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A Psychoacoustic Investigation on the Effect of External Shading Devices on Building Facades

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Abstract: Due to energetic and natural lighting factors, building facades often present external shading devices, but the acoustic properties of such devices have not yet been well studied. This study was carried out using a full-scale model of a portion of a shading device, in a semi-anechoic chamber, using traditional and sound absorbing louvres. The psychoacoustic effects produced by the shading system were evaluated through comparisons between averaged values of loudness, roughness and sharpness levels, as well as sound pressure levels as reference. Results highlighted that the sound absorbing shading device offers good attenuation in terms of loudness, roughness and sound pressure level, with a small reduction in sharpness. The traditional shading system studied does not efficiently reduce the analysed parameters, or even worsens the situation. Several analyses of variance were carried out, one for each situation studied. The sound source position and the louvres' tilt angle both produce statistically significant effects on almost all of the variations of the parameters studied. The analyses of the partial eta squared factors highlighted that source position and louvre tilt angle affect the variations of the parameters studied to a different degree in respect of the two types of louvres.

Keywords: building shading devices; insertion loss; psychoacoustics; loudness; roughness; sharpness

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1. Introduction and Objectives

Traffic noise is a major sound pollutant in densely populated cities. It has been largely demonstrated that long-term and short-term exposure to noise has a strong impact on human health and behaviour [1].

There are many possibilities to mitigate traffic noise inside dwellings in crowded cities, using noise barriers between traffic lanes and buildings, or enhancing the facade sound insulation. The efficacy of the noise barriers, of various types and shapes, has also been studied [2–6]. Recent research funded by the European Union's Seventh Framework Programme (FP7/2007-2013—HOSANNA [7]) studied the optimisation of green areas and surfaces, in order to reduce noise propagation in urban areas. Noise barriers often present installation problems due to lack of space between the noise source and the buildings to be protected. If the noise barrier installation is not possible or not effective, the design of the building facade becomes very important. It is quite easy to obtain good performances in sound insulation of the opaque components of a building facade. Furthermore, its shape design represents a good opportunity to protect dwellings from external noise [8–13]. Since the windows represent the weak element in facade sound insulation, they have been widely studied: they represent the visual and the ventilating interface between the internal and the external space of a building. Kang and

Brocklesby [14] presented a laboratory study on the possibility to enhance the noise attenuation of windows, introducing transparent micro-perforated sound absorbing panels, in order to maintain natural ventilation and daylighting comfort. The results of similar experiments, both on a scale model and using a full-scale model, are respectively shown in [15,16].

Different issues arise in buildings with large glazed surfaces on the facade, such as curtain wall systems. For example, they force designers to use shading systems in order to avoid excessive solar irradiation, which can increase the energy consumption to cool the building, while reducing the discomfort due to thermal and glare effects perceived by the users. The efficiency of the external shading devices in terms of the reduction of energy consumption and visual comfort enhancement has been largely demonstrated [17–20], but their acoustic effects on the building facade have not yet been well studied. Some recent works have focused their attention on the acoustic effects of the shading devices on the buildings in terms of sound pressure level (SPL) differences over the building facade (insertion loss (IL), in dB), behind the louvres [21–23]. It has been demonstrated that the external louvres tend to increase the sound pressure level over the facades, since they receive not only the direct sound waves, but also the sound reflections that are generated by the louvres. In [23], a laboratory study was presented to acoustically optimise the louvres, applying to them a layer of sound absorptive material, in order to reduce the sound pressure level over the building facade: The insertion loss provided by the sound absorbing louvres is much higher if compared with the effect of the traditional shading system. The use of the insertion loss in dB is a commonly used procedure in the evaluation of the acoustic effects of a barrier or other building components. However, it has been demonstrated [24–26] that objective values in dB are not necessarily correlated to human perception in terms of the disturbing characteristics of noise. In [27], the airborne sound insulation was studied using a loudness model instead of making a traditional evaluation [28]. The study was conducted in order to introduce a procedure to find a subjective estimation for airborne sound insulation.

This paper presents analyses related to the effect over the building facade of a shading device in terms of variation of some psychoacoustic parameters, namely loudness, roughness and sharpness [29]. The aim of the present work is to study how averaged loudness, roughness, sharpness levels and SPL are modified by the presence of a traditional and an improved shading system considering different configurations of source position and louvres' tilt angle.

Designers can choose between many types of shading devices. The choice can depend both on technical and aesthetical reasons. The main function of these systems is obviously to reduce solar irradiation over the building facade and to improve daylight distribution in the interior; these aspects can affect both the dimensions and the spacing of the louvres. In this work the results of the measurements carried out on a model representative of typical devices extensively used by architects are presented. A 1:1 scale model of a portion of a shading system was tested in a semi-anechoic chamber. Both sound pressure levels and impulse responses measurements were conducted in order to evaluate the variations of the chosen psychoacoustic parameters derived from two noise signals convolved with the measured impulse responses.

The variations of sound pressure levels reported in this paper have been analysed in greater detail in [23].

2. Methodology

2.1. Experimental Set-Up

2.1.1. Model of the Shading System

The model is a portion of a shading device, 4 m × 4 m, with louvres measuring 2 m × 0.2 m, 0.018 m thick, spaced at 0.2 m from each other. The model was completely built from pine plywood slabs, with mullions measuring 2 m × 0.1 m, 0.02 m thick. The model was placed on the floor of the semi-anechoic chamber, simulating a glazed facade. Indeed, the shading devices are usually installed over the glazed surface of the buildings, and glass and concrete have comparable sound absorption properties. The semi-anechoic chamber has a net volume of 796 m^3 (10.1 m × 9.5 m, height 8.3 m): The chamber respects the requirements of Annex A of the ISO 3745:2012 [30], with a low cut-off frequency under 50 Hz and a high frequency above 10 kHz. The top of the model was demarcated by the sound absorbing wedges of the chamber, while the other three sides were delimited by a boundary of polyester fibres, 0.25 m thick and 1 m wide. The absorbing boundary was used in order to reduce as much as possible the sound diffraction through the lateral mullions of the structure. The position of the model inside the semi-anechoic chamber and some dimensional data are shown in Figure 1.

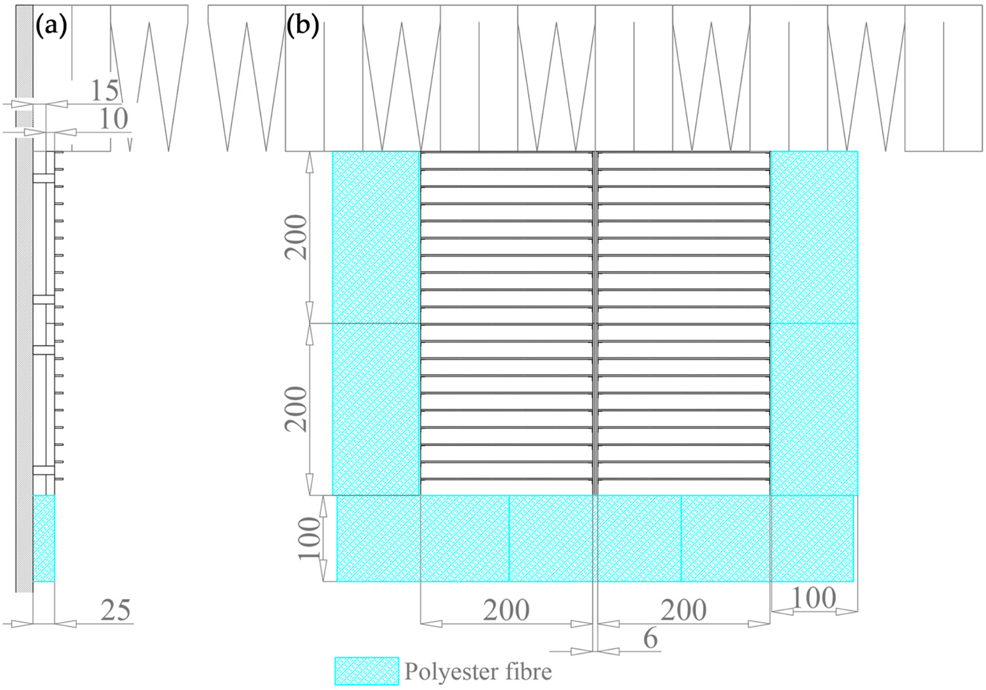


Figure 1. Side (**a**) and plan (**b**) views of the model of the shading devices in the semi-anechoic chamber. Dimensions are expressed in cm.

The study was carried out with two different types of shading device: traditional louvres were used for the first set of measurements, while modified sound-absorbing louvres were used for the second set, in order to evaluate the possibility of an enhancement in the acoustic performance of the system. In order to give sound absorption properties to the shading device, a 3 cm thick layer of expanded melamine was used, fixed to the back of each louvre (Figure 2c). The sound absorption coefficient of the used melamine was measured in impedance tubes [31], with diameters of 4.5 cm and 10.0 cm, respectively: Results are shown in Figure 3. The shading system was analysed with three different tilt angles of the louvres (0°, 30°, 45°) toward the sound source. Measurements were carried out also with the blank floor of the semi-anechoic chamber (Figure 2a,d), in order to find out the reference values to be compared with the effects of the shading system. From now on, the floor of the semi-anechoic room will be called *"facade"*, in order to simplify the reading of the text. Figure 4 shows the three configurations of the facade: without the shading system (Figure 4. Configuration A), with the traditional louvres (Figure 4. Configurations B) and with the sound absorbing ones (Figure 4. Configurations C). The values obtained with configuration A were used as reference in the evaluation of the acoustic effect of the shading system.

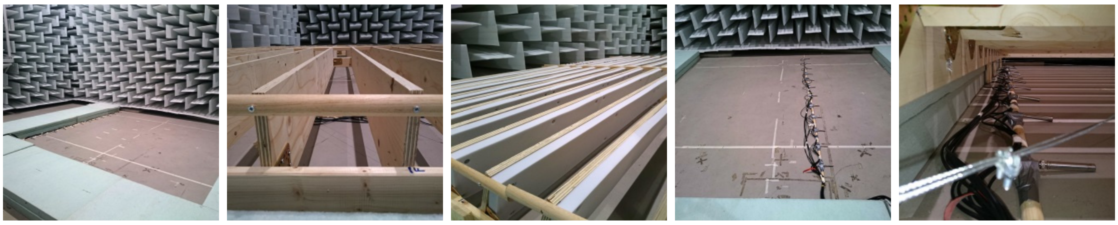

(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 2. (**a**) The blank floor of the semi-anechoic room simulating the plain facade; (**b**) the traditional shading system; (**c**) the sound absorbing louvres; (**d**) the 12-microphones array used in the measurements without the shading system model; and (**e**) the microphones placed on the plane below the model.

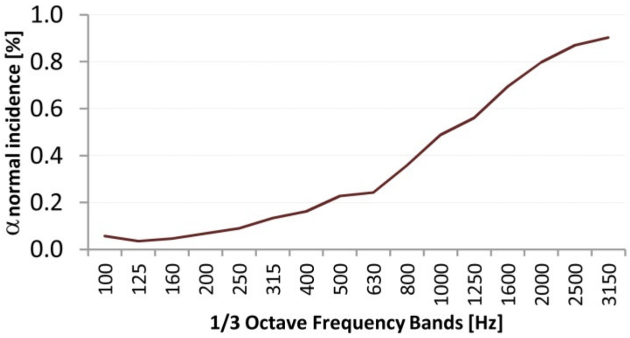


Figure 3. Normal incidence sound absorption coefficient (α) of the material (expanded melamine layer) used in the shading device.

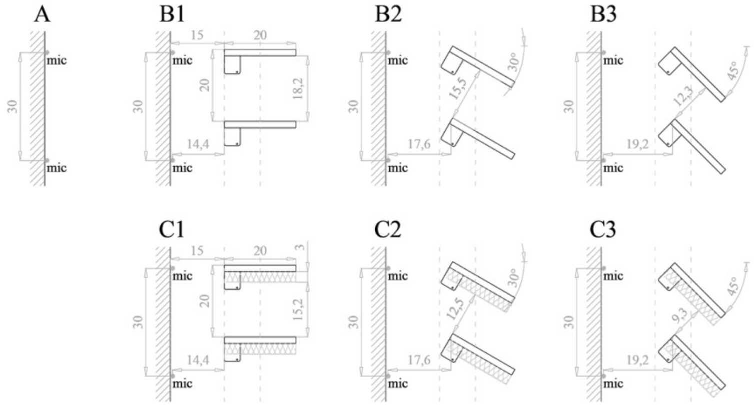
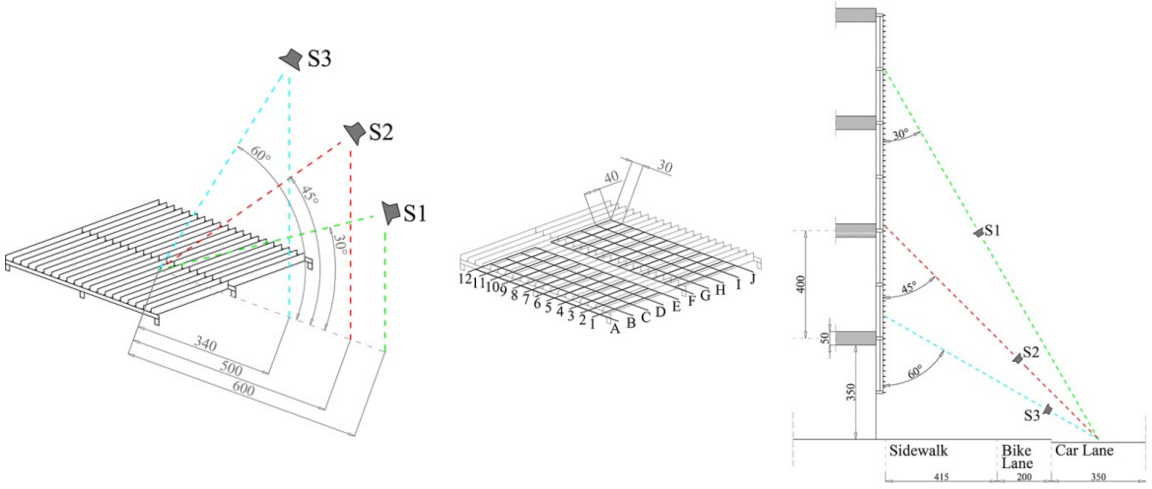


Figure 4. Setup of the different configurations: (**A**) without shading system; (**B1**–**B3**) different tilt angles of the traditional shading system; and (**C1**–**C3**) different tilt angles of the shading system with absorbing material. The dimensions are given in cm.

2.1.2. Sound Source, Excitation Signals and Microphone Grid

A directive loudspeaker, in general utilised for facade sound insulation measurements [32], was used during the experiment. It is clear that the generated sound field is non-homogeneous on the studied surface of 16 m^2, but all the results are evaluated in terms of relative values, and it is possible to affirm that the differences should be the same in all the studied situations. The sound source was placed in three different positions (Figure 5a), in order to evaluate how the shading device behaves with three different angles of incidence of the sound field (30°, 45°, and 60°). The dimensions of the semi-anechoic chamber did not allow to move the source too far from the model, but the different source positions are intended to simulate the effect of the louvres with a fixed sound source position placed on the ground, producing noise toward three corresponding heights of a hypothetical building. Referring to Figure 5c, which shows a building section, the sound source positions S1, S2 and S3, respectively, correspond to the 3rd floor, a floor between the 1st and the 2nd, and the 1st floor.

The measurements were carried out using 12 half-inch pre-polarised condenser microphones PCB 377B02 (PCB® Piezotronics, Depew, NY, USA), with 426E01 ICP® microphone preamplifiers (PCB® Piezotronics, Depew, NY, USA). The microphones were mounted in an array, spaced 30 cm from each other. This array was moved in 10 positions under the model, spaced 40 cm from each other. The complete grid was set with a total of 120 microphone positions, with 12 rows and 10 columns, as shown in Figure 5b. Figure 2d,e shows the details of the microphone array on the floor of the semi-anechoic chamber and under the shading device. The signals of the microphones were acquired by the Sinus Samurai System (SINUS Messtechnik GmbH, Leipzig, Germany). The calibration procedure of the microphones was repeated before and after each measurement sessions. The SPLs were obtained from the described measurements set-up using a pink noise as source signal. The impulse responses (IRs) where obtained from a logarithmic sine sweep signal, with duration of 10 s and a frequency range from 50 Hz to 10,000 Hz.



(**a**) (**b**) (**c**)

Figure 5. (**a**) The three positions of the sound source with respect to the model; (**b**) the grid of 120 microphone positions used in the measurements; and (**c**) section of a hypothetical building facade and a road. The source positions in the semi-anechoic chamber are shown as a fixed road lane. Dimensions are in cm.

2.2. Parameters Selection: SPL and Psychoacoustics Parameters

2.2.1. Sound Pressure Levels

Sound pressure level, in dB, describes the amount of the atmospheric pressure (Pa) variation, in logarithmic scale, due to an acoustic phenomenon. It is calculated with the following Equation (1), where p_{eff}, in Pa, is the effective gap of the atmospheric pressure from its equilibrium value and $p_{ref} = 2 \times 10^{-5}$ Pa.

$$\mathrm{SPL} = 10 \times \log_{10}\left(\frac{p_{eff}^2}{p_{ref}^2}\right) \ [\mathrm{dB}] \quad (1)$$

2.2.2. Loudness

Loudness (N) describes the human perception of the volume of a sound. Loudness level (L_N) is the intensity in dB of a 1-kHz tone perceived to be as loud as the sound being measured. The measurement unit of loudness is the sone, while the loudness levels are represented in phon. The relation between loudness and loudness level is expressed in Equation (2), where L_N is the loudness level in phon and N is the loudness in sone. The sone scale is linear, so as the loudness is doubled so is the perceived volume of a sound, while the same difference corresponds to 10 phon. The A-weighting curve, which is largely used in environmental noise evaluation, only describes the perception of a sound around 40 phons.

$$L_N = 40 + 10\log_2(N)\ [\text{phon}] \tag{2}$$

The perception of loudness depends on the time duration of the studied noise, on its spectral components and it is related to its sound pressure level in dB. In this study, two steady-state signals were used in order to avoid the time dependency of loudness. Loudness levels from the pink noise and the traffic noise signals were obtained using the software Artemis Suite v11 – Psychoacoustics Module (HEAD Acoustics GmbH, Herzogenrath, Germany), according to the DIN 45631:1991 [33].

2.2.3. Roughness

Roughness describes the annoyance of a sound due to its modulation frequency. The unit of roughness is the asper and it is defined with a 1 kHz tone with 60 dB in SPL, 100% modulated with a frequency of 70 Hz. Roughness is not strongly dependent on the sound pressure level. The minimum perceived change in roughness is an increment in the degree of modulation of around 10%, which corresponds to a relative variation of around 17%. For this reason, the variations in roughness were evaluated in terms of ratio (Equation (4)). Roughness was calculated with Artemis Suite software.

2.2.4. Sharpness

Sharpness measures the high frequency content of a sound: A high level at high frequency, with respect of the broad band sound, generates a high sharpness. The reverse sensation of sharpness is the sense of pleasantness of a sound, which depends on sharpness itself, as well as on roughness and loudness. The unit of sharpness is the acum, which corresponds to a narrow-band noise at 1 kHz having a level of 60 dB, and a width corresponding to one critical band. Sharpness in this study was evaluated using the Artemis Suite software, according to the DIN 45692:2009 [34], using the method presented by Aures in [35].

2.3. Experimental Measurements and Data Analysis

2.3.1. Measurement Procedure

Two different types of measurements were made in the semi-anechoic chamber. Sound pressure levels (SPL) and impulse response (IR) measurements were carried out in order to evaluate different acoustic performances of the shading device. The SPLs were used to calculate the sound attenuations in dB given by the louvres (already presented in [23]). The impulse response measurements were conducted in order to evaluate the variations of the chosen psychoacoustic parameters derived from two noise signals convolved with the measured impulse responses.

2.3.2. Convolution Process and Analysis of the Differences of the Studied Values

The two chosen signals to be convolved with the measured IRs are a broadband noise signal, the so-called "pink noise", and the standard traffic noise generated according to the indication of the standard EN 1793-3 [36]. Both signals were created in Adobe Audition 3.0 (Adobe Systems Incorporated, San Jose, CA, USA), as mono signals with a sample frequency of 96 kHz, with a duration of 10 s. The two signals were chosen because, due to their differences, it is possible to obtain different values for the chosen psychoacoustic parameters, which are better correlated to different real situations. Pink noise is a commonly used signal in facade sound insulation measurements, while standard traffic noise is an artificial signal that is used in the IL measurements of noise barriers. In particular, the spectral characteristics of the two signals can affect the loudness level calculations, as further shown by the results of this work.

The impulse response analysis and the following convolution process were carried out in Matlab® R2013a (MathWorks, Natick, MA, USA), using its in-built convolution function. Two normalization factors were applied to the two output signals, according to the scheme in Figure 6, in order to obtain values in Pascal (Pa) for the signals close to the unit. In this way the output signals respectively give comparable psychoacoustic parameters: For example, the loudness values obtained from the convolved pink noise are comparable.

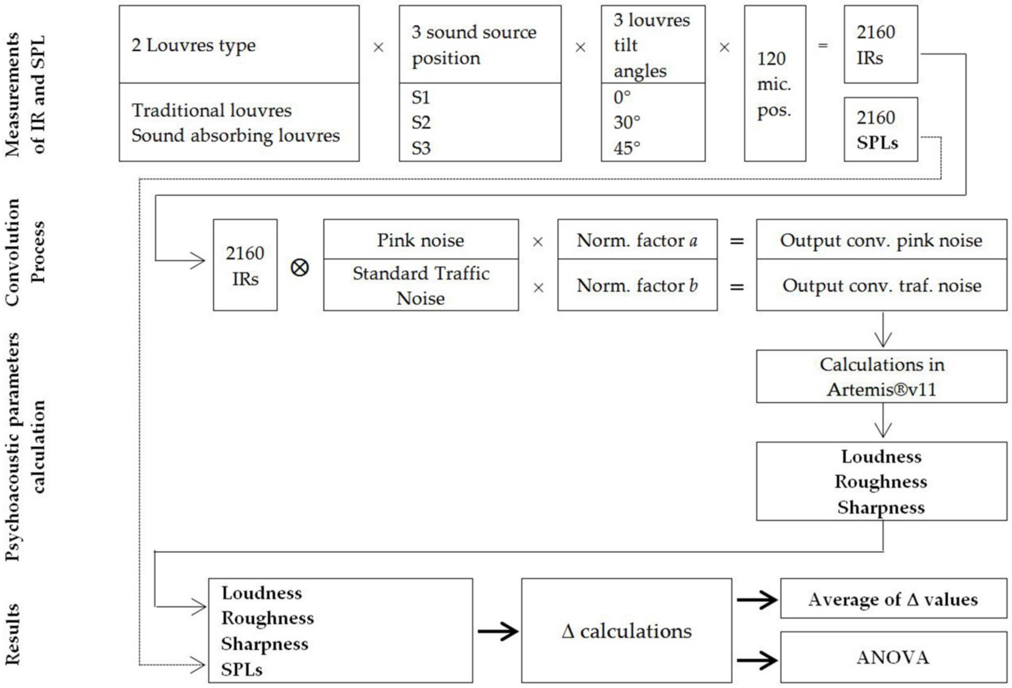


Figure 6. Flow-chart of the entire process to evaluate the acoustic effect of the shading device model: the measurements process with its variables, the convolution process with the two signals, the calculation of the psychoacoustic parameters and the evaluation of the variations over the facade in terms of average values and the statistical analysis of variance (ANOVA).

3. Results and Discussion

The first part of this section presents the averaged loudness, roughness and sharpness levels, as well as the sound pressure levels, in terms of their variations (Figures 7–10), caused by the presence of the shading system in its different configurations. The second sub-section is dedicated to the analyses of variance and their respective effects of size of the fixed parameters on the dependant variables.

The Δ calculations were conducted to evaluate the acoustic effect of the studied shading device on a building facade. All the psychoacoustic parameters studied and the sound pressure levels were analysed in terms of mutual variations, taking as reference the values coming from the measurements with the blank facade. The evaluation in terms of mutual comparisons, between the calculated values of SPL and psychoacoustic parameters, was chosen to avoid some issues deriving from the measurements. In fact, both the sound pressure levels and the impulse response measurements were affected by the sound source directivity. It is assumed that the diverted acoustic field reaches each microphone position in the same way during each measurement. For this reason, the differences in the acoustic field are attributed only to the presence of the shading device, in its various configurations (Figure 6, Section "Measurements of IR and SPL"). This method was chosen in order to avoid also the different sound absorption characteristics of the floor of the semi-anechoic chamber and a glazed facade.

The variations (Δ) in loudness, sharpness and sound pressure levels were calculated with Equation (3), in terms of simple difference. The ratios of roughness were instead obtained with Equation (4), because the ratio is more appropriate than a difference for the evaluation of roughness changes (see also Section 2.2.3).

According to Equations (3) and (4), the higher the values of the result, the better the effect of the shading device. Letters A, B and C refer to Figure 4, where A corresponds to the blank floor of the semi-anechoic chamber, B presents the traditional louvres and C the sound absorbing ones. Subscripts 1 to 10 and 1 to 12 refer respectively to the 10 columns and 12 rows of the microphone grid. The term Val in Equations (3) and (4) refers to the measurements of sound pressure levels (dB) and to the calculated psychoacoustic parameters. Equations (3) and (4) were alternatively repeated to separately evaluate the performance of the traditional louvres (B, in its configurations B1, B2, and B3) and of the sound absorbing louvres (C, in its configurations C1, C2 and C3).

$$(\Delta_{\mathrm{N,Sharp,SPL}})_{12,10} = \begin{bmatrix} (\mathrm{Val}_{\mathrm{B,C}})_{1,1} & \cdots & (\mathrm{Val}_{\mathrm{B,C}})_{1,10} \\ \vdots & \ddots & \vdots \\ (\mathrm{Val}_{\mathrm{B,C}})_{12,1} & \cdots & (\mathrm{Val}_{\mathrm{B,C}})_{12,10} \end{bmatrix} - \begin{bmatrix} (\mathrm{Val}_{\mathrm{A}})_{1,1} & \cdots & (\mathrm{Val}_{\mathrm{A}})_{1,10} \\ \vdots & \ddots & \vdots \\ (\mathrm{Val}_{\mathrm{A}})_{12,1} & \cdots & (\mathrm{Val}_{\mathrm{A}})_{12,10} \end{bmatrix} [\mathrm{phon, acum, dB}] \quad (3)$$

$$\left(\Delta_{\mathrm{Rough}}\right)_{12,10} = \begin{bmatrix} \frac{(\mathrm{Val}_{\mathrm{B,C}})_{1,1}}{(\mathrm{Val}_{\mathrm{A}})_{1,1}} & \cdots & \frac{(\mathrm{Val}_{\mathrm{B,C}})_{1,10}}{(\mathrm{Val}_{\mathrm{A}})_{1,10}} \\ \vdots & \ddots & \vdots \\ \frac{(\mathrm{Val}_{\mathrm{B,C}})_{12,1}}{(\mathrm{Val}_{\mathrm{A}})_{12,1}} & \cdots & \frac{(\mathrm{Val}_{\mathrm{B,C}})_{12,10}}{(\mathrm{Val}_{\mathrm{A}})_{12,10}} \end{bmatrix} [\%] \quad (4)$$

3.1. Average Variations of Loudness, Roughness, Sharpness and Sound Pressure Level over the Building Facade

The variations of the analysed parameters are expressed as averages over all the 120 values coming from Equations (3) and (4). The averages have been repeated for each variable of the measurements set-up. Finally, the obtained values are expressed with respect to the two different louvres types, the three different sound source positions and the three tilt angles of the louvres (18 averages). The psychoacoustic parameters have as additional variable the signal used in the convolution process (pink noise and standard traffic noise), with 36 averages.

3.1.1. Average Loudness Differences: Traditional versus Sound Absorbing Louvres

The loudness levels do not significantly vary in the case of the traditional shading system, with all the source positions, with the louvres tilted at 0° and 30° toward the sound source. The situation changes when the louvres' tilt angle rises to 45°: The presence of the traditional louvres worsens the loudness situation, with an increase of up to 3.5 phons. This is a low variation, corresponding to less than a doubling in sone, but it constitutes a worsening of the loudness over the building facade, due to the presence of the shading devices. The differences are quite similar for the loudness calculated from both signals used. The sound absorbing shading system has a good effect on the average variation of the loudness levels over the portion of the studied facade. The loudness level reduction has a maximum value of 14 phons (standard traffic noise, sound source in position S1, un-tilted louvres—Figure 7). The minimum value of attenuation in terms of loudness is even positive, around 3 phon: It is again a low difference, but this time it represents a reduction in the loudness level. In general, it is possible to assume that, with reference to the loudness levels variations, the shading device has linear dependency on the sound source position: the protection increases inversely proportionally to the angle between the source and the facade plane. Referring to Figure 5c, the shading device offers greater protection in loudness for higher floors. Figure 7 shows a linear dependency even between the louvres' tilt angle and the given loudness level reduction. The effect of the shading device on the loudness level variations is more relevant when the standard traffic noise is studied: This is to be ascribed to the higher levels at higher frequencies in this type of signal. According to an equal-loudness contour [29], it is clear how a high frequency pure tone needs a lower sound pressure level to reach the same loudness as a low frequency pure tone.

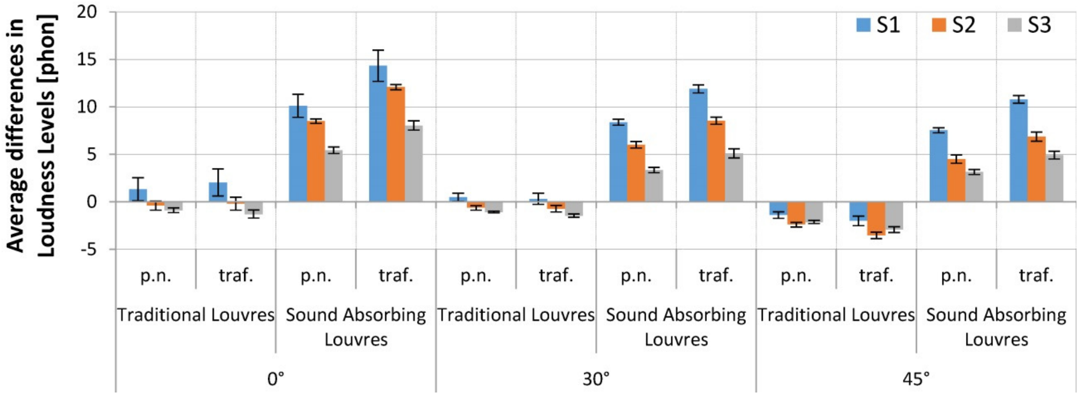


Figure 7. Average differences in Loudness levels due to the presence of the traditional louvres compared to the sound absorbing louvres. The bars in the figure are listed according to the source positions used for the measurements (S1, S2, and S3). Error bars report the doubled standard deviations for each average. The acronym "p.n." refers to the pink noise signal. The abbreviation "traf." refers to the standard traffic noise.

3.1.2. Average Roughness Differences: Traditional versus Sound Absorbing Louvres

Roughness variations were evaluated in terms of asper ratios, in percentage, so values below 1 correspond to a negative impact of the shading device. The performances of the traditional shading system to reduce the roughness sensation over a building facade are not relevant, with average ratio between the shaded situation and the blank facade not exceeding ±10% (0.9–1.1). Indeed, the minimum perceived change in roughness corresponds to an increment or a decrease of around 17% [29]. The roughness highly depends on the modulation of the signal: The traditional shading device seems not to interfere with the sound modulation in any of the studied configurations of the louvres, since they do not present particular performances in their sound absorption, no do they highly interact with the generated acoustic field. The sound absorbing shading louvres give a fair reduction of the roughness of both studied signals, up to a decrease of almost 40% (standard traffic noise, sound source in position S1, un-tilted louvres—Figure 8).

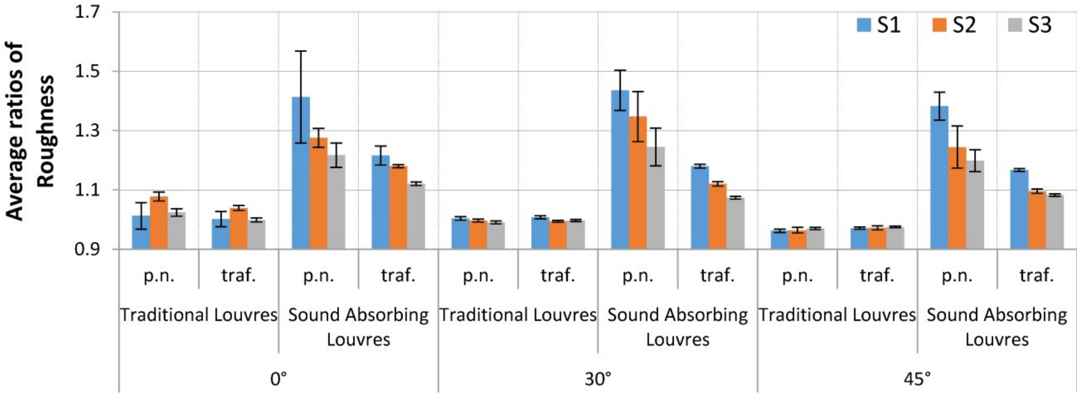


Figure 8. Average ratios of Roughness due to the presence of the traditional louvres compared to the sound absorbing louvres. The bars in the figure are listed according to the source positions used for the measurements (S1, S2, and S3). Error bars report the doubled standard deviations for each average. The acronym "p.n." refers to the pink noise signal. The abbreviation "traf." refers to the standard traffic noise.

3.1.3. Average Sharpness Differences: Traditional versus Sound Absorbing Louvres

The standard shading device has a small impact on the variations of the sharpness over the studied facade. It is however possible to affirm that the sound absorbing shading system behaves better in reducing the sharpness over the building facade, with reductions of up to around 0.6 acum (traffic noise, S1, un-tilted louvres, Figure 9). In the same case, even the sound absorbing shading system is practically ineffective in reducing sharpness, when the sound source position is in S3 (Figure 5a), corresponding to the lower floor of a hypothetical building (Figure 5c). The most effective configuration of the shading device to reduce sharpness is with the sound source in S1 and with un-tilted louvres.

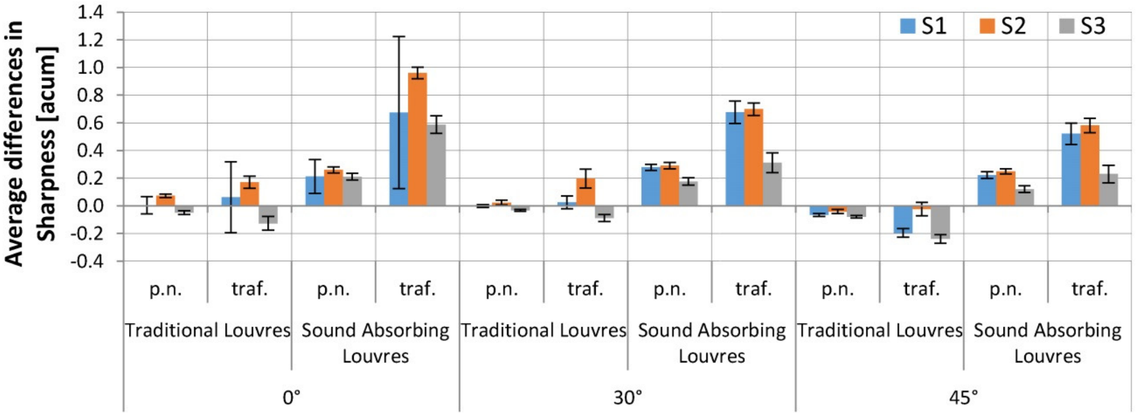


Figure 9. Average differences in Sharpness due to the presence of the traditional louvres compared to the sound absorbing louvres. The bars in the figure are listed according to the source positions used for the measurements (S1, S2, and S3). Error bars report the doubled standard deviations for each average. The acronym “p.n.” refers to the pink noise signal. The abbreviation “traf.” refers to the standard traffic noise.

3.1.4. Average SPL Differences: Traditional versus Sound Absorbing Louvres

The SPL differences in dB are expressed as single frequency broadband values, calculated between 100 Hz and 3150 Hz. A more detailed explanation of the SPL variations over a building facade due to the presence of a shading device can be found in [23]. The shading system plays quite an important role in the SPL changes over a facade. While the traditional louvres can enhance the SPL over the facade by up to 2 dB, the sound absorbing shading device gives a sound attenuation by up to 9 dB. The differences in SPL have a similar behaviour to the loudness levels, regarding the sound source position and the louvres’ tilt angle. This fact is easily understood because loudness depends on spectral content at medium-high frequencies, which is the same range of efficacy as the melamine used in the experiment. The dependences of the SPL reductions on the sound source position and the louvres’ tilt angle (Figure 10) is again similar to what was observed for the difference in loudness.

3.2. Analysis of Variance: Significance and Fixed Factors Effects

An analysis of variance test (ANOVA) was conducted over the calculated Δs values of loudness, roughness, sharpness and sound pressure levels. The statistical analyses were conducted on the line averages of the results given by Equations (3) and (4), as explained in Equation (5).

$$(\Delta_{\mathrm{avg}})_{12,1} = \begin{bmatrix} avg(\Delta_{1,1}, & \cdots & ,\Delta_{1,10}) \\ & \vdots & \\ avg(\Delta_{12,1}, & \cdots & ,\Delta_{12,10}) \end{bmatrix} \tag{5}$$

The input of the ANOVA analyses using as dependant variable the line averages obtained from Equation (5) and the fixed factor were the sound source position and the louvres tilt angle.

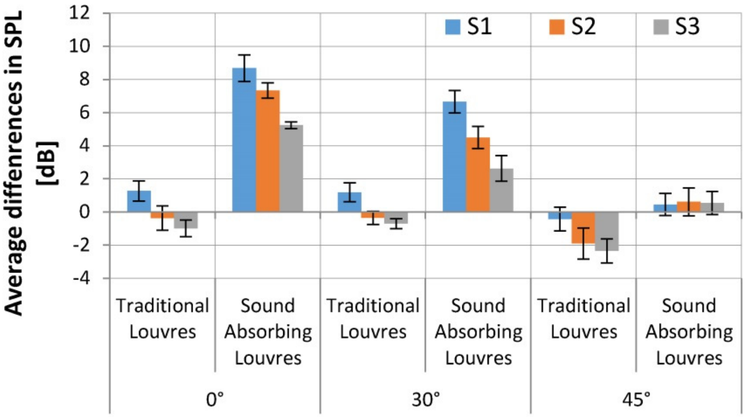


Figure 10. Average differences in Sound Pressure Levels (Insertion Loss in dB) due to the presence of the traditional louvres compared to the sound absorbing louvres. The bars in the figure are listed in function of the source positions used for the measurements (S1, S2, and S3). Error bars reports the doubled standard deviations for each average.

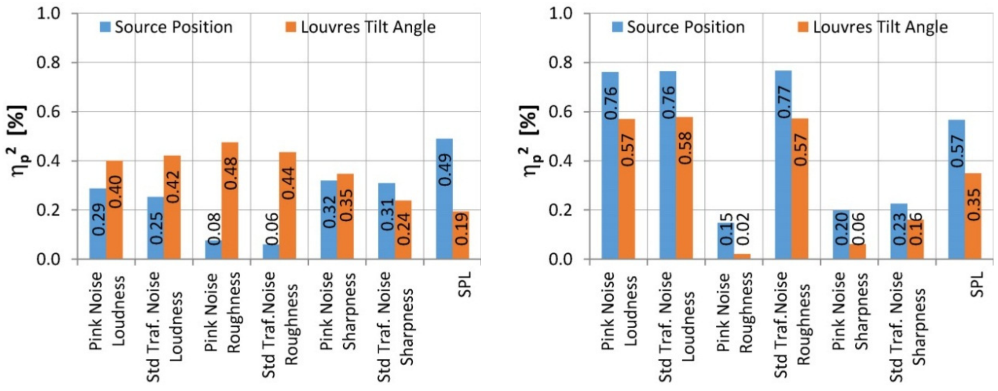
The ANOVA tests are necessary to verify that the variations between the various studied situations are statistically significant, and do not occur due to random factors. A *p*-value under 0.05 has been considered as significant. The ANOVA tests were completed with the calculation of the effect of size ($\eta_p{}^2$) in order to evaluate which factor has a greater effect between the sound source position and the louvres' tilt angle on the Δs of the studied parameters. The ANOVA tests were separately carried out for each data set of the calculated differences: each ANOVA is referred to a single case study. The dependant variable in each ANOVA was the Δ in terms of loudness, roughness, sharpness, sound pressure level, due to the presence of the shading device, in its two main configurations (traditional and sound absorbing). The sound source positions and the louvres' tilt angles were considered as fixed factors. The sound source position is important to determine the acoustic protection as a function of the building height (Figure 5c), while the louvres' tilt angle is a parameter that is more closely related to the energy saving needs of the buildings, and can be decided directly by the designer or by the user. Table 1 reports the *p*-values of the ANOVA tests. Figure 11 shows the effect of size of the sound source position and of the louvres' tilt angles. The complete report of all the ANOVA is in Appendix A (Tables A1–A4). The statistical analyses were conducted with the software IBM-SPSS Statistics v23 (IBM Corp., Armonk, NY, USA).

Table 1. *p*-values calculated from the analysis of the variance for each data set of the calculated Δs. The term "Interaction" is to be intended as the interaction between the sound source position and the louvres' tilt angle.

ANOVA Fixed Factors		**Δ in Loudness Levels**		**Δ in Roughness**		**Δ in Sharpness**		**Δ in SPL**
		p.n.	**traf.**	**p.n.**	**traf.**	**p.n.**	**traf.**	**-**
Traditional Louvres	**Sound source pos.**	$p < 0.001$	$p < 0.001$	0.021	0.048	$p < 0.001$	$p < 0.001$	$p < 0.001$
	Louvres tilt angle	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
	Interaction	0.205	0.071	0.001	$p < 0.001$	0.025	0.668	0.766
Sound Absorbing Louvres	**Sound source pos.**	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
	Louvres tilt angle	$p < 0.001$	$p < 0.001$	0.348	$p < 0.001$	0.044	$p < 0.001$	$p < 0.001$
	Interaction	0.067	0.123	0.985	0.004	0.215	0.369	0.977

3.2.1. Analysis of Variance and Effect of Size of the Loudness Comparisons

The differences in loudness levels are statistically significant, looking at both the effects given by the louvres' tilt angle and the sound source position, while the interaction between the two factors is never significant. This result is repeated for both differences given by the traditional and the sound absorbing louvres. This means that the shading device plays an important role in the variations of the loudness levels, and both the sound source position and the louvres' tilt angle are important.



(**a**) (**b**)

Figure 11. The effect of size for the group mean differences; partial eta squared factor for the mean differences referred to the variances of Loudness Levels, Roughness, Sharpness and SPL: (**a**) traditional louvres; and (**b**) sound absorbing louvers.

The comparison of the effect of size ($\eta_p{}^2$) on the loudness differences (Figure 11) shows that the louvres' tilt angle of the standard louvres has a greater effect on the loudness variations compared to the sound source position, while the opposite behaviour is observed for the sound absorbing louvres. The loudness level attenuation given by the traditional louvres is quite poor, if not negative (Figure 7). Tilting the louvers produces greater effects on the façade loudness levels than changing the sound source position, because they become transparent to the generated acoustic field (Figure 11a). The reverse situation observed with the sound absorbing louvers (Figure 11b) is due to the fact that the sound absorbing material plays an important role independently of the louvres' tilt angle, because the material quantity in the shading system does not change. In this case the sound source position seems to have a greater effect because the free space between the louvres, seen from the position of the sound source, becomes smaller as the angle between the loudspeaker and the facade plane is reduced (Figure 5a,c). Similar behaviours in $\eta_p{}^2$ are observed for both studied signals.

3.2.2. Analysis of Variance and Effect of Size of the Roughness Comparisons

The ANOVA carried out on the Δ_s in roughness shows that the fixed factors play a statistically significant role on the roughness variation on the facade, even in their interaction. Only two exceptions were found when the sound absorbing device is observed, with pink noise: The louvres' tilt angle and the interaction of the two fixed factors are not statistically significant. This fact can be more easily understood looking at the averages ratios, reported in Section 3.1.2: The values slightly vary due to the tilt angle, and the standard deviation is quite high. This is ascribed to the fact that roughness strongly depends on the degree of modulation. Both the traditional and the sound absorbing shading device can vary the modulation frequency only by attenuating some components of the sound spectrum, which modulate more: this can depend on the sound absorption and sound screening effects of the used materials, which do not change with the louvres' tilt angles nor with the sound source position.

The $\eta_p{}^2$ has a similar behaviour to what was observed for the differences in loudness levels.

3.2.3. Analysis of Variance and Effect of Size of the Sharpness Comparisons

The sound source position and the louvres' tilt angle have a statistical significance on the variation of the sharpness over the studied facade portion, with both studied signals. Their interaction is not statistically significant, except when the standard louvres in presence of pink noise are observed.

The η_p^2 has an unclear behaviour with similar values for each factor. The results of both the ANOVA and the analyses of η_p^2 are to be ascribed to the characteristic of sharpness itself, which depends on the high frequency content of the studied signal. The shading system acts as a great diffuser/absorber and it is impossible to evaluate if the source position or the louvres' tilt angle plays a more important role on the sharpness variations. The sound absorbing system mainly works at high frequency (Figure 3) and subsequently the sharpness is reduced.

3.2.4. Analysis of Variance and Effect of Size of the SPL Comparisons

The ANOVA highlighted statistically significant variations in sound pressure levels due to the separate actions of the sound source position and the louvres' tilt angle, but similarly to what was observed for the loudness levels, their interaction is not statistically significant.

The η_p^2 analysis shows that the SPL variations over the facade, in both cases with standard and sound absorbing louvres, are mainly influenced by the sound source position. This is an important finding that means that the noise protection given by the shading device increases faster with the building height than with the louvres' tilt angle. This aspect is ascribed to the fact that at higher floors the louvres appear closer to each other and denser, with respect to the noise source placed at the bottom.

4. Summary and Conclusions

This work represents a first approach to the evaluation of the variability of some psychoacoustic parameters over a building facade, due to the presence of a shading device, both with traditional and sound absorbing louvres. The experimental data were obtained during a measurements campaign conducted on a 1:1 scale model of a portion of a shading device to be installed over a building facade in a semi-anechoic chamber. The acoustic insertion loss given by the shading device model has been discussed in greater detail in [23]. The large amount of impulse response measurements were convolved with two different noise signals in order to calculate loudness, roughness and sharpness, which were evaluated with mutual comparison between the situation with the shading device, in its various configurations, and the blank facade (the floor of the laboratory).

The results of the measurements and post-processing procedures generated a large amount of data, which were investigated with an analysis of variance to evaluate the statistical significance of the variations of the sound pressure levels and of the chosen psychoacoustic parameters. The ANOVA tests carried out on the different data-sets highlight that in general the measured differences are statistically significant, with respect to the variations of the sound source position and the louvres' tilt angles. The combination of the two factors is in general not statistically significant. There is a significant difference in the behaviour of the η_p^2 in the separate analysis of the psychoacoustic parameters deriving from the presence of the traditional or the sound absorbing shading system. The effects of the louvres' tilt angle seem to be more relevant with respect to the sound source positions in the data set related to the standard louvres, while the tendency is reverse when the sound absorbing louvres are observed. It is possible to ascribe this fact to the poor sound absorption properties of the standard louvres made of simple plywood: for this reason they play an important role as a barrier when they are un-tilted and they can intercept the acoustic field that comes from below. The opposite tendency is observed for the sound absorbing shading system: this can be attributed to the fact that the expanded melamine used in the experiment modifies the content in frequencies of the sound pressure field arriving on the facade and the louvres' tilt angles are less relevant, in view of the quantity of sound absorbing material. The generated sound field is intercepted by the same amount of material with a small consideration of the louvres' tilt angle, while varying the sound source position.

In conclusion, it is possible to affirm that the shading device plays an important role in the variations of sound pressure level and loudness, has quite a good effect on roughness, while it has practically no effect on sharpness. It is possible to say that the traditional shading system has a negative effect as it increases both the sound pressure levels and the loudness over the studied facade portion.

The sound absorbing shading device, on the contrary, can reduce both the loudness and the sound pressure level, respectively, by up to 14 phons and 8 dB. The loudness reduction given by the sound absorbing louvres represents an important result, since loudness is a subjective acoustic parameter, more related to human noise perception, if compared with the sound pressure level in dB, or in dB(A).

The external shading devices have an important role both in controlling the internal comfort of the building for its users and in reducing the cooling energy consumption. This research highlights that an acoustic optimisation of the louvres can additionally play an important role in reducing not only the sound pressure levels over the building facade, but in particular the magnitude perception of the noise. An accurate research activity is needed in order to study in greater detail the psychoacoustic analysis of the shading devices. Further investigations should optimise the louvres' materials, their tilt angle, their spacing and dimensions, in order to simultaneously maximise energy saving, daylighting distribution and the acoustic and psychoacoustic protection of the building facade.

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Author Contributions: The study of the acoustic behaviour of the external shading devices began as a collaboration between the University of Florence (Simone Secchi) and the University of Ferrara (Patrizio Fausti). It was then continued at the University of Sheffield (Jian Kang) where Nicolò Zuccherini Martello carried out a period of research. Nicolò Zuccherini Martello designed and built the shading device model. Together with Patrizio Fausti and Simone Secchi, he carried out the measurements in the semi-anechoic chamber of the University of Ferrara and made the post-processing of the collected data. Nicolò Zuccherini Martello elaborated the impulse responses in order to analyse the psychoacoustics parameters. Francesco Aletta provided useful hints for the psychoacoustic and for the statistical analysis of the data-set of the variations of sound pressure levels, loudness, roughness and sharpness. Jian Kang supervised the whole process for the evaluation of the psychoacoustic parameters and the statistical analysis.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix

Table A1. Two-way Factorial ANOVAs results referred to the differences in Loudness.

ANOVA Fixed Factors	Dependent Variable: Differences in Loudness Levels	
	Traditional Louvres	Sound Abs. Louvres
Sound Source Position (p.n.)	$F(2, 99) = 20, p = 5.07 \times 10^{-8}, \eta_p^2 = 0.29$	$F(2, 99) = 157.22, p = 1.87 \times 10^{-31}, \eta_p^2 = 0.76$
Sound Source Position (traf.)	$F(2, 99) = 16.75, p = 5.43 \times 10^{-7}, \eta_p^2 = 0.25$	$F(2, 99) = 159.88, p = 9.93 \times 10^{-32}, \eta_p^2 = 0.76$
Louvres Tilt Angle (p.n.)	$F(2, 99) = 33.11, p = 9.76 \times 10^{-12}, \eta_p^2 = 0.40$	$F(2, 99) = 65.67, p = 7.01 \times 10^{-19}, \eta_p^2 = 0.57$
Louvres Tilt Angle (traf.)	$F(2, 99) = 35.96, p = 1.83 \times 10^{-12}, \eta_p^2 = 0.42$	$F(2, 99) = 152.59, p = 2.82 \times 10^{-19}, \eta_p^2 = 0.58$
Factors Interaction (p.n.)	$F(4, 99) = 1.51, p = 0.20, \eta_p^2 = 0.06$	$F(4, 99) = 2.27, p = 0.07, \eta_p^2 = 0.08$
Factors Interaction (traf.)	$F(4, 99) = 2.23, p = 0.07, \eta_p^2 = 0.08$	$F(4, 99) = 4.20, p = 0.12, \eta_p^2 = 0.07$

Table A2. Two-way Factorial ANOVAs results referred to the differences in Roughness.

ANOVA Fixed Factors	Dependent Variable: Differences in Roughness	
	Traditional Louvres	Sound Abs. Louvres
Sound Source Position (p.n.)	$F(2, 99) = 4.04, p = 0.021, \eta_p^2 = 0.075$	$F(2, 99) = 8.59, p = 3.63 \times 10^{-4}, \eta_p^2 = 0.148$
Sound Source Position (traf.)	$F(2, 99) = 3.13, p = 0.048, \eta_p^2 = 0.06$	$F(2, 99) = 162.48, p = 5.39 \times 10^{-32}, \eta_p^2 = 0.77$
Louvres Tilt Angle (p.n.)	$F(2, 99) = 44.86, p = 1.35 \times 10^{-14}, \eta_p^2 = 0.475$	$F(2, 99) = 1.066, p = 0.35, \eta_p^2 = 0.021$
Louvres Tilt Angle (traf.)	$F(2, 99) = 38.14, p = 5.23 \times 10^{-13}, \eta_p^2 = 0.43$	$F(2, 99) = 66.13, p = 5.77 \times 10^{-19}, \eta_p^2 = 0.57$
Factors Interaction (p.n.)	$F(4, 99) = 5.10, p = 0.001, \eta_p^2 = 0.171$	$F(4, 99) = 0.09, p = 0.98, \eta_p^2 = 0.04$
Factors Interaction (traf.)	$F(4, 99) = 6.65, p = 8.81 \times 10^{-5}, \eta_p^2 = 0.21$	$F(4, 99) = 4.10, p = 0.004, \eta_p^2 = 0.14$

Table A3. Two-way Factorial ANOVAs results referred to the differences in Sharpness.

ANOVA Fixed Factors	**Dependent Variable: Differences in Sharpness**	
	Traditional Louvres	**Sound Abs. Louvres**
Sound Source Position (p.n.)	$F(2, 99) = 23.19$, $p = 5.47 \times 10^{-9}$, $\eta_p{}^2 = 0.32$	$F(2, 99) = 12.2$, $p = 1.84 \times 10^{-5}$, $\eta_p{}^2 = 0.198$
Sound Source Position (traf.)	$F(2, 99) = 22.13$, $p = 1.14 \times 10^{-8}$, $\eta_p{}^2 = 0.31$	$F(2, 99) = 15.00$, $p = 1.91 \times 10^{6}$, $\eta_p{}^2 = 0.23$
Louvres Tilt Angle (p.n.)	$F(2, 99) = 26.26$, $p = 7.07 \times 10^{-10}$, $\eta_p{}^2 = 0.35$	$F(2, 99) = 3.22$, $p = 0.04$, $\eta_p{}^2 = 0.06$
Louvres Tilt Angle (traf.)	$F(2, 99) = 15.48$, $p = 1.41 \times 10^{-6}$, $\eta_p{}^2 = 0.24$	$F(2, 99) = 9.87$, $p = 1.20 \times 10^{-4}$, $\eta_p{}^2 = 0.16$
Factors Interaction (p.n.)	$F(4, 99) = 2.92$, $p = 0.02$, $\eta_p{}^2 = 0.10$	$F(4, 99) = 1.47$, $p = 0.21$, $\eta_p{}^2 = 0.06$
Factors Interaction (traf.)	$F(4, 99) = 0.59$, $p = 0.67$, $\eta_p{}^2 = 0.02$	$F(4, 99) = 1.08$, $p = 0.37$, $\eta_p{}^2 = 0.04$

Table A4. Two-way Factorial ANOVAs results referred to the differences in Sound Pressure Levels.

ANOVA Fixed Factors	**Dependent Variable: Differences in Sound Pressure Levels**	
	Traditional Louvres	**Sound Abs. Louvres**
Sound Source Position	$F(2, 99) = 47.58$, $p = 3.31 \times 10^{-15}$, $\eta_p{}^2 = 0.49$	$F(2, 99) = 64.67$, $p = 1.07 \times 10^{-18}$, $\eta_p{}^2 = 0.57$
Louvres Tilt Angle	$F(2, 99) = 11.91$, $p = 2.32 \times 10^{-5}$, $\eta_p{}^2 = 0.19$	$F(2, 99) = 26.53$, $p = 5.93\text{E}{-10}$, $\eta_p{}^2 = 0.35$
Factors Interaction	$F(4, 99) = 0.46$, $p = 0.77$, $\eta_p{}^2 = 0.02$	$F(4, 99) = 0.11$, $p = 0.98$, $\eta_p{}^2 = 0.005$

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