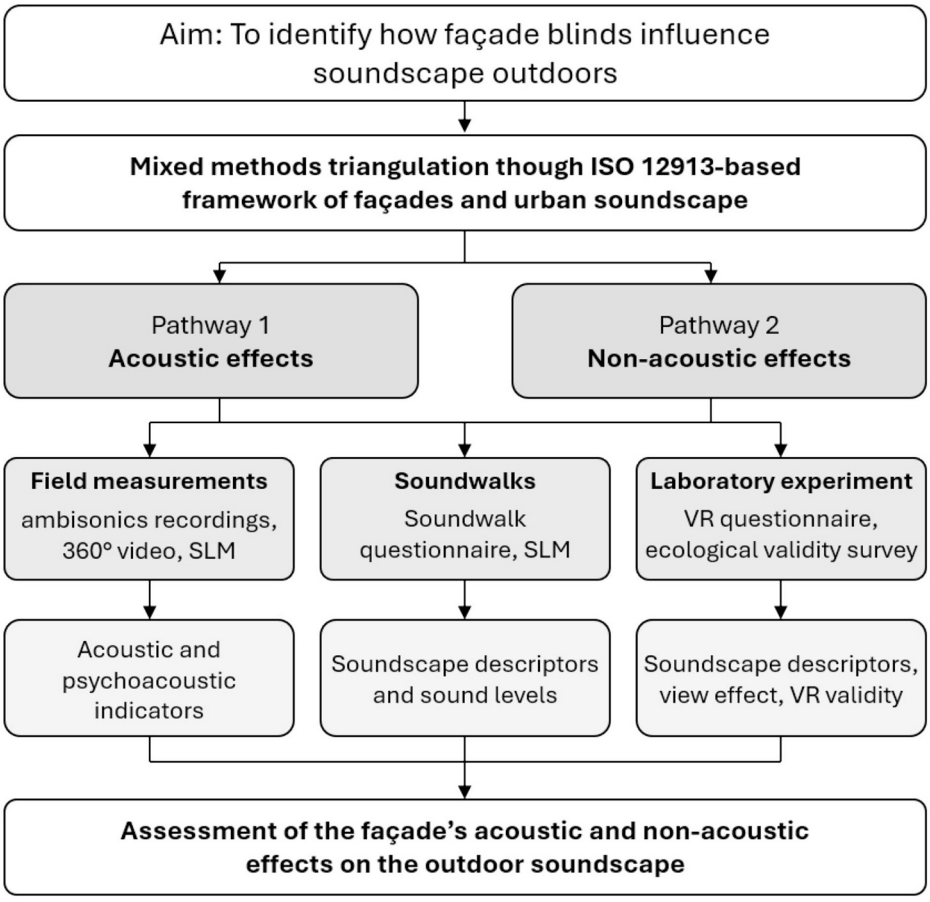


Fig. 1. Workflow of the study, starting with the aim, followed by the application of the framework which addresses two pathways via three data collection campaigns, each with its own methods, tools, and measurable outcomes.

Fig. 1 shows how these two pathways were addressed through three complementary data collection campaigns. The first involved environmental measurements and recordings to characterize the acoustic signature of the façade blinds. The second consisted of on-site soundwalks to capture perceptual responses in the real environment. The third consisted of an immersive virtual reality (VR) experiment, used to reproduce the same situations under controlled laboratory conditions. This process followed the principle of triangulation promoted in ISO/TS 12913-3:2025 and in previous mixed-method soundscape research, where multiple sources of evidence are used to strengthen interpretative reliability [29].

The analysis followed the ISO 12913 soundscape framework, particularly ISO/TS 12913–2:2018 for data collection and the former ISO/TS 12913-3:2019, which has been updated in 2025 [11]. The analysis was subsequently checked with the 2025 revision, and the reported workflow remains consistent.

2.1.1. Study location

The case study was conducted around Building #2 on the campus of the Detmold School of Design, Germany. In Fig. 2, a top view of the campus shows the building, with the east, south and west façades highlighted with a dashed line representing the façade shading system. A set of measurement points perpendicular to the south façade is also shown. Additionally, the path that participants followed during the soundwalks is also shown, starting in building #4 for the introduction, and continuing to either side of the building.

The building was selected because it incorporates an automated external shading system composed of metallic venetian blinds (Fig. 3a) covering more than 100 m^2 of façade surface across the east, west, and south orientations. When the blinds are rolled up, they are concealed within an external compartment located at the floor-slab level (Fig. 3b). The blinds are automatically actuated in response to environmental conditions such as solar exposure and wind. Under normal operations, the façade moves automatically at different times every day, which was not reliable for this experiment. To ensure experimental control, the researchers used manual controls located inside the building to activate the blinds on a single floor of the east or west façade as needed. Therefore, for this experiment, the movement of only the ground floor was considered.

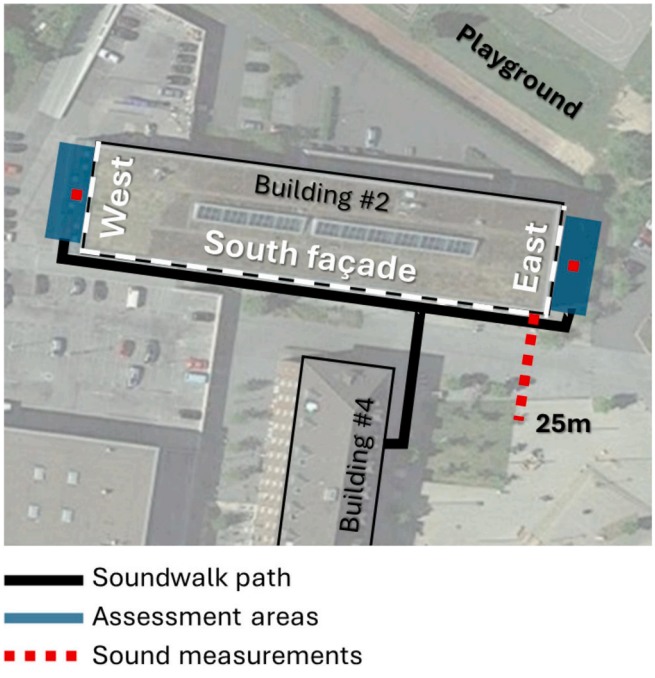


Fig. 2. Study location, soundwalk path, assessment areas and measurement points.

The perceptual assessment focused on the east and west façades since they have comparable widths of approximately 19 m (Fig. 3c and d), while differing in height by approximately 3 m and in their surrounding contexts (east with seating area and trees, and west near the parking lot).

The south façade was excluded from the perceptual assessment because its geometry differs substantially from east and west, measuring approximately 100 m. However, acoustic and psychoacoustic measurements (see Section 3.1) were conducted perpendicular to the south façade rather than to the east or west, since placing the tripod for recordings at different distances would have required standing on vehicular roads, which was not permitted.

2.1.2. Participants

Two participant groups were recruited, corresponding to the two perceptual assessment methods of the study: the on-site soundwalks and the laboratory experiment. Recruitment was carried out through the network of the Institute for Design Strategies. Participation was voluntary, anonymous, and uncompensated.

The soundwalk group consisted of 41 participants (48.78% female), with a mean age of 27.29 years, (range = 22–34 years) and represented 18 nationalities. The VR group included 34 participants (50.0% female), with a mean age of 28.15 years among the participants who reported their age (range = 22–42 years), representing 13 nationalities.

2.1.3. Ethics approval

This study formed part of the first author's PhD research project "Façades and Urban Soundscape" and received ethics approval from the TU Delft Ethics Committee in March 2024. All participants provided informed consent prior to participation. Signed consent forms were stored securely in the research lab and treated confidentially throughout the project.

2.2. Field measurements, audio and video recordings

Field measurements and recordings without participants were conducted between June and August 2023, between 09:00 and 16:00. The building is located close to a playground, which represents one of the main sound sources in the immediate surroundings during the time periods when children are active. Therefore, the recordings for this study were conducted in both conditions, with and without playground noise. Additionally, two façade conditions were recorded, when the blinds are moving, or when they are still. The west side of the building is adjacent to a campus parking area, which is not a high-volume road. Therefore, passing cars were avoided during the recordings and were not considered a main sound source in this experiment.

Measurements were carried out around the building using a tripod equipped with a Class 2 sound level meter, a first-order ambisonics microphone, and a 360-degree video camera. The tripod height was 1.60 m, corresponding to standard head height and ensuring consistent positioning across all recordings.

The equipment used in the field campaign is listed in Table 1. A Class 2 sound level meter was used to measure A-weighted sound pressure levels over time. Spatial audio was recorded using a first-order ambisonics microphone, which captures directional sound information along orthogonal axes and enables later binaural rendering for psychoacoustic analysis and immersive reproduction [30]. Simultaneous 360-degree video recordings were made to support synchronized audiovisual reproduction in VR.

The field measurements were conducted with the aim of characterizing the acoustic environment around the building in its real context, while controlling the measurement conditions as much as possible considering the unpredictable nature of outdoor urban dynamics. Additionally, according to the manufacturer specifications, the Class 2 sound level meter provides a resolution of 0.1 dB and an accuracy of approximately ±1.4 dB at 1 kHz for A-weighted measurements.



Fig. 3. (a) Close up of the blinds; (b) view of the retraction cavity where blinds hide; (c) east façade; (d) west façade.

Table 1
Equipment for field measurements and recordings.

Item	Description
Tripod	Height of 1.60 m for three devices
Sound level meter (SLM)	PeakTech 8005 – Class 2 (dBA)
Soundfield microphone	Zoom H3-VR, first order ambisonics
360-degree video camera	Garmin VIRB 360

Two sets were recorded: first, for future VR reproduction, spatial video and audio recordings along with sound levels from a distance of 10 m from the center of the façade, on east and west sides. Second, sound levels and ambisonics recordings were conducted at different distances from the south façade: 1, 5, 10, 15, 20, and 25 m.

2.3. On-site soundscape assessment by means of soundwalks

2.3.1. Questionnaire

A questionnaire was developed based on Method A of ISO/TS 12913–2:2018, which uses five-point Likert scales to document subjective appraisal of the acoustic environment and is widely used in soundscape studies [31,32]. The same questionnaire core was used for both the soundwalk and VR experiments in order to allow direct comparison across methods.

The questionnaire included the standard eight perceptual attributes (pleasant, calm, uneventful, monotonous, annoying, chaotic, eventful, and vibrant) as well as four additional items: overall sound quality; overall visual quality; appropriateness; perceived loudness. The full questionnaire is provided in Appendix A.

2.3.2. Procedure

A soundwalk, in the context of ISO 12913, is understood as a structured guided visit focused on listening to the acoustic environment [33]. Soundwalk sessions were organized in October 2024, during which participants assessed the soundscape four times: twice on one side (without blinds moving, and with blinds moving), then walking to the other side of the building, and assessing two more times. To reduce order effects, groups began the sequence under different starting conditions, varying façade orientation and blind state.

Each session began indoors, with an introduction of about 30 min, during which participants received instructions, signed the consent form, and could ask questions. Then, they would leave the building and either go to the east or west sides, conduct two soundscape assessments, and then go to the other side for other two assessments. After completion, participants filled in a short post-participation survey covering socio-demographic information and were invited to provide brief qualitative feedback on their experience. During the soundwalks, sound level measurements were also carried out in order to document the environmental conditions associated with each perceptual assessment (Fig. 4).

2.4. Soundscape assessment by means of laboratory experiment

2.4.1. VR experiment setup

A room in Building #4 of the campus was assigned for surveying participants. The indoor space was purposely left as neutral as possible, with white walls, a window providing natural light and ventilation, and the minimum furniture required: a table with a computer where the researcher conducted the experiment, and a non-rotating chair where participants could sit and wear the VR headset holding a remote control with their preferred hand to answer the questions. The cables of the VR headset were hung from the room ceiling to provide easier mobility. The room conditions were kept as consistent as possible by considering temperature and ventilating the space naturally before each participant entered, and keeping the same artificial lighting settings. Fig. 5a shows the room layout for the VR survey; Fig. 5b shows the process while a participant takes the survey and the responsible researcher can track the view and progress on the screen.

The user interface was created with the gaming engine Unity, and the VR headset was the Reverb G2 model with integrated off-ear spatial audio headphones from HP, which provides 360-degree visual and aural input where participants can rotate their head and explore the surrounding visual environment with directional sound.

2.4.2. Procedure

Participants scheduled individual appointments for the experiment. Upon arrival, they were welcomed by the researcher, who then read the information sheet out loud and explained the procedure. Then, the participant would have to fill in a consent form before putting on the VR



Fig. 4. (a) Soundwalk procedure; (b) east façade during a soundwalk; (c) west façade during a soundwalk.

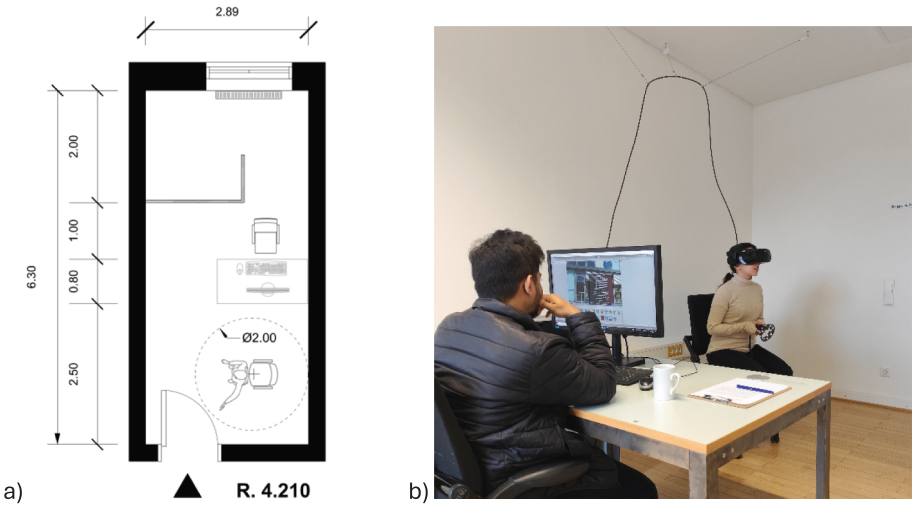


Fig. 5. (a) Room layout; (b) VR survey.

headset. Fig. 6a shows the experimental procedure for the VR survey. To get familiar with the virtual reality environment and hand control, an introductory scene was presented, where participants would fill in their socio-demographic data. Next, participants were exposed to 16 randomized scenes to avoid order effects, with a 5-minute break after the eighth scene. Each scene lasted two minutes with the possibility to extend the time or finish faster and move on to the next scene, depending on the participant's pace.

The 16 audiovisual scenes combined façade orientation (east/west), blind state (still/moving), playground activity (inactive/active), and view direction (toward/away from the façade). The scenes were presented in immersive VR using synchronized visual and spatial audio stimuli that responded to participants' head movements. After assessing all 16 scenes, participants selected the END button and removed the VR headset. The experiment lasted approximately one hour.

2.4.3. *Ecological validity survey*

After the VR assessment, participants were asked to fill in an additional pen-and-paper survey including 9 items adapted from Latini et al. [34] to assess their experience and acceptance of the VR setup. These responses, together with the main study outcomes, were used to evaluate the extent to which the VR findings can be generalized to real-world settings. The ecological validity survey is provided in Appendix B.

2.5. *Data analysis*

The dataset collected for this study comprised multiple sources such as sound level measurements, spatial audio and video recordings, and the information collected from questionnaires regarding people's perception and socio-demographic characteristics. These datasets were processed using a custom digital workflow developed in Python

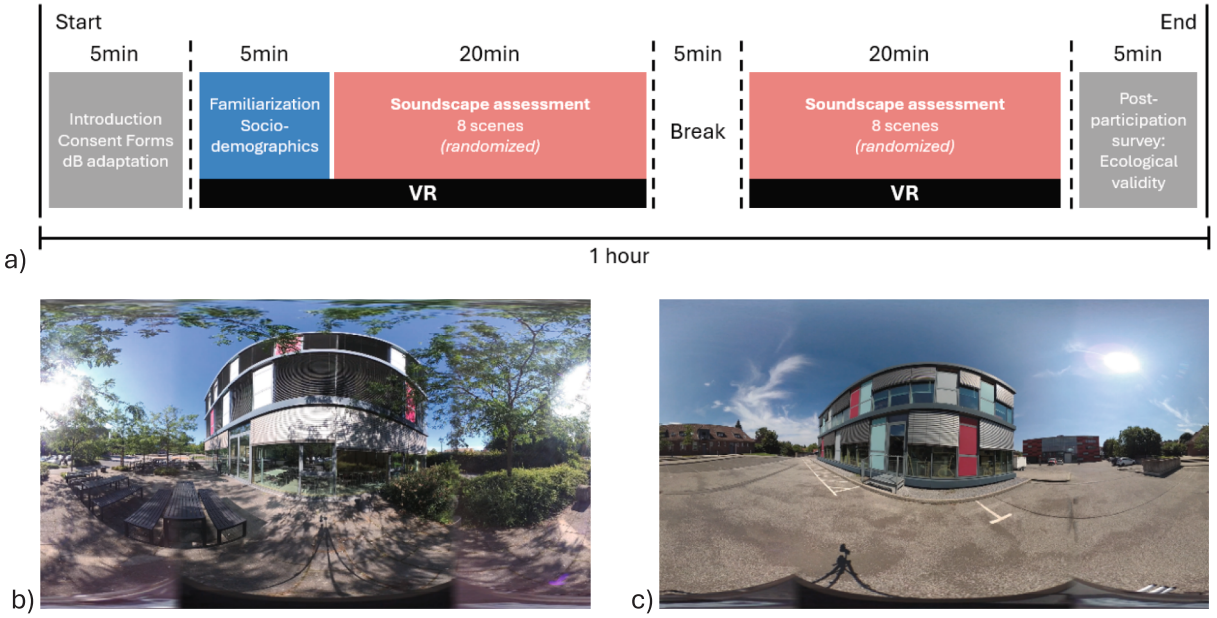


Fig. 6. (a) Procedure for laboratory experiment; (b) east side VR scene; (c) west side VR scene.

v.3.11.4, combining a series of custom scripts compiled in Jupyter Notebook designed for acoustic and perceptual data analysis. Visual Studio Code (Microsoft, 2026) was used as the development environment for writing Python scripts and generating the figures.

2.5.1. Workflow for acoustic and psychoacoustic analysis

The acoustic and psychoacoustic analysis in this study was performed using a set of open-source Python libraries designed specifically for audio signal processing and soundscape assessment. The following tools formed the core of the digital workflow for psychoacoustic analysis in Python: Librosa [35], a library for music and audio analysis, used here primarily for extracting and visualizing waveforms and spectrograms from binaural.wav files; Soundscapy [36], a modular framework based on ISO 12913 methods. Soundscapy integrates three specialized libraries: Python Acoustics, a general-purpose signal processing library supporting operations such as filtering, FFT, and energy calculations; scikit-maad [37], a toolbox developed for ecoacoustic and bioacoustic research; and MoSQITo [38], a framework for psychoacoustic analysis.

Using the workflow of Soundscapy, the dBA levels measured on-site can be used to calibrate the binaural analysis and obtain the psychoacoustic parameter loudness [39], and then derive sharpness and roughness. The psychoacoustic analysis in this study aligns with recommendations from Part 3 of the ISO 12913 standard, specifically by using LAeq, loudness (Zwicker), sharpness and roughness (Table 2).

2.5.2. Workflow for perceptual data analysis

Perceptual data were collected following ISO 12913–2:2018, specifically using Method A, which involves the evaluation of eight perceptual attributes (pleasant, annoying, calm, chaotic, eventful, uneventful, monotonous, vibrant). The dataset of perceptual attributes is then used to find the two coordinates Pleasantness (P) and Eventfulness (E) derived from the formulas described in [7,11]. The coordinates are then used to populate soundscape scatter plots and enable the comparison of multiple assessments.

$$\text{Pleasantness (P)}: \ P = (p - a) + \cos(45^\circ)\cdot(ca - ch) + \cos(45^\circ)\cdot(v - m) \quad (1)$$

$$\text{Eventfulness (E)}: \ E = (e - u) + \cos(45^\circ)\cdot(ch - ca) + \cos(45^\circ)\cdot(v - m) \quad (2)$$

where: p = pleasant; a = annoying; ca = calm; ch = chaotic; v = vibrant; m = monotonous; e = eventful; u = uneventful.

Table 2
Acoustic and psychoacoustic indicators, following ISO/TS 12913–3:2025.

Indicator	Standard	Unit	Symbol
Continuous equivalent sound pressure levels	ISO 1996-1:2003	dBA	LAeq
Loudness (Zwicker)	ISO 532-1:2017	sones	N_5
Sharpness	DIN 45692	acum	S_{avg}
Roughness	ECMA-418–2	asper	R_{avg}

2.5.3. Comparison between on-site and laboratory perceptual assessments

The ecological validity of the VR study was examined in line with standard factorial design practice [40]. To compare the perceptual patterns observed on-site and in the laboratory, separate three-factor ANOVAs were run for each method and each perceptual attribute. Façade-blind state (still vs. moving), playground activity (inactive vs. active), and orientation (east vs. west) were treated as fixed factors. Participant ID was included as a blocking factor to account for between-participant variability and the repeated-measures structure of the data. With the aim of identifying the main trends in each perceptual attribute, the significance level $\alpha = 0.05$ was adopted [41], treating $p < 0.05$ as evidence that a factor or interaction had a meaningful influence on the ratings.

The analytical approach follows previous VR–soundscape research. In [42], in situ soundscape and VR evaluations were compared using repeated-measures MANOVA/ANOVA to test the influence of reproduction method and location on perceived quality and spatial attributes. [43] conducted a systematic review of the ecological validity of immersive VR soundscapes, revealing that statistical comparisons of subjective responses between virtual and real environments are common practice in the field. Similarly, [44] analyzed perceptual ratings across urban locations, population densities and VR conditions, treating the perceptual attributes as dependent variables shaped by the experimental method. In line with these studies, the use of parallel factorial ANOVAs for the soundwalk and VR datasets, with Participant ID included as a

block, provided a suitable basis for comparing the perceptual patterns observed across both methods.

3. Results

3.1. Influence of automated blinds on the acoustic environment

To characterize the acoustic effect of the automated blinds and its spatial decay around the building, a series of measurements and recordings were conducted at 1, 5, 10, 15, 20, and 25 m from the façade under low background conditions. Fig. 7 presents the corresponding waveforms and spectrograms for the six measurement positions. Each recording starts with an upward blind movement of approximately 15 s, followed by a pause of about 3 s and a downward movement of approximately 15 s.

At 1 m from the façade (Fig. 7a), LAeq increased to 61.5 dBA while the blinds were moving. The spectrogram shows that the motorized blinds generated a broadband signal, while the downward movement produced an additional visible pattern corresponding to a screeching noise. With increasing distance, the effect of the blinds became progressively weaker and less distinct from the background signal. From 15 m onward, sound levels remained within the background range of approximately 34.0–39.7 dBA. At 25 m (Fig. 7f), the effect of the blinds was barely noticeable in the waveform and spectral content, blending almost completely with the background sound.

Consistent with this distance-based dBA characterization, the measurements taken during the soundwalk sessions at 10 m from the façade also showed higher LAeq values when the blinds were operating under both quiet and playground conditions. In the soundwalks without playground noise, sound levels on the East façade increased from 43.3 to 47.4 dBA to 58.6–60.7 dBA, and on the West façade from 43.8 to 46.7 dBA to 52.1–56.5 dBA. In the soundwalks with playground noise, the same pattern was observed, with the East façade increasing from 54.3 to 62.5 dBA to 60.1–63.3 dBA, and the West façade from 50.6 to 51.4 dBA to 55.2–55.6 dBA. The LAeq values reported correspond to approximately 3-minute assessments. They therefore describe the acoustic conditions in short time periods, rather than long-term daily exposure levels.

Next, the ambisonics recordings from the six distances were used to extract binaural data and derive psychoacoustic indicators. Fig. 8 shows the relative change of decibel levels along with the psychoacoustic indicators loudness, roughness, and sharpness at different distances from the façade. The indicators were taken from ISO 12913. As seen in Fig. 8, the values of all indicators were highest near the façade and weakened with distance. In the first meters, N_5 drops sharply, while the continuous sound pressure level (LAeq) declines more steadily until 15–25 m where it stays within the range of background sound levels (between 34.0 and 39.7 dBA). Roughness reflects fast amplitude fluctuations and declines sharply with distance along with loudness. Sharpness reflects the high-frequency content and it remains steady over the first 5 m, and then decreases steadily along with LAeq.

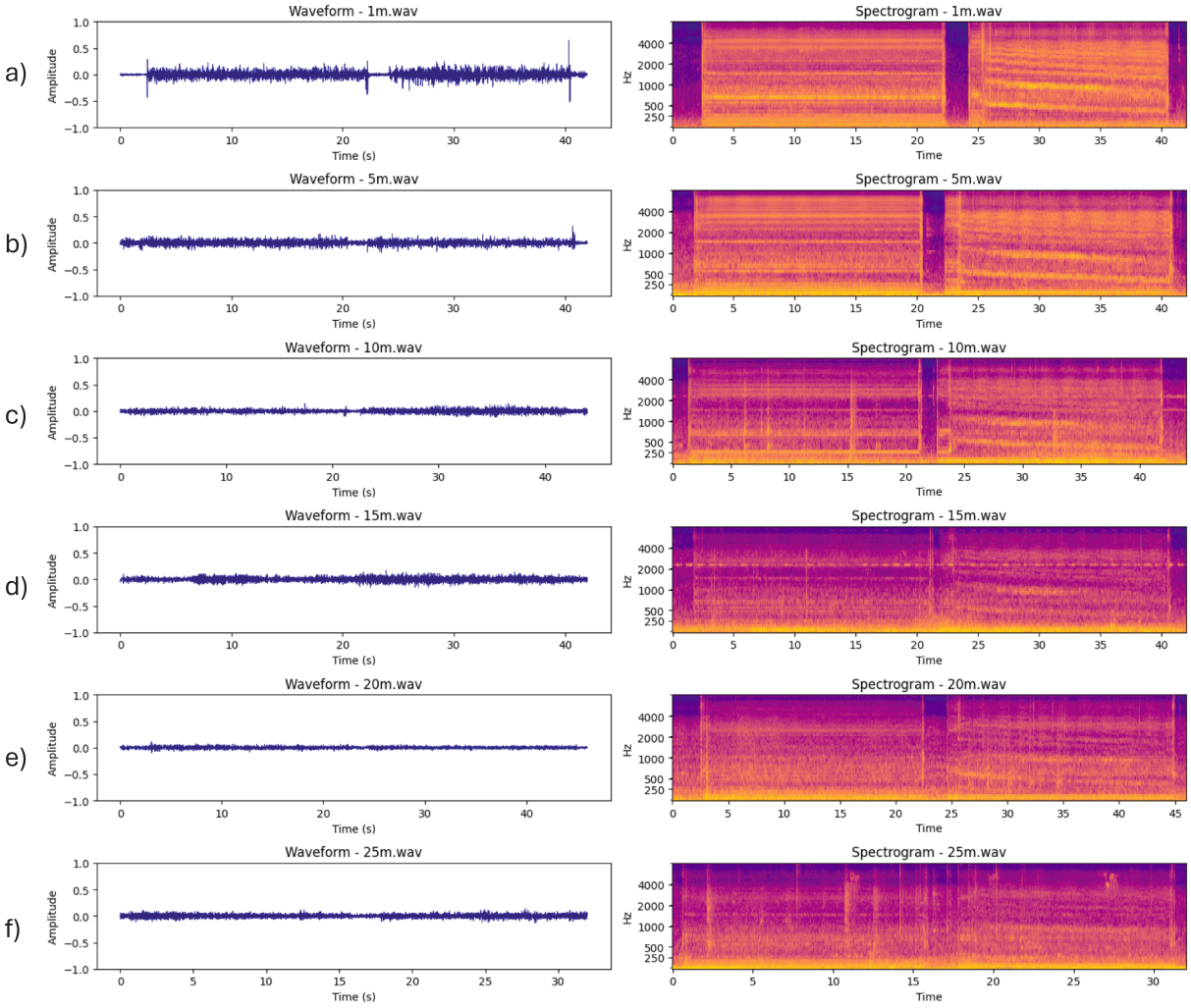


Fig. 7. Amplitude and spectrograms recorded at six different distances from the façade.

Distance (m)	LAeq (dBA)	Loudness (sones)	Roughness (asper)	Sharpness (acum)
1	61.5	16.24	0.053	1.712
5	50.3	8.23	0.040	1.712
10	44.7	5.65	0.029	1.486
15	37.4	3.05	0.017	1.345
20	39.7	3.37	0.014	1.330
25	34.0	2.26	0.010	1.129

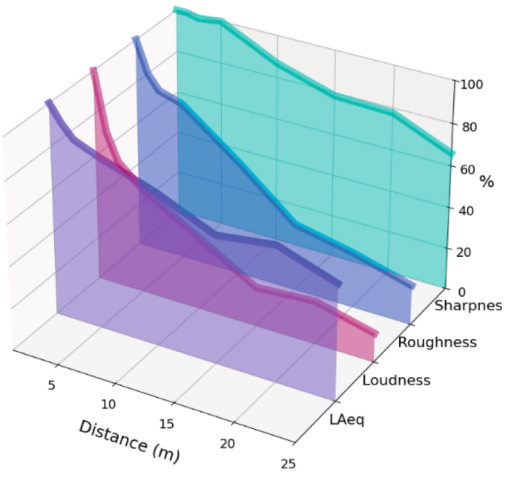


Fig. 8. Relative change of acoustic and psychoacoustic indicators over distance.

3.2. *Influence of automated blinds on soundscape descriptors*

To evaluate how automated façade blinds influence sound perception, the dimensions of Pleasantness and Eventfulness were investigated, as shown in Fig. 9. The two scatter plots present the average group scores for the east and west orientations, comparing soundwalk (SW) and virtual reality (VR) assessments. Markers represent the mean perceptual response for a specific experimental condition, and background markers represent individual assessments. Continuous lines connect paired mean conditions that share all characteristics except for the façade blind state (still vs. moving). These lines represent the displacement within the Pleasantness–Eventfulness space attributable to blinds movement. Their direction and length indicate the perceptual shift caused by the moving blinds. Asterisks (*) mark statistically significant differences between still and moving conditions (paired *t*-test, $p < 0.05$).

General agreement was found between both methods in the direction of the façade-blind effect. In most conditions, movement of the blinds produces a shift towards the annoying and chaotic directions. The most consistent pattern is observed under quiet conditions, where blind movement leads to a shift of quadrant in the soundscape scatter plots, from calm, to chaotic and monotonous.

However, the magnitude of these effects differs between methods. The perceptual shifts associated with blind movement appear more pronounced in VR than in the soundwalk condition, as indicated by longer displacement vectors. An exception to this agreement is observed on the west side, where, in the soundwalk condition, participants on-site appear less affected by blind movement, showing smaller or negligible perceptual shifts.

Fig. 10 presents the distribution of individual ratings for Pleasantness and Eventfulness across both sides of the building. The density

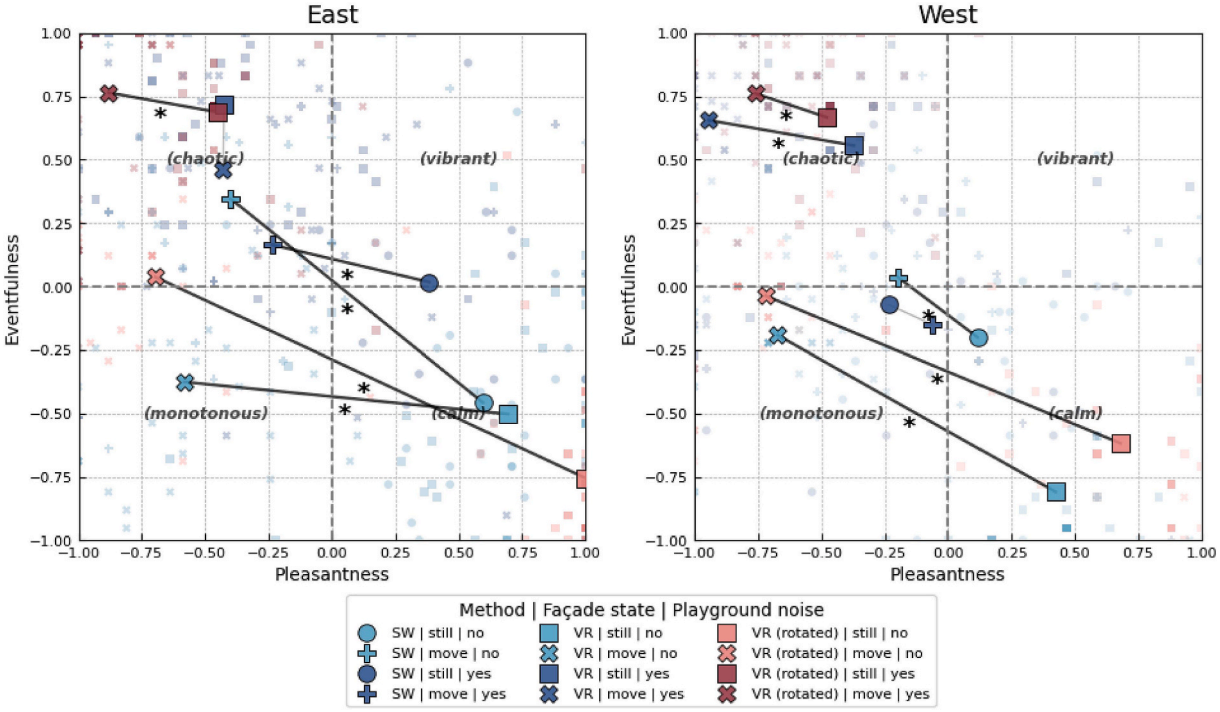


Fig. 9. Scatter plots for the east and west façades for both groups (soundwalk and VR). The lines connect two points where all conditions are the same, except for façade state; the asterisk (*) denotes statistical significance.

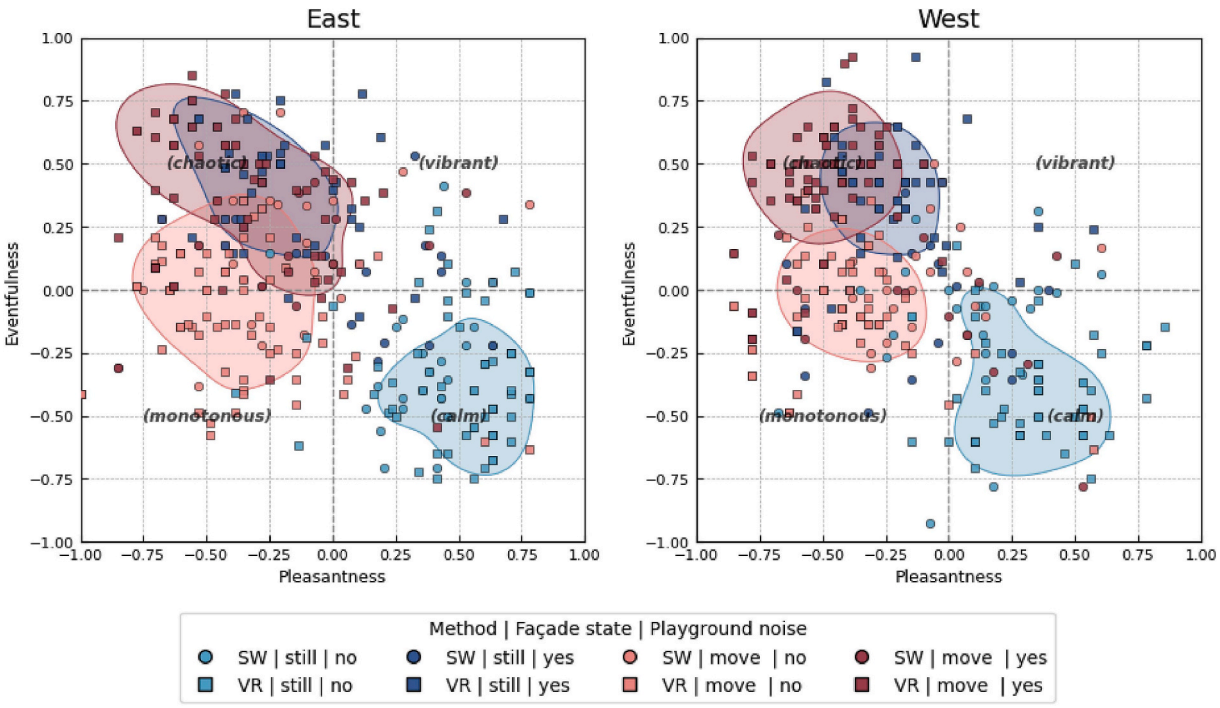


Fig. 10. Distribution of individual Pleasantness and Eventfulness ratings for east and west orientations. Density envelopes indicate the 50th percentile of the combined soundwalk (SW) and VR samples.

envelopes represent the 50th percentile of the combined soundwalk and VR samples, indicating the area where approximately half of participants' responses are concentrated for each condition.

Across both east and west orientations, consistent clustering patterns emerge for the four experimental conditions. Scenarios with still façade blinds and no playground noise cluster predominantly within the calm quadrant (positive pleasantness, negative eventfulness), with some spread toward the vibrant region. This indicates that, in the absence of additional major acoustic events, the environment is generally perceived as calm: pleasant and uneventful.

When the façade blinds are moving in the absence of playground noise, the distribution shifts toward lower pleasantness and higher eventfulness. This results in a perceptual transition from calm toward more annoying and monotonous soundscape appraisals. The displacement is clearly visible in both orientations.

Under playground noise conditions, ratings cluster in the chaotic quadrant (negative pleasantness, positive eventfulness). In this context, the shift from still to moving façade blinds remains observable; however, its magnitude appears reduced compared to the quiet scenario, as the perceptual space is already chaotic.

In addition to the eight perceptual attributes used to construct the circumplex model, the questionnaire also included items on *overall sound environment*, *overall visual environment*, *appropriateness*, and *perceived loudness*. The results show that *overall sound environment* was generally rated lower when the blinds were moving, while *perceived loudness* was rated higher, particularly in the VR assessment. *Overall visual environment* changed less in the soundwalks, where ratings remained generally positive, but in VR it showed clearer differences across façade side and blind state. *Appropriateness* showed a similar pattern, tending to decrease in moving-blind scenes, especially in VR.

3.3. Reliability of VR assessment compared to on-site assessment

3.3.1. Variance of perceptual attributes between soundwalks and VR

To assess whether VR results reflect the observations on-site, separate three-factor ANOVAs were performed for each method (soundwalk and virtual reality) for all eight perceptual attributes (pleasant, vibrant, eventful, chaotic, annoying, monotonous, uneventful, calm). In both cases, façade blind state (still, moving), playground activity (no, yes) and orientation (east, west) were fixed factors, with Participant ID as a blocking factor. Table 3 summarizes how well the VR condition reproduces the soundwalk pattern of main effects for the three experimental factors.

Each attribute was analyzed for soundwalks and VR alike by mean values, F-value, which expresses how much variance is explained by a factor relative to residual error, and the associated p-value, which gives the probability of obtaining F under the null hypothesis of no effect [45].

In soundwalks, pleasant values are higher when the façade is still and drop when its moving (mean = 3.41 vs 2.49; $F = 35.39$, $p < 0.001$), and generally higher on the east than the west side (3.16 vs 2.73; $F = 7.67$, $p < 0.01$). In VR, the same pattern appears but much stronger: mean pleasant values drop sharply with façade movement (3.17 vs 1.79; $F = 449.42$, $p < 0.001$) and playground noise (3.11 vs 1.85; $F = 380.39$, $p < 0.001$), with the east again slightly more pleasant than the west. VR therefore reproduces the soundwalk pattern for pleasant very well but provides slightly amplified results.

In soundwalks, calm is higher for still façades than moving ones (3.17 vs 2.49; $F = 25.04$, $p < 0.001$), with only small average differences

Table 3
Comparison of main effects from three-factor ANOVAs (façade blinds state, playground activity, orientation) on perceptual attributes in soundwalks and VR data. ✓ = similar significant effect; (✓) = similar trend, but the effect is weaker or significant only in soundwalks or VR; ↺ = shift in dominant factor between soundwalks and VR; X = no clear main effect in soundwalks nor in VR.

Attribute	Façade blinds state	Playground activity	Orientation
pleasant	✓	(✓)	✓
calm	✓	(✓)	(✓)
uneventful	(✓)	↺	X
monotonous	X	↺	X
annoying	✓	(✓)	X
chaotic	✓	(✓)	X
eventful	↺	(✓)	X
vibrant	↺	(✓)	(✓)

between inactive and active playgrounds (2.87 vs 2.75; ns) and a strong façade × orientation interaction favorable to the east side. In VR, calm is strongly reduced by both façade movement (3.11 vs 1.65; $F = 494.77$, $p < 0.001$) and playground activity (3.14 vs 1.63; $F = 530.37$, $p < 0.001$), and is higher on the east than on the west side (2.54 vs 2.22; $F = 24.43$, $p < 0.001$). Here VR again mirrors the soundwalk structure (movement reduces calm, east is calmer), but with much larger effect sizes.

In soundwalks, uneventful is higher for still façades than moving ones (3.28 vs 2.89; $F = 6.41$, $p = 0.013$), with playground showing no main effect and a trend towards higher uneventful on the west side (3.24 vs 2.94; $F = 3.72$, $p \approx 0.056$). In VR, uneventful is dominated by playground activity: inactive playgrounds are much more uneventful than active ones (3.52 vs 2.18; $F = 289.88$, $p < 0.001$), while façade state and orientation show no main effects.

In soundwalks, monotonous has no strong main effects of façade, playground or orientation (all $p > 0.25$), and means remain close across conditions (around 3.1–3.3), with only a modest façade × orientation interaction being the parking lot side slightly more monotonous. In VR, playground activity clearly reduces monotonous values (3.66 vs 2.62; $F = 173.87$, $p < 0.001$), while façade blinds state has no main effect on monotonous (3.18 vs 3.10). VR showed a clear reduction in monotonous ratings under playground-noise conditions, whereas this pattern was only weakly evident in the soundwalks.

In soundwalks, annoying increases with façade movement (3.24 vs 2.47; $F = 19.41$, $p < 0.001$), whereas playground activity has little main effect. Orientation mainly appears in interactions (façade × orientation: $F = 13.52$, $p < 0.001$). In VR, both façade blinds movement and playground activity contribute strongly: annoying is higher for moving blinds (4.12 vs 2.74; $F = 309.44$, $p < 0.001$) and active playgrounds (4.10 vs 2.76; $F = 289.95$, $p < 0.001$), with a large façade × playground interaction ($F = 90.68$, $p < 0.001$). VR therefore reflects the soundwalk trend that blinds movement increases annoyance, but also reveals a much stronger contribution of playground noise than appears on-site.

In soundwalks, chaotic increases with façade movement (3.29 vs 2.30; $F = 35.77$, $p < 0.001$), while playground and orientation have modest main effects but significant interactions (e.g. façade × playground: $F = 7.34$, $p < 0.01$). In VR, chaotic is higher for moving façades (3.87 vs 2.70; $F = 229.80$, $p < 0.001$) and for active playground (4.13 vs 2.43; $F = 479.01$, $p < 0.001$), with a strong façade × playground interaction ($F = 97.09$, $p < 0.001$). Aside from the higher magnitude, VR clearly preserves the soundwalk result, increasing chaotic levels even when the playground noise is active.

In soundwalks, eventful is mainly driven by façade state: moving blinds are more eventful than still blinds (3.13 vs 2.73; $F = 8.18$, $p < 0.01$), while playground shows no main effect and orientation is only a weak trend. In VR, eventful is dominated by playground activity: active playgrounds are more eventful than inactive ones (3.66 vs 2.41; $F = 301.12$, $p < 0.001$), while façade state has no main effect (3.05 vs 3.02). VR therefore captures playground activity as the main driver of eventful, however in soundwalks the main driver is façade blinds state.

In soundwalks, vibrant shows relatively subtle changes, slightly higher with playground activity (3.22 vs 2.86; $F = 1.37$, ns). In VR, both façade blinds state and playground activity matter: vibrant is higher for still façades (3.26 vs 2.77; $F = 43.07$, $p < 0.001$) and active playgrounds (3.44 vs 2.59; $F = 126.90$, $p < 0.001$). VR thus partially matches the soundwalk direction but gives a stronger role to playground noise than to façade movement.

3.3.2. Post-participation survey

As part of the ecological validity assessment, a post-participation questionnaire was completed by 22 of the 34 VR participants. As shown in Table 4, all positively framed items had mean scores of approximately 4 (slightly agree). The item concerning symptoms associated with cybersickness had a mean score of 2.18 and a median of 1 (strongly disagree), indicating that participants generally found the VR setup realistic and comfortable, with limited discomfort.

Table 4
Mean and median scores of ecological validity survey for VR participants.

Item	Mean	Median
I appreciate the **graphics** and images of the virtual model	4.36	4
I perceived the virtual environment as **a place I experienced**	4.64	5
During the experience, **I felt present** in the environment	4.68	5
I perceived the virtual model as **immersive**	4.05	4
During the experience, I was **not aware of the real world around me**	4.55	5
The objects inside the virtual model seem **proportionally correct** (i.e., size and distance)	3.95	4
I had the feeling of being able to **interact** with the environment	3.23	4
I found the virtual environment **realistic**	4.36	5
I experienced: **general discomfort** – fatigue – eye strain – headache – vertigo	2.18	1

3.4. Influence of view direction on soundscape descriptors

The influence of participant view was evaluated by comparing responses when facing directly the façade to when the participants was facing the opposite direction while listening to identical audio stimuli. Fig. 11 presents the soundscape scatter plot for the VR group. Markers represent mean ratings for each condition, and background markers are individual assessments. Lines connect paired mean assessments that share the same orientation (east/west), blind state (still or moving), and playground condition (active/inactive), differing only in view direction (toward the façade vs. 180 degree rotation).

In the absence of playground noise, view direction produces noticeable shifts. When the blinds are moving and participants look directly at them, indicating reduced Eventfulness and, in some cases, slightly increased Pleasantness. This corresponds to a small transition from the chaotic region toward more monotonous or calmer appraisals. In other words, seeing the blinds move appears to moderate the perceived intensity of the mechanical noise. For still blinds without playground noise, changes in view direction mainly affect Pleasantness. Facing away from the façade slightly increases Pleasantness compared to facing toward it, while Eventfulness remains relatively stable.

When playground noise is active, most ratings cluster in the chaotic quadrant regardless of whether participants look toward or away from the blinds. However, even under these noisier conditions, looking directly at moving blinds tends to slightly reduce perceived chaos compared to hearing the same condition without visual attention to the source. Overall, view direction affects sound perception when the blinds move, but its effect is more evident without playground noise.

4. Discussion

4.1. Assessment of façade effects on soundscape

The acoustic and non-acoustic effects produced by the automated shading system were assessed using the framework for façades and urban soundscape, in alignment with the ISO 12913 series [9–11]. The findings should be interpreted as a context-dependent case study of one building and one motorized venetian blind system, rather than as a general characterization of all automated façades. Within this scope, the results provide empirical evidence of how an automated façade can act as an active sound source in the outdoor soundscape, with effects that depend on the surrounding context: under quieter background conditions, the blind sound was more clearly distinguishable, while under louder background conditions it was partly masked, reducing the magnitude of the observed effect but without eliminating it.

Regarding the effects on the acoustic environment, this study focused specifically on sound emissions. The results show that the operation of the blinds leads to notable sound generation, with the highest sound level measured (61.5 dBA) 1 m from the façade, dropping to 50.3 dBA at 5 m, falling below 45 dBA by 10 m, and blending with the background levels of approximately 34–39 dBA between 15 and 25 m. Regarding the

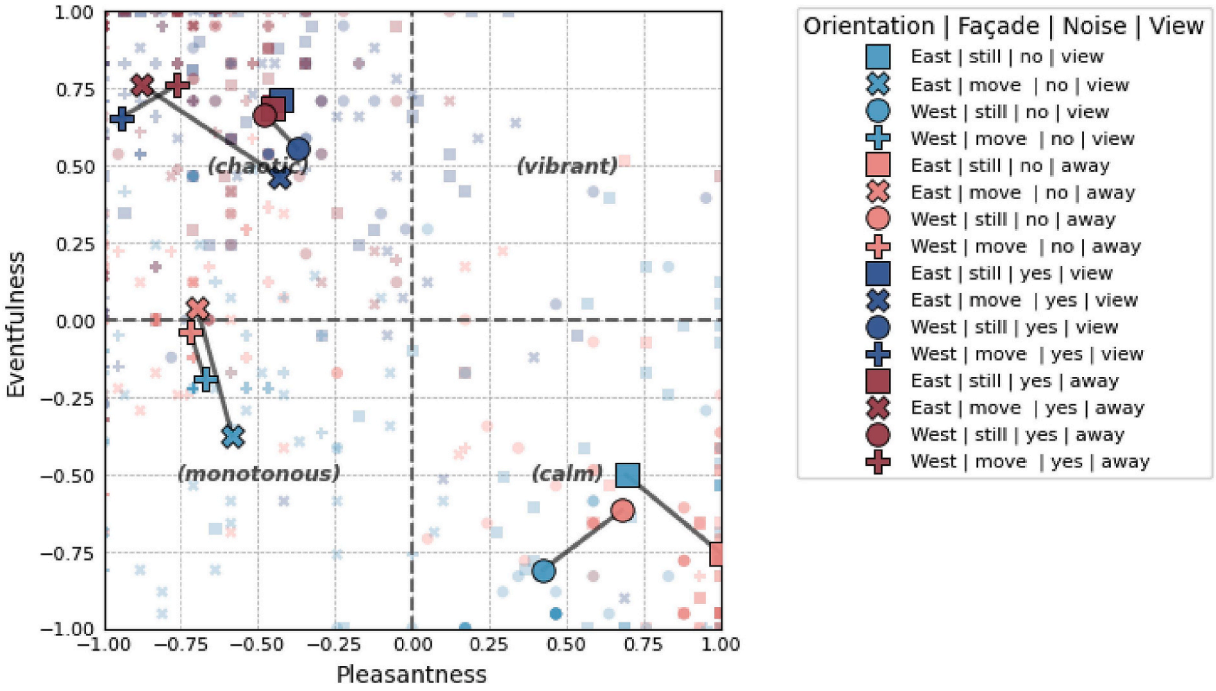


Fig. 11. VR assessment results showing the effect of view direction. Lines connect paired assessments with the same location and sound stimulus, differing only in whether participants were looking toward the building or away from it.

psychoacoustic indicators, loudness shows that the area close to the façade (below 5 m) seems the most critical. Roughness and sharpness show that the effect of the blinds might not raise LAeq significantly between 15 and 25 m but it is still slightly noticeable in the frequency domain and likely still audible although not louder than the background sound. Read against established outdoor health-based reference values, the near-façade condition is not negligible. The WHO Guidelines for Community Noise [46] recommend that steady daytime sound levels on balconies, terraces, and outdoor living areas should not exceed 55 dB LAeq to avoid serious annoyance and 50 dB LAeq to avoid moderate annoyance. On that basis, the 1 m measurement exceeded the upper daytime benchmark. Therefore, although blinds movement represents short operational noise events rather than a constant steady source, their operation is relevant in the immediate outdoor zone, leading mostly to negative effects. This leads to the question of what will happen when most buildings on a street have mechanical blinds and these short operational events occur repeatedly throughout the day.

Regarding the acoustic effects on the soundscape, the results show that façade-blind movement consistently shifted the assessed environment. Under quiet background conditions, ratings shifted from pleasant and calm toward chaotic and annoying. Under playground-noise conditions, where the soundscape was already positioned in the chaotic region even without blind movement, the operation of the blinds still produced a significant effect, moving further in the chaotic direction. There was general agreement in the effect trends observed on-site and in VR, particularly for the attributes pleasant, calm, annoying, and chaotic, indicating that the perceptual effect of the blinds was robust across both methods (soundwalk and laboratory experiment). The VR assessments showed larger effect magnitudes. Previous research has shown that immersive virtual reality can provide ecologically valid sound-environment assessment under controlled conditions [43], while laboratory soundscape reproduction may preserve perceptual trends but alter their strength relative to in-situ assessment [47].

Regarding the non-acoustic effects of the façade on the soundscape, viewing direction altered soundscape appraisals. In the VR experiment, especially in the east-side scenario, participants listened to the same moving-blinds sound while either facing the façade or facing away from it. When the moving blinds were visible, soundscape appraisals shifted toward a more monotonous appraisal, consistently under both quiet and playground conditions. In this sense, the same mechanical sound may be appraised differently when it is experienced as an observable façade operation rather than as an unexplained background noise. This interpretation is supported by the additional questionnaire items on perceived loudness, visual quality, appropriateness, and overall sound quality, and reinforces the framing of this study as a multisensory soundscape assessment rather than only a noise assessment. This is consistent with soundscape research, which has repeatedly shown that visual context and source visibility can modify soundscape assessment. In a laboratory experiment [48], audio and visual information had effects on overall soundscape and landscape satisfaction. In VR-based residential soundscape studies, [49] found that visual indicators can independently and interactively influence Pleasantness and Eventfulness, and [50] reported that the visibility of roadways and vehicles correlated negatively with soundscape perception. [51] highlighted the importance of audio-visual environmental indicators for residential soundscape and satisfaction, and [52] showed that landscape spatial elements influence soundscape composition and acoustic indicators.

4.2. *Implications for practice and policy*

At a conceptual level, this study shows how the framework of façades and urban soundscape can be used to analyze building façades as elements that shape the surrounding acoustic environment and its appraisal. In that sense, the present study is an integration of the soundscape approach to façade design and engineering: the automated blinds affected the acoustic environment by raising sound levels and altering spectral content. Additionally, a direct view to the moving blinds also influenced sound perception, changing how the same mechanical sound was experienced and evaluated. This dual pathway is consistent with established soundscape research showing that non-auditory factors such as the visual environment influence sound perception [53]. The present work opens the way for future studies to examine the acoustic and non-acoustic effects of façades on the soundscape in a systematic process that is up-to-date with state-of-the-art

research.

The results do not argue against automated shading systems, whose energy and comfort benefits remain important. Rather, they indicate that acoustic performance should be considered alongside thermal, daylight, and energy criteria when selecting and operating such systems. The negative acoustic impact could be reduced through quieter components, appropriate maintenance, controlled operating speeds, and control strategies that avoid frequent or simultaneous movement near sensitive outdoor areas.

These findings point to a policy gap: while environmental noise regulations increasingly recognize acoustic quality, they still offer no clear route for assessing building-generated sounds in the construction industry. The WHO Environmental Noise Guidelines for the European Region address major sources such as road, rail, aircraft, wind turbines, and leisure noise, but not building-related mechanical noise [54]. The EU Environmental Noise Directive is built around strategic noise mapping; however, those maps do not consider any sounds potentially generated by buildings [55].

Sustainability frameworks within the construction industry still give limited attention to acoustics relative to other performance domains. In LEED v5 BD + C [56], indoor acoustics-related aspects are worth 1–2 points out of a 110-point scorecard, that is, roughly 1.8% of the total certification score; WELL v2 [57] addresses sound through one of its ten concepts and addresses acoustic design strategies more than LEED, although still carrying limited weight relative to the other performance domains.

This research also adds to the conversation on integrating the emerging *noise footprint* concept into architecture and façade engineering. In recent work [58], noise footprint has been framed as a cumulative burden over time, analogous to the role of carbon footprint in sustainability discourse. In contrast, in aviation and other industries, the term has existed for decades and is typically related to spatial mapping of sounds generated by products and operations [59]. Both interpretations are potentially useful: the first by addressing long-term acoustic responsibility, and the second for mapping the localized influence of a noisy building over distance. For example, the long-term noise footprint could be estimated by considering the sound generated by each operation together with its duration, frequency, and the number of moving elements over a given period. Separately, spatial noise mapping could be used to represent how the sound generated by the façade decreases with distance and which surrounding outdoor areas are affected. These two approaches could support the comparison of alternative façade systems, maintenance conditions, and control strategies.

4.3. Limitations of the study

This study has several limitations. First, it is based on a single case study of one particular building and its motorized venetian-blinds system in a specific campus setting, so the findings should not be generalized to all automated façade types or urban contexts. This is particularly relevant because newer shading technologies may operate differently or more quietly. Second, the context was controlled as much as possible in both the soundwalks and in the VR experiment by intentionally conducting the assessments in the absence of other people on site. Moreover, only two background sound conditions were considered: quiet and playground activity. Other common campus scenarios, such as human voices, music, or spontaneous vehicle noise were not included. The influence of seasons is also considered a relevant aspect, since changes in temperature, sky conditions, or visible vegetation might influence perceptual assessments. Third, all participants were recruited through the university community, which may have limited the demographic and perceptual diversity of the sample. Finally, although the VR experiment broadly reproduced the on-site trends and was rated as realistic by participants, it should still be understood as an approximation of in-situ experience rather than a full substitute for it.

5. Conclusions

This study investigated how automated motorized venetian blinds influence the outdoor soundscape around a university campus building through both acoustic and non-acoustic pathways. The results showed that blind operation increased sound levels in the immediate surroundings of the façade, in this case by up to 61.5 dBA at 1 m, and blended with the background sound at about 20–25 m. Beyond that distance, sound levels do not increase much anymore, but the blinds operation is still noticeable in the frequency domain.

Across on-site soundwalks and the immersive VR experiment, blinds movement shifted soundscape appraisal in a consistent direction. Under quiet conditions, the automated façade shifted the assessment away from pleasant and calm toward chaotic, annoying and monotonous. Under playground-noise conditions, where the soundscape was already positioned in the chaotic quadrant, blind operation still produced a further negative effect. Although the VR experiment generally produced larger effect magnitudes than the soundwalks, the direction of the perceptual change was similar in both methods.

The study also showed that sound perception was affected by visual context. In the VR experiment, changing the view direction while keeping the acoustic stimulus constant altered the appraisal of the same sound environment. In particular, direct visual connection with the moving façade blinds tended to reduce chaotic appraisal. This indicates that the influence of automated façades on soundscape can be due to acoustic and/or non-acoustic (visual) effects. While these results are limited to one building and one shading technology, they provide an empirical basis for future work on other façade types, other urban contexts, and more comprehensive multisensory assessment methods.

CRediT authorship contribution statement

Alvaro Balderrama: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Alessandra Luna-Navarro:** Writing – review & editing, Resources, Methodology, Conceptualization. **Jian Kang:** Writing – review & editing, Methodology, Conceptualization. **Hussam Al Basha:** Software. **Eric Verschuur:** Methodology. **Daniel Arztmann:** Supervision, Resources. **Ulrich Knaack:** Supervision, Conceptualization.

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Declaration of competing interest

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Appendices A and B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apacoust.2026.111498.

Data availability

The datasets generated and analyzed during the current study, as well as the analysis scripts, are available in Zenodo at https://doi.org/10.5281/zenodo.19500125.

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