Applied Acoustics 196 (2022) 108885
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Assessment of Acoustic Metawindow unit through psychoacoustic analysis and human perception

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Abstract

Acoustic metamaterials (AMMs) have become so far a resourceful solution for standard materials' physical limitations, and their tuneable acoustic properties have shown potential for noise reduction and absorption over standard materials. At the same time, the building's features' ergonomics value has been discovered to play a key role in indoor well-being. So AMM-based design features, such as windows, should be not only assessed through physical parameters (*SPL*, *IL*, and *TL*) but also investigated by psychoacoustics and human perception. Therefore, the methodology presented in this paper has been developed by firstly measuring and recording a previously developed acoustic metawindow (AMW) unit effect over seven environmental sound recordings, and secondly, merging soundscape-based questionnaires (performed in laboratory and online) and analytical physical and psychoacoustic assessment of the AMW unit. A significant quantitative impact on Loudness, Roughness, and Sharpness was achieved through the AMW unit (between 1 and 15.58 times the just noticeable difference of each psychoacoustic parameter). Moreover, participants qualitatively perceived an effect of neutralisation over the seven sound recordings with the AMW unit effect. After pondering the soundscape rates of the environmental recordings with and without the AMW unit effect separately, a percentage comparison highlighted that the first resulted as 7% less chaotic than the second one, 8% less eventful, 9% less vibrant, 23% more monotonous, and 22% more uneventful. In addition, sound sources related to middle-high frequency resulted specifically neutralised. Finally, Loudness was reduced by the AMW unit effect for the same environmental noise recordings in both the quantitative (psychoacoustic parameters) and qualitative (soundscape descriptors) methods. This research could be the first step toward a tuneable AMMs-based window design from physical, psychoacoustic and human perception points of view, creating a new paradigm for natural ventilation/heating control combined with noise reduction systems.

https://doi.org/10.1016/j.apacoust.2022.108885 0003-682X/Ó

1. Introduction

Acoustic metamaterials (AMMs) have lately opened up a wider range of applications in building acoustics, also related to the simultaneous natural ventilation/thermal regulation [1–7]. AMMs overcome several limitations of standard acoustic materials and are the perfect candidate for playing a key role in regulating indoor comfort from the users' perspective through the building’s features’ advances [8–10]. At the same time, psychoacoustic parameters and soundscape questionnaires have been developed to assess the impact of specific acoustic environments on human perception [11,12]. This is a crucial step in developing a more comprehensive experimental approach and expanding the physical, ergonomic and social meaning of the acoustic environment where users are [13,14]. If such an approach was applied to building’s features that can control the acoustic environment, this would inevitably intersect with another science that concerns interactions among humans and other system elements: Ergonomics.

Environmental external inputs, indoor comfort needs, and ergonomics have become a fundamental part of the design innovation process of building [15,16]. Although many methods have been developed to investigate and test the physical or psychophysical effectiveness of built environment features, such as the window [12–14,17–19], the window's ergonomic design criteria have only been drawn recently [20]. In previous studies indeed, the interaction between people and windows was further investigated through participatory ergonomics to optimise the building systems performance and ergonomics through architectural and engineering design [20]; however, there are still no clear guidelines on how to assess the effectiveness of a specific AMM based window from a psychoacoustic and human perception point of view.

The acoustic metawindow (AMW) effectiveness in terms of psychoacoustic impact needs then to be assessed analytically; moreover, the AMW effect on environmental sound recordings must be judged by human perception following the soundscape approach [21] in order to understand if the AMW has an impact quantitatively and qualitatively on the indoor environment. Finally, correspondence between the analytical and experimental psychoacoustic analysis (Loudness) over a building’s feature acoustic impact must be established. In order to reach these aims, the AMW unit acoustic effect is first applied to several ordinary environmental acoustic scenarios [22], and the resulting soundwaves are measured, recorded and analysed analytically through psychoacoustic parameters (see Figure 1). Secondly, as shown in Figure 1, a soundscape questionnaire-based experiment is run to evaluate the perceivable effect of the AMW in terms of improving the indoor sound environment according to different outdoor environmental noise and indoor functions. Thirdly, the analytical and experimental results are compared to check if they are reliable to each other. Through such a new methodology, the impact of the Acoustic Metawindow (AMW) unit on the environmental indoor human perception could be assessed, creating a new paradigm for AMM based systems for natural ventilation combined with noise reduction systems.

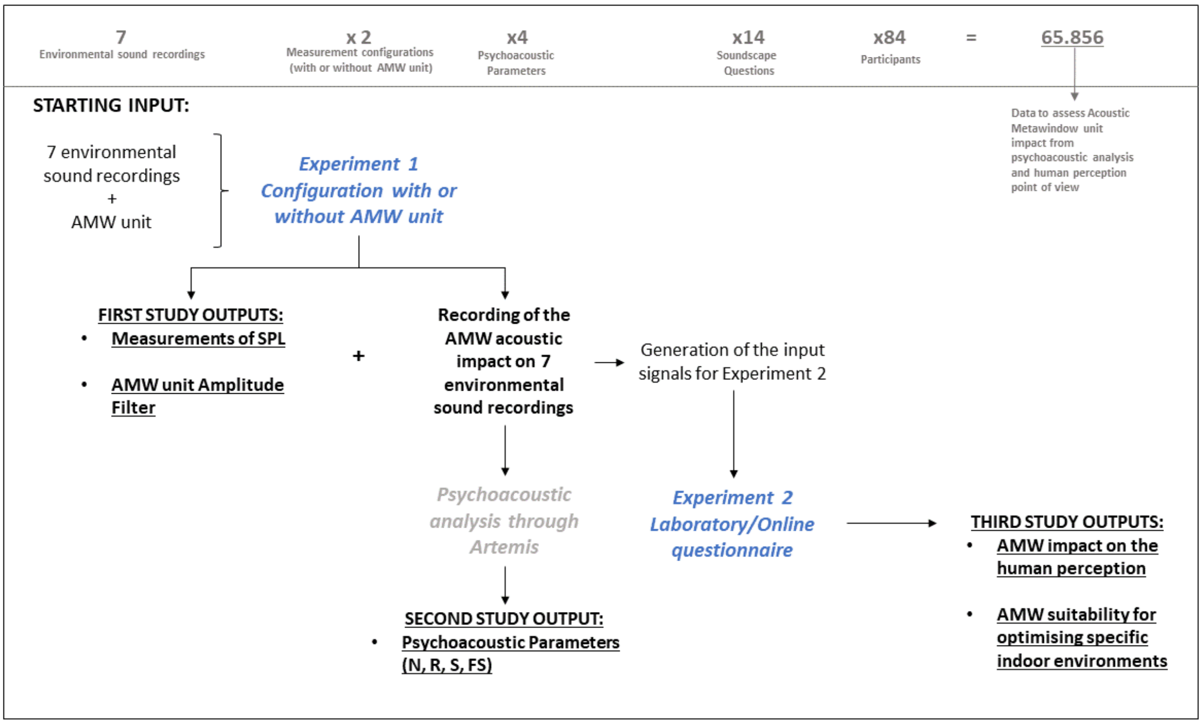

Figure 1 Flowchart of the methodology from the starting inputs to the outputs of the study.

2. Materials and methods

In previous research, the AMW unit has been demonstrated to achieve significant broadband sound reduction and customisable ventilation at the same time [7]. In the presented study, the AMW unit's effect on seven different types of environmental sounds is first experimentally recorded and then analysed in terms of psychoacoustic parameters. Furthermore, in the second stage of the study, the AMW unit effect recordings are presented randomly and non-identifiable to 84 participants. Their perception is investigated through an experimental laboratory and online questionnaire. The window prototype's experimental recordings and measurements have been run in the anechoic chamber of the acoustics laboratory in the Department of Mechanical Engineering of the National University of Singapore (NUS). The experimental laboratory questionnaire was conducted in a controlled environment room at the University of Perugia (IT) [23] and online on a second stage. Moreover, a technical note has been presented to support the methodology in this paper to discuss and highlight the robustness of the experimental method (which includes laboratory and online questionnaires) [24].

2.1 Experimental setup for the input signals

The AMW unit consists of a cubic main body of volumetric dimension of 0.4mx0.4mx0.13m with an embedded AMM system in the window frame space already tested parametrically through FEM, as shown in Figure 2.a [6,7]. The soundwave enters from the outdoor environment through area A, then part of it gets reflected by the front panel, while another part passes through the AMM units and reaches the indoor environment. The resulting soundwave measured in the indoor environment is reduced in terms of SPL due to an acoustic stopband generated by the resonant tubular array inspired by the acoustic black hole effect [25]. More details about the simulation results, the theoretical analyses, and the prototyping process can be found in our previous publications [6,7]. The unit is placed at the centre of a small-size anechoic chamber (inner dimension is 2mx2mx2m, cut off frequency is about 300 Hz). The AMW is attached on the outdoor side with a loudspeaker coupled with a power amplifier FRS 10 WP 8 OHM No. 2101 by VISATON (frequency range from 90 Hz to 19000 Hz and input power of 25 W) connected to the computer of the laboratory as shown from Figure 2.b. The model is fixed to the loudspeaker to avoid any sound leakage from the two systems junction. The *SPL* measurements were performed at the same three positions, A, B, C (Figure 2.b), using a sound level meter with a built-in FFT analyser (Aihua AWA6228). Insertion Loss (*IL)* was calculated following the equation:

$$\mathrm{IL_{AMW}} = \mathrm{SPL_{woAMW}} - \mathrm{SPL_{wAMW}} \quad (\mathrm{dB}) \qquad 1$$

where SPL_{woAMW} is the measured SPL without the AMW in the experimental setup, while SPL_{wAMW} is the measured SPL with the AMW in the experimental setup.

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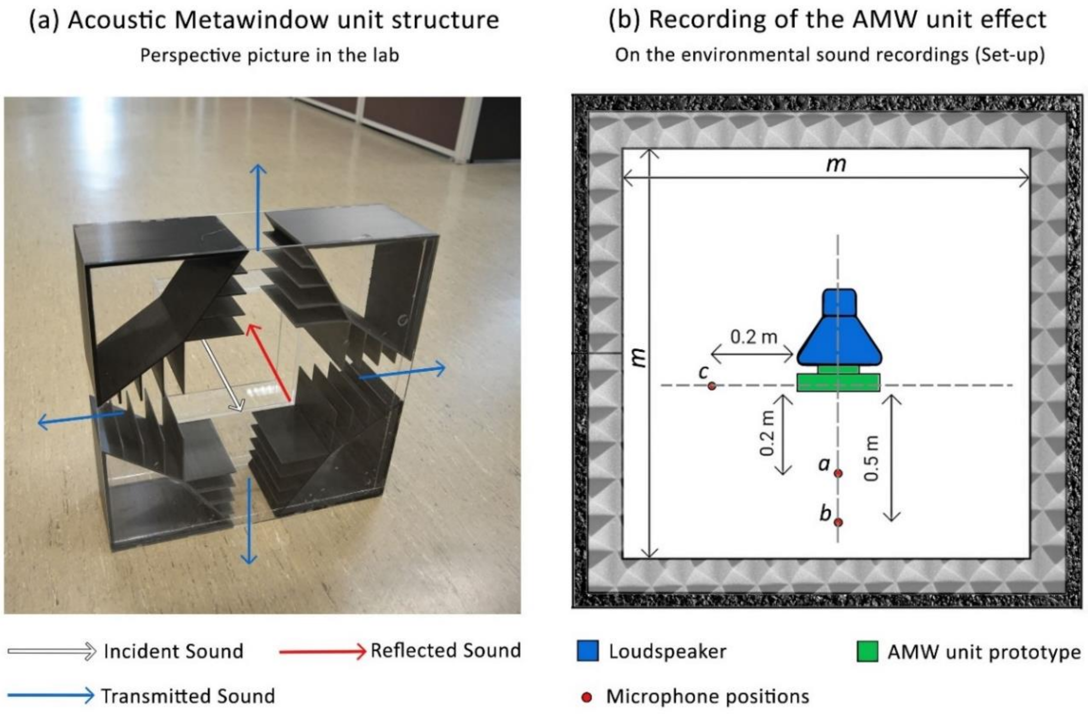
(a) Acoustic Metawindow unit structure
Perspective picture in the lab

(b) Recording of the AMW unit effect
On the environmental sound recordings (Set-up)

Figure 2 a) Perspective picture of the AMW unit prototype with schematics of the affected sound wave phenomenon and; b) setup of the anechoic chamber setup for the recording of the AMW effect over the environmental sounds.

2.2 Psychoacoustic parameters

Following the EU Directive on Environmental Noise [26], certain noise levels during the day and night time must be ensured to guarantee the people a limit of exposure to sounds in public spaces, which kept increasing during the last 50 years due to the wild urbanisation worldwide. According to WHO, 30% of the EU population is exposed to noise levels exceeding 55 dB(A) during nighttime [27]. However, since Schafer [28] defines the soundscape concept, a new methodology specifically focused on people's psychoacoustic perception of spaces has entered modern acoustics. Simultaneously, new soundscape-inspired descriptors focused on people's perception in specific soundscape environments (called psychoacoustic parameters) were added to the standard ones (as the *A-weighted SPL*) [11,12,14,29]. The use of such new parameters is also encouraged by the International Organization for Standardization, which defines soundscape as *'the acoustic environment as perceived or experienced and/or understood by a person or people, in context'*. [30] Therefore, it is clear how this new acoustic approach put more effort into enhancing the more pleasant sounds rather than the mere reduction of the noise level. [31]

Psychoacoustic parameters have been selected to study the capability of the AMW unit prototype to facilitate the perception of desirable sounds coming from the outdoor, which can be considered one of the most important features which influence the global assessment of public and private indoor spaces quality. [22] The selected parameters have been used to evaluate the recorded data from the anechoic chamber tests through a descriptive analysis of the effectiveness of the AMW unit on the user performed through the HEAD Artemis 11.0 software. The present research has been developed through the study of a physic parameter, such as *SPL*, and psychoacoustic parameters, such as Loudness (*N*), roughness (*R*), sharpness (*S*) and fluctuation strength (*FS*), to evaluate the effect of the AMW unit in the seven experimental acoustic environments. Specifically, following table D.1 - ISO/TS 12913-3 [32], the statistics pool in Artemis has been used in order to calculate percentile values of the time-dependent curve for each psychoacoustic parameter considered: N_5 (from ISO 532-1 [33]), S_5 (from DIN 45692 [34]), R_{10} and F_{10} (from Fastl and Zwicker [12]). It is crucial to involve all these parameters since the perception of sounds involves a complex chain of events to interpret the information contained in sound signals emitted from sound sources [21]. While sound parameters (such as *SPL* and *IL*) can help study the physical tolerance of the auditory perception's human organ, psychoacoustics is the science of sound perception, investigating the statistical relationship between acoustic stimuli and hearing sensations.

To quantitatively analyse the impact of the AMW unit in terms of psychoacoustic parameters over all the different soundscape recordings, the obtained values are expressed with respect to the two configurations (with and without the AMW unit in Eq.1), the seven different environmental recordings and the three measuring points in the anechoic chamber (Figure 2 points a-c). In order to verify the efficiency of the AMW unit in improving the user acoustic comfort conditions, it is necessary to detect the minimum differences in these metrics which are subjectively perceived: just noticeable differences (JND) [35], *ΔMIN*, for each parameter used for the analysis: 3 dB for *SPL*, 32 phon for Loudness, 17% asper for *R*, 0.04 acum for sharpness and 17% vacil for fluctuation strength. Moreover, for the sake of simplicity, the microphone position is labelled with letters from a to c (Figure 2 points a-c) as it changes in terms of distance from the point where the source is perpendicular to the AMW unit and 0.2m and 0.5m far perpendicularly (respectively measurement point a and b) and 0.2m far laterally (measurement point c) (see Figure 2.b). As described above, environmental recordings are labelled by numbers from 1 to 7. For each psychoacoustic parameter, the value *ΔX* has been considered as the difference of the parameter *X*, evaluated with and without the AMW unit interposed between the source and the microphone. Then each *ΔX* value was divided by each specific *JND* to determine how perceivable is the AMW unit contribution in terms of psychoacoustic parameters (*Eff(X)*). Below is shown an example with (*Eff(N)*):

$$Eff(N) = \frac{\Delta N}{JND(N)} \qquad 2$$

where

- $\Delta N = N_{without} - N_{with}$
- $JND(N)$ = just noticeable difference (JND) of N from a human hearing system in terms of each psychoacoustic parameter [35]

2.3 Experimental setup for the laboratory human perception questionnaire

The test room where the first part of the experiment was held (4x4x2.7 m) is located inside the laboratories of the Engineering Campus of the University of Perugia (Italy, Cfa Köppen-Geiger climate class [36]). The test room indoor conditions are thermally controlled through air conditioning (AC) and a radiant system. The experiment was held at stationary and thermally neutral conditions: air temperature at 21 °C and MV at fan speed level L2. According to the standards [37], internal conditions are continuously monitored to assess thermal, visual, and air quality status. The presented experimental campaign provided acoustic stimuli through wired noise-cancelling headphones (model WH-1000XM4, by Sony) to reduce the AC fan noise in the background as much as possible.

The internal background noise level within the test room was mapped through a sound level meter (model SOLO SLM, by 10dB) on a 9-point grid at 1.10 m height (which corresponds to the average height of a sitting person's auditory system) in order to capture the background noise contributed by a level L2 of fan speed setup of the mechanical ventilation (MV) system (Figure 3), corresponding to a 0.6 ACH (air changes per hour). Overall, the internal background noise sound level ranged between 22.8 and 40.4 dB. This was reduced broadly to 29dB by the Active Noise Cancelling properties of the headphones used [38]; however, from a sound pressure level (*SPL*) analysis in frequency, peaks are still highlighted at a low-frequency range (below 500Hz).

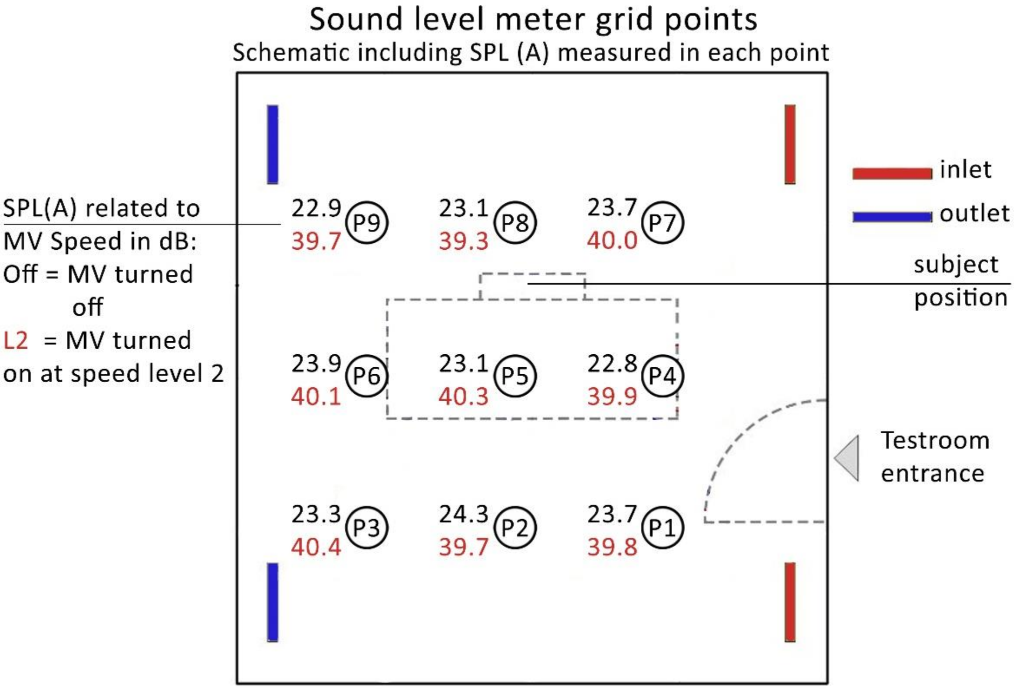

Figure 3 b) Schematic of the Test room where the laboratory questionnaire took place with measurement points to determine background noise highlighted. Background noise level analyses are included considering the MV system off (black font) and operating at the second (L2) level of inlet flow (red font). The sound level meter was placed at 1.1m height at each measurement point.

From a visual point of view, there was no specific stimulus inside the test room (Laboratory experiment), while for the Online test, the visual stimuli were randomly occurring due to different environmental conditions where the participants took the questionnaire. However, an isolated room where participants could be alone while taking the questionnaire was required for the Online test. Visual stimuli can influence human perception; for this reason, a 5-point Likert scale was used to assess the visual perception of the surrounding environment where the participants took the questionnaire according to the standards [37]. From this assessment, the participants judged the visual stimuli Neutral from a Comfort and Sensation Vote point of view [23]. For this reason, the visual stimuli are considered here as non-significantly influencing human perception.

2.4 *Participants*

In this research, the sampling has no specific requirements since the study's aim includes all the different kinds of users of indoor spaces. For this AMW unit human perception experiment, the recruitment was done through the University of Sheffield, the A*STAR and University of Perugia students and staff, and Sheffield's, Singapore's and Perugia's residents. The whole group of participants included 84 individuals, of which 40 females, 43 males, and 1 non-binary with ages between 20 and 60 years old, hailing from Europe and North Africa (77%), Asia (19%), America (4%), and Australia (1%). It is essential to highlight that the study focused on the different backgrounds that would have defined correspondent factors under contextual experience (demographical, space usage, and psychological) [39]. Hence, window design investigation is still at a global environmental stage regarding history/heritage, ethnicity, geography and economic situation. The following graphs (Figure 4, a-c) show the participants' gender, age, and nationality characteristics. Approval from the Ethics Committee from the University of Sheffield was received before starting the experiment.

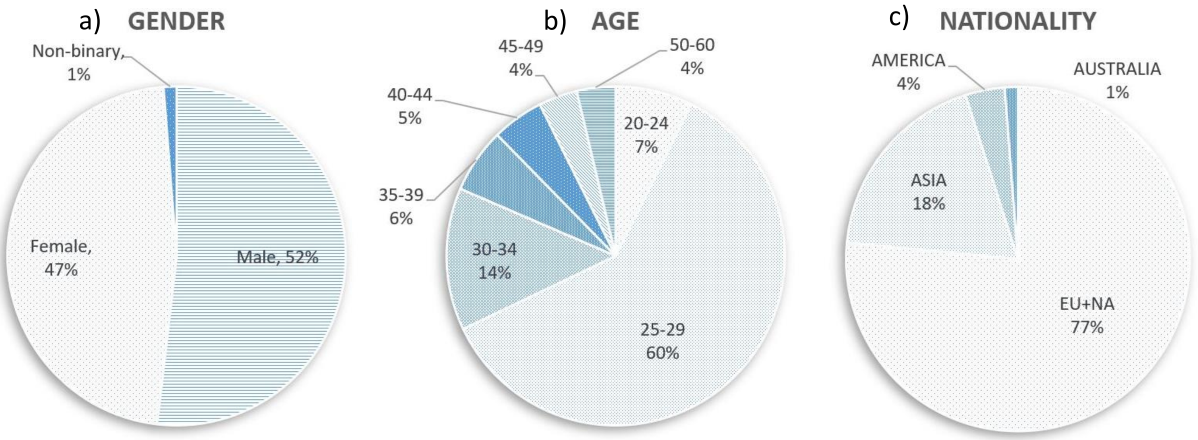

Figure 4 Background of the participants: (a) gender, (b) age, and (c) nationality.

2.5 Soundscape questionnaire to evaluate the AMW unit performance from a human perception point of view

Each Participant listened to and evaluated seven proposed soundscape recordings with and without the effect of the AMW unit (14 recordings in total) comprising the following categories: #1 Beach, #2 Woodlands, #3 Quiet Street, #4 Pedestrian Zone, #5 Park, #6 Shopping Mall, and #7 Busy Street. The recordings were presented randomly. Soundscape descriptors helped the participants to describe each listened recording in terms of the following adjectives: eventful, vibrant, pleasant, calm, uneventful, monotonous, annoying, and chaotic [29,40,41]. It is important to highlight that this study assessed the filtered effect of the outdoor stimuli, while eventual indoor sound input was neglected. The indoor input is supposed to be averagely neutral, and the overall indoor environment where the questionnaire was taken quiet as these were the Laboratory and Online experiment requirements. For this reason, ISO TS 12913-2 attribute scales were used rather than more indoor-focused ones such as those described by Torresin et al. [42] and applied by Jo and Jeon [43]. The questionnaire-based study was set through Gorilla, an online platform, to broaden the sample size in the online second part of the experiment. The questionnaire was developed through 15 questions. The comprehensive list of the questions for the acoustic environmental recordings perception is included below. The first was open reply-based, while the other 14 were based on a 5 point Likert scale.

1. While listening, please write down in the following tab any sound sources you can identify in this sound environment (please separate each sound source with a comma).

2. How did you hear the following four sounds? (Not at all; A Little; Moderately; A lot; Dominates Completely):

2.A Traffic Noise (cars, buses, trains, aeroplanes, etc.)

2.B Other noise (e.g. sirens, construction, industry, loading of goods)

2.C Sounds from human beings (e.g. conversation, laughter, children at play, footsteps)

2.D Natural sounds (e.g. singing birds, flowing water, wind in vegetation)

3. For each of the eight scales below, to what extent do you agree or disagree that the outdoor public space you heard is... (Strongly Agree; Somewhat Agree; Neither; Somewhat Disagree; Strongly Disagree) - 3.A Pleasant; 3.B Chaotic; 3.C Vibrant; 3.E Uneventful; 3.F Calm; 3.G Annoying; 3.H Eventful;

4. Overall, how would you describe the outdoor public space you have just heard? (Very good; Good; Neither bad nor good; Bad; Very bad)

5. How loud would you say this environment was? (Not at all; Slightly; Moderately; Very; Extremely)

During both the laboratory and online questionnaire, the participants did not have a time limit to evaluate each listened recording and could replay it as many times as they wanted. Participants' responses for each soundscape recording were multiplied times 0 to 4 according to the participants' rate. Respectively, 'strongly disagree' rates were multiplied times 0, 'somewhat disagree' rates were multiplied times 1, 'neither' rates were multiplied times 2, 'somewhat agree' rates were multiplied times 3, and 'strongly agree' rates were multiplied times 4. Due to their 5-point Likert scale nature, a ponderation was performed to allow clearer visualisation of different soundscape recordings evaluation. Through this ponderation process, the overall soundscape descriptors shown in Figure 6 were calculated as $Total\ ponderated\ vote = \sum X_0 \cdot 0 + X_1 \cdot 1 + X_2 \cdot 2 + X_3 \cdot 3 + X_4 \cdot 4$, where X_0 is the total 'strongly disagree' votes for specific soundscape recordings, X_1 is the total 'somewhat disagree' votes for specific soundscape recordings, X_2 is the total 'neither' votes for specific soundscape recordings, X_3 is the total 'somewhat agree' votes for specific soundscape recordings, X_4 is the total 'strongly agree' votes for specific soundscape recordings. Moreover, standard deviation σ was used to understand how dispersed the data is in relation to the mean participants' vote. In this case, it was calculated as $\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$ where N is the number of participants (84), μ is the mean value of the participants' soundscape vote value, x_i are the individual vote. Low standard deviation means data are clustered around the mean, and high standard deviation indicates data are more spread out.

Furthermore, a specific section included in the related technical note (TN) describes how the responses from the Laboratory and Online questionnaires are reliable and comparable [24]. The TN focuses on performing the first online questionnaire (namely Online 1 on the TN), which involved 16 of the same Laboratory participants (the test was run after three weeks to ensure that participants would not be biased) [24]. Afterwards, the statistical reliability of the sample is analysed to check any significant influence of the different headset set up on the same participants' response to the auditory perception questionnaire. Considering the Laboratory results as headset quality benchmark, intra-rater reliability for the Online 1 experiment is determined by calculating the intra-class correlation coefficient (ICC). As a result, all the 16 participants tested reliability with an ICC $\geqslant$ 0.7 and Cronbach's alpha value $\geqslant$ 0.7 (minimum α =0.723, maximum α =0.875), proving the robustness of the online method used for the questionnaire assessing AMW unit soundscape impact [24].

2.6 AMW unit filtering over seven different environmental sound recordings

Different environmental sound recordings may be affected differently by the AMW, so a preliminary analysis of the AMW unit's filtering capacity is necessary to set a term of comparison for further analytical and experimental results. The environmental sound recordings considered are #1 Beach, #2 Woodlands, #3 Quiet Street, #4 Pedestrian Zone, #5 Park, #6 Shopping Mall, and #7 Busy Street. Moreover, the filtering effect over white noise was also considered to demonstrate the characterisation of real sound sources over a broadband source. In both analysed recordings, the AMW unit Amplitude filter was calculated as:

$$AMW\ unit\ Amplitude\ Filter = \frac{SPL\ (with\ AMW\ unit)}{SPL\ (without\ AMW\ unit)} \qquad 3$$

Where $SPL\ (with\ AMW\ unit)$ is the SPL measured in the first experimental conditions (Singapore) with the AMW unit effect applied, while $SPL\ (without\ AMW\ unit)$ is the original environmental sound recording measured in the same conditions but without the AMW unit effect applied.

Figure 5 shows the environmental sound input spectra and the different filtering capacities of the AMW unit according to the sound input characteristics. For the sake of simplicity of comparison with white noise, in Figure 5.b, only the the root mean square (RMS) of the filtering capacity over the seven environmental sound recordings is shown. The comparison with white noise filtering is needed to highlight the tonal components. Values <1 highlight a filtering capacity, while values ≥1 indicate no filtering effect. Overall, a good filtering performance is clear from 300 to 5kHz, 7k to 8kHz, and 9k to 10kHz. The filtering ability of the AMW unit decrease at 5k-7kHz and 8k-9kHz, and 50-300Hz, and all the studied files are affected by a magnification of the signal culminating at 280Hz. Unfortunately, as highlighted in the results of previous work [7], the AMW unit noise-reducing capacity has a limitation over a lower frequency range. In that specific journal paper [7], an acoustic broadband optimisation was investigated and numerically demonstrated; however, due to the current pandemic situation, the AMW model used for these experiments was the basic one (without broadband optimisation).

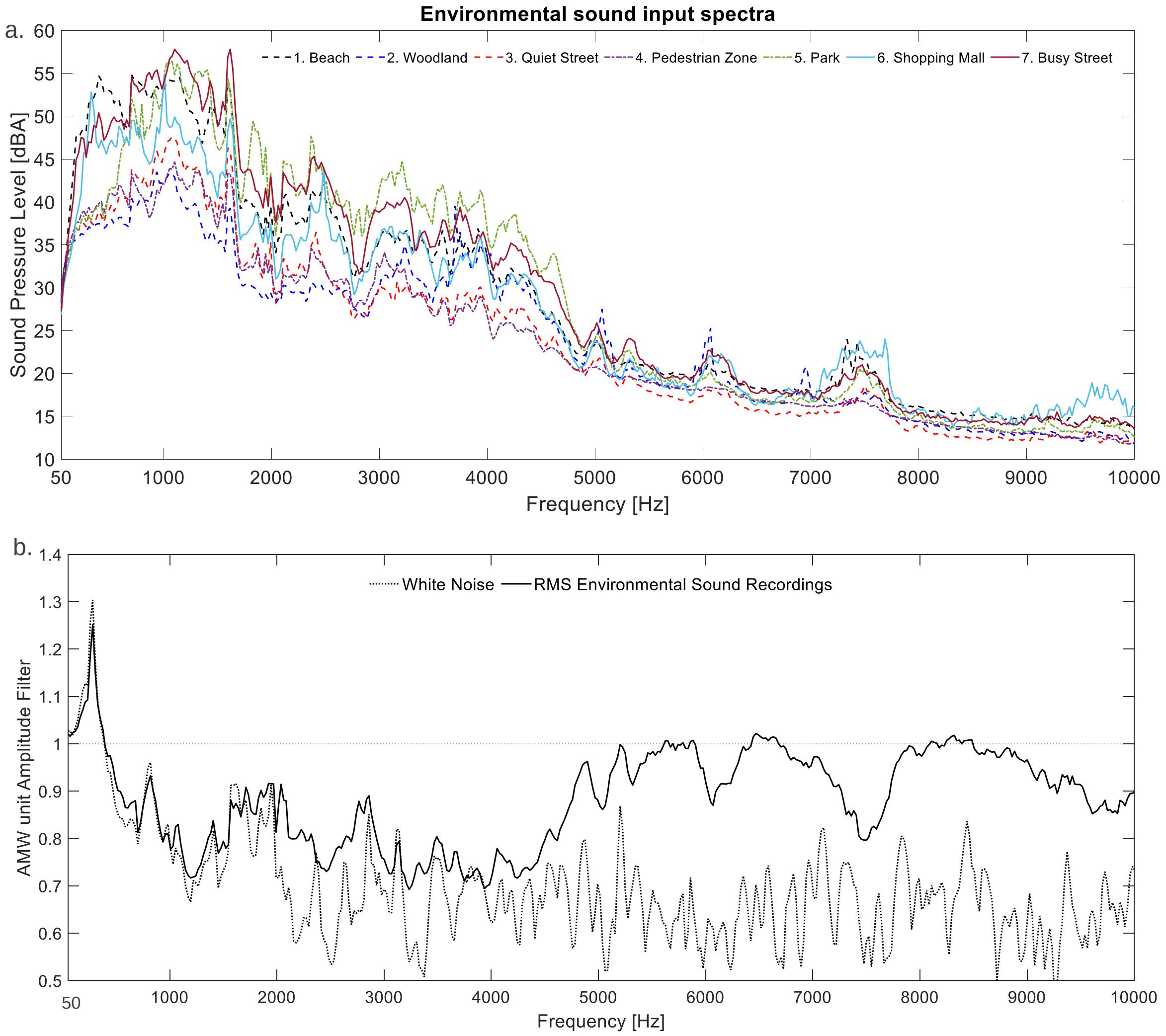

Figure 5 schematics of a) Environmental sound recording spectra and b) AMW unit Amplitude filter of white noise and the RMS of the AMW unit Amplitude Filter related to the 7 environmental sound recordings: #1 Beach, #2 Woodlands, #3 Quiet Street, #4 Pedestrian Zone, #5 Park, #6 Shopping Mall, and #7 Busy Street.

3. Results

The impact of the AMW unit on the environmental indoor human perception is assessed through the mixed methods analysis (quantitatively through psychoacoustic parameters and qualitatively through soundscape questionnaires) and by comparing them to check if they are reliable on each other.

3.1 Psychoacoustic effect of the AMW unit

This section examines the impact of the AMW unit in terms of psychoacoustic parameters over all the different soundscape recordings. Table 1 shows the AMW psychoacoustic effect impact, assessed experimentally from the laboratory measurements and following Eq. 2; here, the effectiveness of the AMW unit contribution is indeed expressed in terms of the RMS value between the *Eff(X)* of the seven environmental sound recordings and different measuring points in the anechoic chamber (Figure 2 points a-c). Loudness (*N*) is effectively reduced, specifically for a perpendicular distance of 0.5 m, with RMS(Eff) between 3.12 and 3.89 times the *JND*. Point c is not significantly affected as it is placed in the direction of the lateral opening of the AMW unit, so it does not benefit from any acoustic diffraction effect. A significant decrease in *R* is also perceived in terms of *JND* through the application of the AMW unit. Unlike *N*, its contribution is perceivable throughout all the measuring points with an RMS(Eff) between 1.41 and 2.18 times the *JND*. This is probably due to the medium-high frequency pitch of the recordings (see Figure 5), typically characteristic in sound signals with perceivable R. Differently from the *N* perception, the *R* seems to be reduced sensibly through the model also in measurement point c, showing an overall significant impact of the AMW unit on this psychoacoustic parameter. Sharpness (*S*) is influenced by the AMW unit consistently overall the three measurement points. Interestingly, especially in measurement points a and b, the S reduction in JND is particularly high (RMS(Eff) reaches 12.12 and 15.58 in these measurement points). Overall this determined a significant psychoacoustic impact of the AMW unit over *S*, even though this weight function increases rapidly toward the highest frequency bands [12]. For this reason, this analysis highlights a significant effect of the AMW unit on S due to the topical characterisation of the medium-high frequency filtering capacity of the AMW unit with middle-high frequency peaks reduction (100-4500 Hz) (see Figure 5). Finally, Table 1 shows a much inconsistent impact of AMW unit over *FS JND*. The contribution is indeed mostly negligible in this psychoacoustic parameter. As inversely related to *S*, *FS* was expected to be minimally impacted by the AMM-based system. This psychoacoustic factor needs to be considered when designing a window for environments where FS is a particular issue.

Table 1 RMS of Effectiveness of the AMW unit (EffX) according to four psychoacoustic parameters: Loudness (N), Roughness (R), Sharpness (S), and Fluctuation Strength (FS). The table show data gathered from the three measuring points a, b, c in Figure 2.b. The values presented in the table are RMS of the values related to the seven considered environmental sound recordings (with and without the AMW unit effect. JND multiples are highlighted in italic, while the highest JND multiple is highlighted in bold format.

		RMS(Eff) (all environmental sound recordings)			
		N	R	S	FS
Measuring points	a	*3.89*	*2.11*	*12.12*	0.02
	b	*3.12*	*2.18*	***15.58***	0.06
	c	0.73	*1.41*	*6.11*	0.01

3.2 AMW unit effect on human perception through soundscape descriptors

Following the psychoacoustic analysis, which highlighted a significant contribution of the AMW unit over N, R, and S, a more in-depth investigation must be run focusing on its impact on human perception. The Soundscape questionnaire is a valid method to understand this research question [29], and this section analyses the overall participants' evaluation of each heard environmental sound recording and compares the perception influenced by the AMW unit. Response difference between with and without AMW recordings is defined as statistically appreciable when it is over 10%. Figure 6.a shows the overall participants' evaluation of the first six recordings: #1 Beach (without and with the AMW unit), #2 Woodland (without and with the AMW unit), and #3 Quiet street (without and with the AMW unit). σ is considerably low and ranges between 14-21% for all the soundscape descriptors in the judged environmental sound recordings #1, #2, and #3. Overall the original three recordings (without the AMW unit) are perceived as slightly less eventful and vibrant than the other configuration (between 5-13% of those with the AMW unit effect). The AMW unit effect significantly increases the monotonous and uneventful component (20% more), especially for the #1 Beach and #3 Quiet street. #2 Woodland is negatively affected in terms of pleasantness, 17% less than the original one.

The participants' evaluation of recordings #4 Pedestrian zone and #5 Park is shown in Figure 6.b. In this case, the participants perceive an overall higher decrease in eventfulness, vibrancy, and pleasantness than in the previously analysed recordings. σ has a minimum of 3 and a maximum of 7, so it is still low for all the soundscape descriptors in these two environmental sound recordings #4, #5. #4 Pedestrian zone_w and #5 Park_w are negatively affected in terms of pleasantness, 19% less than the original one. In addition, these two recordings with the AMW unit effect are judged sensibly more monotonous and uneventful than the original recordings (especially #5 Park_w, 26% more monotonous and 22% more uneventful). They show, then, a general neutralisation of the heard environment through the window prototype.

Figure 6.c shows the overall participants' evaluation of the last four recordings: #6 Shopping Mall (without and with the AMW unit) and #7 Busy street (without and with the AMW unit). Overall the configuration with the AMW unit is perceived as slightly less chaotic and eventful (between -3 and -10%); However, in #6 Shopping Mall_w as observed in #4 Pedestrian zone_w, this configuration is perceived as slightly more annoying and consequently less pleasant. Following the studies of Di Blasio et al., many "talking sources" are identifiable in this environmental sound recording, including music playing, people chatting, and radio advertisement [44]. As explained by Di Blasio et al. and Haapakangas et al., our brain tends to pay much more attention to these sources, rather than music or natural sound sources, because it naturally tries to understand the message they are communicating [44,45]. The application of the AMW unit tends to neutralise sound sources with high pitches, including the "talking" ones (e.g. birds, human voices, car horns, kids playing). The human brain naturally feels more stressed about the neutralising effect on human voices because its message cannot be easily elaborated. So this could be the reason why participants judge the recording as more annoying than the original one. σ is considerably medium-low and ranges between 20-31% for all the soundscape descriptors in both judged recordings #6, #7 but is still significant for the experiment.

For these reasons, even if the AMW unit impact has been proved, there is still work to do to understand if this implies an improvement of the indoor soundscape and how it can serve specific functions according to different outdoor noise sources. For example, following this study's results, the actual AMW unit configuration could be suitable for an indoor function that requires a quiet and calm environment (such as libraries, studying rooms, religious places, and meditation rooms).

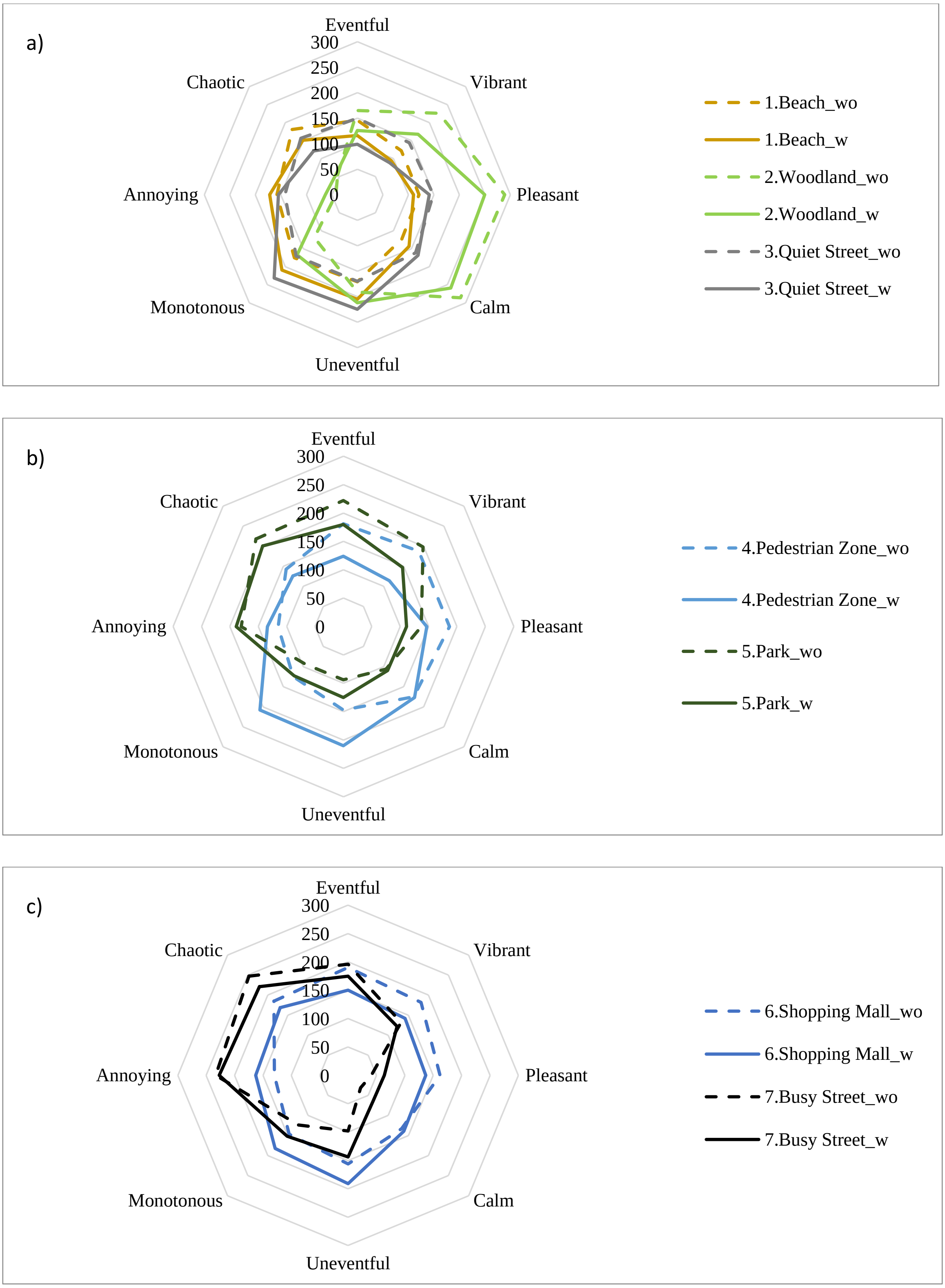

Figure 6 Overall participants evaluation of the 14 soundscape recordings: #1 Beach (without and with the AMW unit), #2 Woodland (without and with the AMW unit), #3 Quiet street (without and with the AMW unit), #4 Pedestrian zone (without and with the AMW unit), #5 Park (without and with the AMW unit), #6 Shopping Mall (without and with the AMW unit), and #7 Busy street (without and with the AMW unit).

These two first analyses showed encouraging results about the AMW unit potential in terms of psychoacoustics and human perception. Overall, the AMW unit proved to affect the incoming soundwave by reducing Loudness, Roughness, and Sharpness. From the Loudness point of view, its reduction can improve indoor environmental comfort; However, further study might clarify if also Roughness and Sharpness decrease has a positive or negative impact, probably according to the outdoor sound sources. Another factor highlighted by these analyses is the increase in the Uneventfulness and Monotonousness (and correspondent decrease in Chaotichness, Eventfulness, and Vibrancy) through the AMW unit. This may suggest that this type of window is not only useful for noise reduction while allowing natural ventilation (as highlighted in former studies [7]) but could also be suitable for improving indoor environments that generally require a more neutral and calm setup.

3.3 AMW unit effect on Loudness through psychoacoustic analysis and human perception evaluation

After having demonstrated the impact of the AMW unit in terms of psychoacoustic parameters and human perception point of view, the vote on a common parameter, namely Loudness, can be compared to understand if there might be a correlation between the quantitative and qualitative analysis method. Soundscape's loudness is crucial for human well-being and comfort [41]. Hong et al. demonstrated how perceived Loudness could directly influence the soundscape quality and, therefore, the physical stress that a person may develop due to it. At the same time, Hong et al. argue that higher Loudness can be expected and pleasant in specific recreational environments such as concerts and recreational activities. In this study, Loudness has been analysed analytically through the HEAD Artemis suite (representing the magnitude of an auditory sensation and calculated according to ISO 532-1 [33]) and experimentally through the participants' evaluation.

The two Loudness (Psychoacoustic and Perceived) are compared in Figure 7 with two different evaluation scales highlighted on the right (for the first one) and the left (for the second one). Psychoacoustic Loudness is expressed as determined by Eq. 2 of the previous Section 2.2. In contrast, Perceived Loudness was evaluated for all the recordings in the laboratory and online questionnaire with a 5 Likert scale (Not at all Loud, Slightly Loud, Moderately Loud, Very Loud, and Extremely Loud). Therefore, the results compared in this schematic should be evaluated as inversely proportioned, which means that a higher level of *Eff(N)* corresponds to a lower rate of Perceived Loudness.

From Figure 7, a correspondence can be observed especially referring to the Loudness related to soundscape #1 Beach and #7 Busy Street. Both analyses show preliminary agreement in their Loudness reduction results through the AMW unit application. According to the Psychoacoustic Loudness rate, a less perceivable change in Loudness is highlighted from Psychoacoustic and Perceived analysis for recordings #2 Woodlands, #3 Quiet Street, #4 Pedestrian Zone, and #6 Shopping Mall. The only Perceived Loudness rate that appears not to follow the Psychoacoustic one is from recording #5 Park. By analysing this recording more in-depth qualitatively, there are several sound sources such as (quotations taken from the participants' notations for Question n.1) "*children playing and laughing*", "*people/families having fun*", and "*exciting environment*". At the same time, this recording has a higher rate in terms of pleasantness compared to recording #2,3,4,6, where also human-derived sounds are mostly absent (again quotations taken from the participants' notations for Question n.1 "*natural*", "*mechanical*", "*people shouting").* So while the overall Loudness impact of the AMW unit effect is captured equally from the Psychoacoustic and Perceived point of view, for this specific recording #5, it can be derived that the Loudness perception of it might be significantly affected by the positive interpretation of the characterising sound sources from the participants' perspective. Following this flow, the disagreement between analytical and perceived responses resulting from the two methods' different analysis approaches could be why the qualitative and quantitative methods should be both considered when designing AMMs-based building features for ergonomics and soundscape purposes.

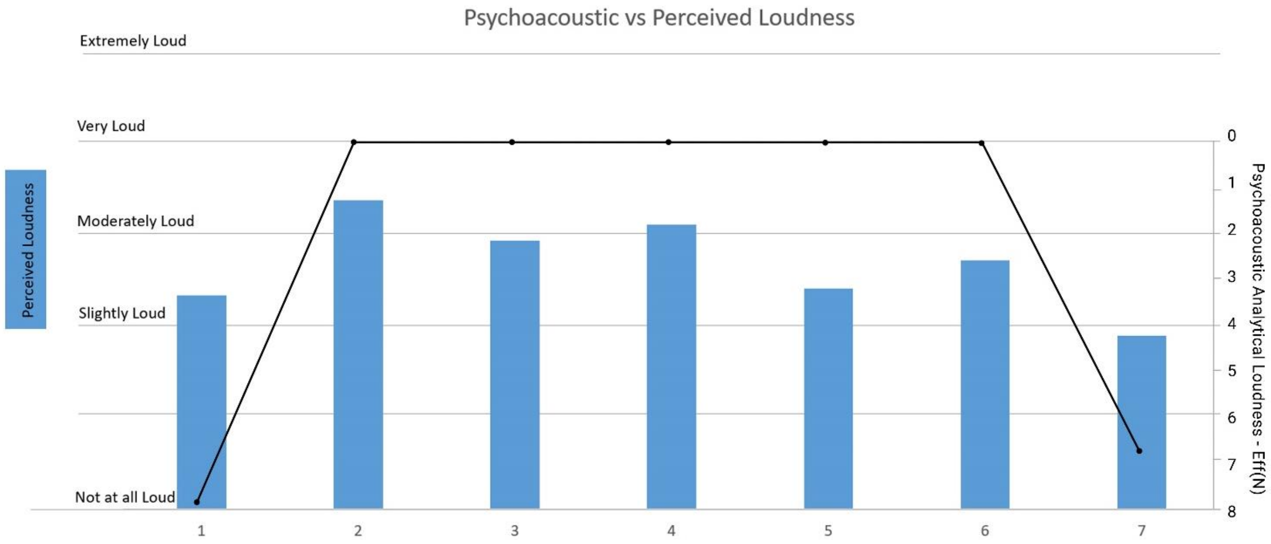

Figure 7 Comparison of psychoacoustic analytical results (solid black line) and experimental perceived results of Loudness in each soundscape recording in the configuration with the AMW unit applied (bar graphs): #1 Beach, #2 Woodland, #3 Quiet street, #4 Pedestrian zone, #5 Park, #6 Shopping Mall, and #7 Busy street.

4. Conclusions

This study aims to highlight the AMW unit's potential to control indoor environmental comfort beyond SPL. The factors considered at first (in the previous publication [7]) helped to define a balance between the ergonomic value of the window design and optimised noise control combined with natural ventilation. This paper discusses the balance between noise control and psychoacoustic and human perception impact of the AMW unit on a number of outdoor environmental sound recordings to understand the impact of such new technology on an objective and subjective sphere. The AMW unit impact was investigated in this paper through experimental testing and human perception-based laboratory and online questionnaires.

Firstly, the proposed window proved to have a perceivable impact in terms of psychoacoustic just noticeable difference (*JND*) for Loudness (reduction between 3.12 and 3.89 times the *JND*), Roughness (reduction between 1.41 and 2.18 times the *JND*), and Sharpness (reduction between 12.12 and 15.58 times the *JND*). Loudness decrease determines a positive impact of the AMW on the analysed environmental sound recordings, while further investigation is needed to establish what kind of impact Sharpness reduction and Roughness reduction imply. Then Soundscape questionnaire qualitatively connoted the AMW unit as significantly reducing vibrancy, chaos and eventfulness, showing a general neutralisation over most of the perceived soundscapes through the window prototype. Recordings of the seven environmental sounds with the AMW unit effect were overall more calm, monotonous and uneventful than the original ones. Specifically, after pondering the soundscape rates of the environmental recordings with and without the AMW unit effect separately, a percentage comparison highlighted that the first resulted as 7% less chaotic than the second one, 8% less eventful, 9% less vibrant, 23% more monotonous, and 22% more uneventful. Furthermore, from comparing the quantitative (psychoacoustic parameters) and qualitative (soundscape descriptors) methods, Loudness resulted simultaneously reduced by the AMW unit effect for the same environmental noise recordings.

In the previous study [7], the AMW unit prototype proved to have a customisable broadband noise reduction and effective natural ventilation potential quantitatively included in an ergonomic design. This study showed the potential of the AMW unit in neutralising a range of environmental sounds (especially those at middle/high frequencies) from both quantitative and qualitative points of view. Moreover, due to its customisable acoustic nature, further studies could investigate the shifting of such neutralising effect to a specifically targeted frequency range [7]. Therefore, the AMW design could be applied to specific indoor functions (requiring different indoor soundscape characteristics at different degrees) and following the previously established ergonomic design criteria [20] with significant ergonomic and environmental comfort improvements over standard windows.

Acknowledgements

The authors would like to thank Prof Zhenbo Lu from Sun Yat-Sen University (CN) for the support in the first laboratory measurements in Singapore, and Dr Ilaria Pigliautile and Prof. Anna Laura Pisello from Perugia University (IT) for providing and helping set up the laboratory in Perugia for running the first part of the human perception experiments.

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