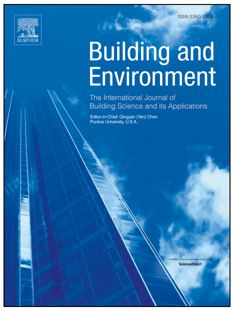

Indoor soundscape assessment: A principal components model of acoustic perception in residential buildings

Simone Torresin, Rossano Albatici, Francesco Aletta, Francesco Babich, Tin Oberman, Stefano Siboni, Jian Kang

PII: S0360-1323(20)30526-6

DOI: https://doi.org/10.1016/j.buildenv.2020.107152

Reference: BAE 107152

To appear in: *Building and Environment*

Received Date: 5 May 2020

Revised Date: 17 July 2020

Accepted Date: 19 July 2020

Please cite this article as: Torresin S, Albatici R, Aletta F, Babich F, Oberman T, Siboni S, Kang J, Indoor soundscape assessment: A principal components model of acoustic perception in residential buildings, *Building and Environment* (2020), doi: https://doi.org/10.1016/j.buildenv.2020.107152.

Indoor soundscape assessment: a principal components model of acoustic perception in residential buildings

Simone Torresin [a, b, *], Rossano Albatici [a], Francesco Aletta [c], Francesco Babich [b], Tin Oberman [c], Stefano Siboni [a], Jian Kang [c]

[a] Department of Civil Environmental and Mechanical Engineering, University of Trento, Via Mesiano 77, 38123 Trento, Italy; simone.torresin@unitn.it, +39 0471 055 692; rossano.albatici@unitn.it; stefano.siboni@unitn.it

[b] Institute for Renewable Energy, Eurac Research, A. Volta Straße/Via A. Volta 13/A, 39100 Bolzano-Bozen, Italy; francesco.babich@eurac.edu

[c] UCL Institute for Environmental Design and Engineering, The Bartlett, University College London (UCL), Central House, 14 Upper Woburn Place, London WC1H 0NN, UK; f.aletta@ucl.ac.uk; t.oberman@ucl.ac.uk; j.kang@ucl.ac.uk

* Corresponding author

Abstract

Models of perceived affective quality of soundscapes have been recently included into standards to guide the measurement and improvement of urban soundscapes. Such models have been developed in outdoor contexts and their validity in indoor built environments is unclear. A laboratory listening test was performed in a mock-up living room with a window sight, in order to develop an indoor soundscape model for residential buildings. During the test, 35 participants were asked to rate 20 different scenarios each. Scenarios were defined by combining four indoor sound sources and five urban environments, filtered through a window ajar, on 97 attribute scales. By applying principal component analysis, *Comfort*, *Content*, and *Familiarity*, were extracted as the main perceptual dimensions explaining respectively 58%, 25% and 7% of the total variance. Relationships between the principal component scores, acoustic parameters and indoor and outdoor sound categories were investigated. *Comfort*, *Content*, and *Familiarity* were found to be better predicted respectively by loudness N_{10}, level variability L_{A10}-L_{A90} and sharpness S. The magnitude of linear-mixed-effect model predictions sensibly improved by accounting for sound categories, thus pointing at the importance of semantic meaning of sounds in indoor soundscape assessment. A measurement system is proposed, based on a 2-D space defined by two orthogonal axes, *Comfort* and *Content*, and two additional axes, *Engagement* and *Privacy – Control*, rotated 45° on the same plane. The model indicates the perceptual constructs to be measured (e.g. in post-occupancy evaluations), the attribute scales to be employed and actions to improve indoor soundscape quality, thus providing a reference for both research and practice.

Keywords

Indoor soundscape, acoustic comfort, acoustic perception, residential, Indoor Environmental Quality

1. Introduction

Building acoustic research and practice have traditionally focused on the control of airborne and structure borne sound, transmitted through or originated from building structures and building services. Particularly for dwellings, the rationale behind acoustic design has been to reduce noise levels to which building occupants are exposed in order to prevent the emergence of annoyance and other negative health outcomes. Efforts have been made to simulate and measure the sound transmission loss of building components (among others [1–4]), and to develop related metrics and single-number quantities (e.g. [5]). The effectiveness of the design action has been assessed through site measurements and occupant surveys (POE) focusing on the self-reported evaluation of noise levels and sound privacy [6], eventually integrating the identification of annoying sources. POE results have showed the general inadequacy of buildings in providing acoustic environments satisfactory to their occupants, especially in the case of residential buildings [7]. Researchers have been questioning for long time the efficacy of current metrics and measurement methods in representing people´s perception [8–12]. Associations are typically tested between objective metrics related to the magnitude of transmission loss across building structures and subjective descriptors mainly related to people´s annoyance and disturbance caused by noise. The derived picture can be in any case incomplete due to the variables under investigation. As regards the objective metrics, it must be noticed that noise level reduction does not necessarily result in less annoying or more positively perceived environments [13–15], as loudness can be even sometimes desired. Equally loud sounds can trigger very different perceptual responses depending on a multitude of factors, besides sound level (e.g. the meaning attributed to the sound source, spectral and temporal characteristics of sound stimuli, personal traits, building and urban context, socio-economic, situational and environmental factors [16]). As regards subjective descriptors, issue diagnosis and annoyance assessment might lead to neutral environments, but this might not necessarily translate into pleasantly experienced acoustic environments. Indeed, as sound has been traditionally considered as “unwanted” (i.e. noise) little has been said about “wanted” sounds or sounds of preference. This latter aspect is furtherly emphasized by the recent shift in the building industry target from designing acceptable spaces to going beyond occupants´ lack of complaints and diseases, in order to release buildings that are able to support task performance and enhance people´s health and well-being [17]. Understanding human perceptual response to the acoustic environment (i.e. the soundscape) is therefore the foundation for filling the gap between predicted and experienced acoustic performance of built environments.

The term soundscape has been defined by ISO 12913-1 standard as the “acoustic environment as perceived or experienced and/or understood by a person or people, in context” [18]. The perceptual point of view on the physical phenomenon (i.e. the acoustic environment) and the context in which perception occurs are both central to the soundscape concept. Depending on physical, psychological and sociological factors, sound can be thus wanted or unwanted, and this discrimination is based on people’s perception [19]. The meaning carried by sound is explicitly acknowledged by soundscape research [14] and exploited for the design of healthier and more enjoyable environments [19–22]. If soundscape studies have traditionally involved urban areas and outdoor spaces, indoor soundscape research has been gaining momentum in recent years to address the perceived acoustic quality of indoor environments [23–25].

Several models have been proposed, which identify perceptual dimensions underpinning the affective response to soundscapes along which to assess people’s perception and evaluate the effectiveness of design actions. Models were usually based on Semantic Differentials or Visual Analogue Scales, whereby participants were requested to rate sounds according to a number of attribute rating scales. Principal Component Analysis (PCA) or factor analysis were then applied to reduce attributes to a set of principal dimensions. Such dimensions described most of the variance in the data and were interpreted according to the attributes with whom they were most strongly associated.

The review by Ma et al. analyzed studies on the subjective assessment of indoor and outdoor sounds and derived three main dimensions related to *Evaluation*, *Potency*, and *Activity* (EPA) [26], in agreement with the classical model of affective meaning by Osgood [27,28]. However, the analysis regarded both specific sound types and complex acoustic scenes, without a distinction between indoor and outdoor contexts. When specifically referring to complex acoustic environments (i.e. not just a sound type), many of the dimensions identified in the literature [13,29–38] could be coherently explained under Russel´s circumplex model of affect [39]. According to this latter, affective responses can be understood as a linear combination of two independent dimensions, one related to valence ("a pleasure – displeasure continuum") and the other to arousal (an "alertness" continuum) [40]. When translated into soundscapes, affective responses can be represented in a two-dimensional model (cf. Figure 8 in Discussion section) where the main orthogonal dimensions are *Pleasantness* (how pleasant or unpleasant the soundscape is) and *Eventfulness* (how many sound events are present, most usually related to human activity) [38,41]. The model also included a second set of alternative orthogonal dimensions representing *Calmness* (how calm or chaotic the soundscape is) and *Excitement* (how vibrant or monotonous) [38,41], reported at a 45° rotation from the two main dimensions. Vibrant soundscapes are thus interpreted as both pleasant and eventful, chaotic soundscapes as both eventful and annoying, monotonous soundscapes as both annoying and uneventful, whereas calm soundscapes as both uneventful and pleasant [38,41]. Orthogonal to this two-dimensional model would be *Appropriateness*, a dimension expressing the extent to which a soundscape is appropriate to a space [42].

Following the model by Axelsson et al. [38], ISO/TS 12913-2 technical specification proposed the measurement of perceived affective soundscape quality through 8 five-level Likert scales: pleasant, chaotic, vibrant, uneventful, calm, annoying, eventful, and monotonous, ranging from "strongly agree" to "strongly disagree" (cf. Method A in [43]). This assessment method allows soundscapes to be plotted into a two-dimensional space on their pleasantness and eventfulness coordinates [41], with a strong, practical application in decision making processes. Indeed, as pointed out by Cain et al., the 2-D visualization of soundscapes would allow decision makers to set targets for design interventions and to assess the effectiveness of design actions in terms of perceptual outcomes [13].

It must be noticed that models of soundscape perception have been developed from listening tests in neutral laboratory settings playing outdoor sounds and it is not clear whether such models are equally valid indoor. Compared to outdoor contexts, indoor soundscapes are characterized by: 1) a combination of sounds generated by both external and internal sources, 2) the presence of a reverberant sound field in the enclosed space, 3) a greater variety of tasks performed by people (i.e. not only relaxing or walking through places), 4) the longer time spent by people immersed into them, and 5) the lower availability of control over the acoustic environment (e.g. people cannot usually move to a different place). Such peculiarities may induce to question a straightforward application of urban soundscape models to indoor built environments as some perceptual dimensions might be specific to outdoor contexts and new ones may arise when dealing with indoor environments.

Given this knowledge gap, a listening test was conducted to derive an indoor soundscape model capable of guiding soundscape assessment and design in residential buildings. The aim of the study was thus twofold: (i) to define and analyze the dimensions underlying acoustic perception in indoor residential living rooms and (ii) to discuss the potential implications of such a model for building design practice. The basic perceptual dimensions were extracted from a large set of attribute ratings scales by applying PCA. Exposure conditions were obtained by combining audio recordings related to different outdoor urban contexts with audio recordings related to different indoor sound sources. Insights on the perceptual dimension meaning were derived by investigating relationships with (psycho)acoustic parameters, demographic data and sound categories and by testing main and interaction effects of indoor-generated and outdoor-generated sounds. In the present study, a first element of novelty was represented by the simulation of typical indoor conditions in which soundscapes stem simultaneously from outdoor sounds transmitted through the building façade and sounds generated from indoor sources. Cognisant of the importance of the meaning carried by sounds for soundscape evaluation [14], by borrowing a methodology from urban soundscape studies [38], experimental design was based on the control of sound type rather than by the control of building features or physical properties of the sound field. A second element of novelty concerned the performance of listening tests in an immersive listening room furbished as a mock-up living room, thus requiring test participants a minimized process of abstraction compared to tests performed via headphones in neutral laboratory settings.

2. Methods

2.1 Participants

Thirty-five participants took part in the experiment (17 females, 18 males, mean age: 31.7 years, s: 7.2 years). They were mainly university students and researchers invited via adverts on social media and email, self-reporting no hearing impairment and good English level. Participants were offered a small monetary compensation as a token of appreciation for their time.

2.2 Factors and categories employed in the factorial design of the experiment

Two factors were controlled in the experiment: the type of outdoor urban context (Factor A) and the type of indoor sound source (Factor B). Twenty exposure conditions were obtained by the combination of five outdoor acoustic environments and four indoor sound sources, according to a within-subjects full factorial design experiment. Factors were chosen to replicate typical indoor scenarios in which outdoor sounds filtered through ventilation openings in the building façade are combined with sounds generated indoor.

It must be noticed that the purpose was not to study a space with a specific layout, building features and resulting sound field. Factors that have been already traditionally investigated in building and room acoustic research (e.g. influence of volume, transmission loss provided by building structures, background noise levels) have been purposefully excluded and the focus has been on the control of sound type instead (cf. Section 4.3).

Four urban contexts in the city of London where selected to be representative of the most commonly heard sounds in residential urban buildings [44–46]: a heavy traffic street, a light traffic street, a pedestrian area and a garden. A control condition was included, corresponding to an extremely silent outdoor context (i.e. no sound transmitted through the façade).

As regards indoor sound source location, in the present experiment, Factor B was varied across categories (or levels) representing different types of indoor sound sources located in the same room as the listener and deemed representative for a living room. The term “category” is hereinafter used in place of “level”, more common when referring to factorial design, as the latter might be misleading in the acoustic context. By assuming a residential building with a HVAC system, a condition played sound from an air inlet. Other conditions were activity-based instead. The living room is supposed to be a place dedicated to social and recreational activities, such as socializing, watching TV, listening to music, reading and playing [47]. A TV video in English language was included to represent the conditions in which speech reception is important, such as when watching TV or talking to people. A condition with instrumental music and a condition without indoor sound sources were included as well, to represent situations in which people are reading or relaxing at home. Factors and categories are summarized in Table 1. The methodology approach for the recording of sound material related to the different experimental categories is provided in Appendix A.

Table 1 – Factors and categories considered in the design of the experiment. For each category, a description of sound composition is provided together with the dominant sound category.

Factor	Categories	Sound composition	Dominant sound category
A	1 - No added sound	Laboratory background noise	-
	2 - Heavy traffic	Car traffic, bus stopping, siren, vehicle horns, construction works	Technological
	3 - Light traffic	Faint car traffic, vehicle horns, background urban sounds	Technological
	4 - Pedestrian area	Human voices, laughter, footsteps	Human
	5 - Garden	Bird twittering, background urban sounds	Natural
B	1 - Fan noise	Ventilation noise	Technological
	2 - Music	Instrumental music	Music
	3 - TV	Scientific documentary in English language	TV
	4 - No added sound	Laboratory background noise	-

2.3 Experimental set up and exposure conditions

The experiment was conducted at the UCL IEDE Acoustics Lab in London. In order to minimize the process of abstraction required by test participants compared to neutral laboratory conditions, some pieces of furniture were placed inside the facility: an armchair, a lounge table, a plant, and a television. A curtain was hung at 0.95 m from the front wall to integrate a 55” display projecting a window view and to hide the loudspeakers located behind.

A schematic representation of the laboratory setup is provided in Figure 1. The room was box-shaped, with dimensions of 3.49 m (width), 3.35 m (length), 3.16 m (height), considering the available floor area in the mock-up condition. A comfortable armchair on which the listener was seated was positioned at 1 m from the curtain and 1 m from the side wall. The reverberation time ($T_{30,500Hz\text{-}2kHz}$) measured in the test conditions with the interrupted noise method (6 microphone-source combinations, 2 source positions, 3 decays in each position) was 0.13 s [48].

One-minute audio excerpts were reproduced to match the A-weighted equivalent continuous sound pressure level ($L_{Aeq,1min}$) at the listener's head to the one measured *in situ* (see Appendix A), for the exact excerpt. The five Genelec 8331 SAM™ three-way coaxial loudspeakers employed for the stimuli playback are indicated in Figure 1. Details on the laboratory set up, exposure duration and employed reproduction system as regards ecological validity are provided in Appendix B.

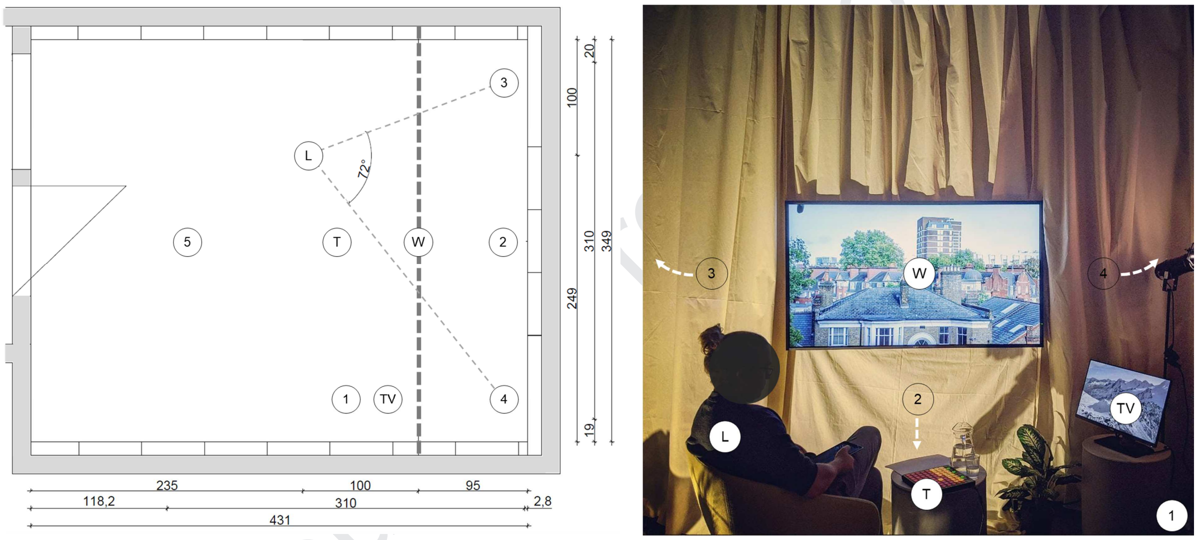

Figure 1 – Plan (to the left) and picture (to the right) of the test facility. Loudspeaker positions are depicted by numbers. Different loudspeakers were employed for signal playback: (1) for "music" and "TV", (2) for "pedestrian area", (3) and (4) for "heavy traffic", "light traffic" and "garden", (5) for "fan noise". Loudspeakers (2), (3), and (4) were hidden behind the curtain. L, T, W and TV indicate respectively the listener, lounge-table, display and TV positions

For the purpose of model derivation, it was fundamental to characterize the acoustic stimuli to which the participants were exposed during the listening tests. Binaural recordings of the 20 acoustic exposure conditions were performed at the listener positions. ArtemiS $_{SUITE}$ v.10 software was used to calculate a set of acoustic and psychoacoustic indicators, related to:

- overall loudness: A-weighted equivalent continuous sound pressure level ($L_{Aeq,1min}$) and the loudness exceeded 10% of the time (N_{10}) calculated according to [49];

- temporal variability: difference between 10% and 90% statistical levels, expressed in terms of A-weighted equivalent continuous sound pressure level (L_{A10}-L_{A90}) and loudness (N_{10}-N_{90}); Fluctuation Strength (FS) and Roughness (R);
- spectral content of sound: difference between C and A-weighted sound pressure level ($L_{Ceq,1min}$-$L_{Aeq,1min}$, hereinafter L_C-L_A), and Sharpness (S).

Single values for sound levels were calculated as the energetic average of left and right ear values, whereas the single values for psychoacoustic parameters were calculated as the arithmetic average between left and right metrics. The acoustic characterization of factors and experimental categories adopted in the full factorial design is provided in Table 2. Spectra are showed in Figure 2. Laboratory background noise conditions were reported for control conditions wherein no sound stimuli have been added. For reference purposes, 35 dB can be considered a typical required background noise level limit for living rooms ($L_{Aeq,16hr}$ [50], for a review cf. [24]).

Table 2 – Acoustic characterization of the one-minute audio excerpts combined to compose the exposure conditions

Factor	**Category**	**$L_{Aeq,1min}$ (dB)**	**N_{10} (sone)**	**L_{A10}-L_{A90} (dB)**	**N_{10}-N_{90} (sone)**	**FS (vacil)**	**R (asper)**	**L_C-L_A (dB)**	**S (acum)**
A	1 - No added sound	25.8	0.8	15.7	0.1	0.005	0.008	46.9	1.55
	2 - Heavy traffic	67.6	21.6	73.6	12.4	0.043	0.039	63.9	1.74
	3 - Light traffic	44.0	4.1	41.7	0.8	0.007	0.021	52.0	1.14
	4 - Pedestrian area	32.9	1.9	32.7	0.6	0.009	0.013	47.9	1.41
	5 - Garden	37.0	2.8	36.0	0.7	0.005	0.016	50.1	1.35
B	1 - Fan noise	31.0	1.4	23.5	0.2	0.004	0.011	45.5	1.47
	2 - Music	43.6	5.4	46.4	3.3	0.036	0.023	52.5	1.70
	3 - TV	46.3	5.0	50.7	4.1	0.088	0.019	50.6	1.63
	4 - No added sound	25.8	0.8	15.7	0.1	0.005	0.008	46.9	1.55

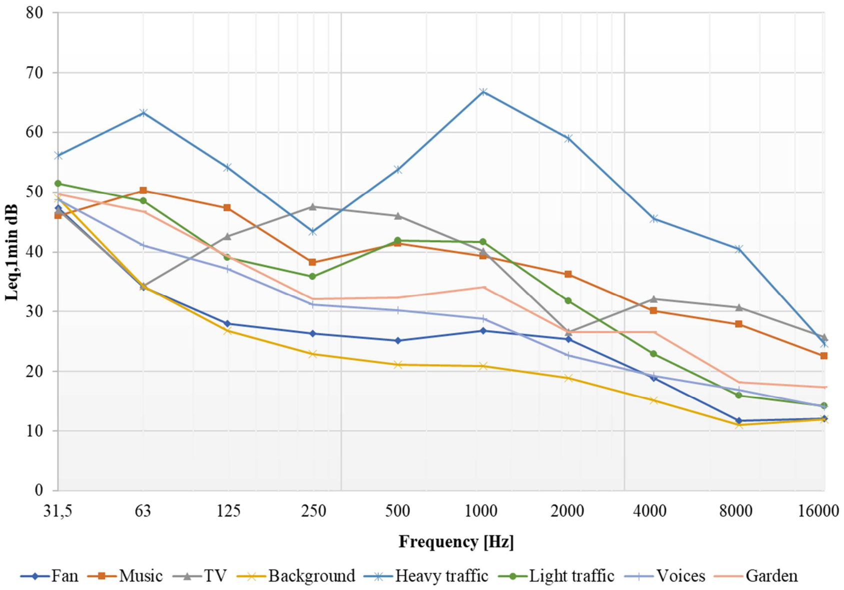

Figure 2 – Spectra of the one-minute audio excerpts combined to compose the exposure conditions

The "objective" psychoacoustic and acoustic data derived from measurements have been thus related to the "subjective" evaluations provided by participants.

2.4 Attribute rating scales

Subjective assessment was performed through a set of 97 unidirectional attribute scales aimed at describing the affective response to indoor soundscapes. Attributes from Axelsson et al. [38] were integrated with items coming from focus group and previous literature in order to specifically address the peculiarities of indoor perception. The process of attribute selection is detailed in Appendix C.

Each attribute was rated by means of visual analog scales of "attribute – soundscape match", following the approach by Axelsson et al. [38]. Scales were implemented in REDCap survey app as bar sliders supplied with labels at the end points (i.e. "No match at all", "Perfect match"). A rating viewer allowed participants to visualize the numeric evaluation from 0 to 100 while sliding the bar, "representing how well the attribute matched their soundscape perception" [38].

2.5 Test procedures

The experiment was carried out between November and December 2019. Upon arriving, participants were asked to sign the informed consent. A training session was firstly proposed in order to familiarize the testers with the mock-up living room, the test procedure and the attribute meaning. Participants singularly experienced all the 20 acoustic scenarios presented in random order over consecutive sessions. Instructions were provided during the training session both orally and via the survey app to “direct the subjects’ response strategy towards an everyday situation in order to enable the reactivation of cognitive processes elaborated in actual situations” [51]:

“Imagine being at home, relaxing in your living room. You may listen to sounds coming from the outside, through a window ajar, and to sounds generated in the room where you are in now.

Please judge to what extent the attributes listed in the following are applicable to the acoustic environment you are experiencing. Please indicate your judgment by putting a mark on the scale delimited by: ´No match at all (0)´ and ´Perfect match (100)´”(adapted from [38]).

After a one-minute exposure, participants were asked via a message appearing on the TV display (“P*lease start the questionnaire*”) to scale the soundscape they were immersed in on the touchscreen handset. During the soundscape assessment, participants were exposed to one-minute repetitions of the sound stimuli previously experienced. After scaling the 97 attributes, subjects were instructed to launch the subsequent session through a message provided in the survey app (e.g. “*Please, press button 1”*). Attribute order was randomized across the different sessions. To limit subject fatigue, every 5 sessions a break was scheduled and proposed via the survey app. Overall, the experiment lasted approximately 2.5 hours. The study was approved via the UCL IEDE Ethics departmental procedure on 16 September 2019.

2.6 Data analysis

All statistical analyses were performed using the software R [52]. A preliminary outlier analysis identified three participants that provided more than 97 outlying ratings over the 20 conditions, defined according to the 1.5 x IQR (Interquartile Range) rule. A data check revealed incongruence in their answers, leading to their exclusion. Therefore, the presented results referred to a final data set on m = 32 participants.

Based on the arithmetic means of the ratings provided by the 32 participants, PCA was performed to reduce the 97 attributes to a number of principal components (PCs) explaining most of the data variation.

As PC´s interpretation was rather straightforward (cf. Section 3.1), no rotation was applied in order to avoid component adjustments that would result in a variance redistribution among the rotated components and other rotation drawbacks (cf. Appendix D).

A repeated measures correlation analysis was run to assess the relationships between the extracted perceptual dimensions (i.e. the scores of the responses given by each participant for each exposure condition along the extracted PCs) and the (psycho)acoustical parameters characterizing each exposure condition.

Linear mixed-effects models (LMM) were computed in order to predict the effect of sound categories, demographic features (i.e. gender and age) and (psycho)acoustic parameters on the extracted perceptual dimensions. Sound categories were defined as dichotomous variables that represented sound types dominating each acoustic scenario, as indicated in Table 1. Sounds were categorized as Technological (i.e. fan noise, light traffic, heavy traffic), Human (i.e. sounds from the pedestrian area), Natural (sounds from the garden), Music and TV sounds. The first three categories have been traditionally used in urban soundscape studies (i.e. Technological, Human, Natural sounds [38]), while the last two were deemed relevant for the tested indoor conditions (i.e. Music and TV).

Two-way repeated measures ANOVAs were performed to evaluate how the extracted PCs were affected by the five types of outdoor acoustic environment (Factor A) and the four types of indoor-generated sounds (Factor B), in the tested acoustic conditions. Further details on statistical methods are provided in Appendix D.

3. Results

3.1 Principal component analysis

The first three PCs explained respectively 58%, 25% and 7% of the total variance. In addition, three further components met the Kaiser´s criterion (eigenvalue > 1 [53]), explaining together an additional 7% of the variance. The interpretability of components and the visual inspection of the scree plot [54] suggested retaining the first three PCs, that accounted for 90% of the total variance.

Figure 3 shows the PC1-PC2 plot, whose data points give the components of the (p = 97) attributes (i.e. the vectors of the original basis) along the first and second PCs. Similarly, Figure 4 shows the PC3 – PC2 plot. The graphical representation is made to allow for a direct comparison with results from Axelsson et al [38]. Three areas are indicated according to the distance between the attributes and the origin (v_a): Zone 1, $v_a^2 < 0.50$; Zone 2, $0.50 \leq v_a^2 < 0.70$; Zone 3, $v_a^2 \geq 0.70$, where v_a^2 represents the amount of variance in the attribute explained by the two PCs forming the plot [38]. Therefore, attributes closer to the center are not perfectly represented by the plotted PCs.

The interpretation of the PCs relied on the identification of the variables that were most correlated in either a positive or negative direction [38,39]. The full component matrix, reporting how the retained components loaded on each variable, is provided in Appendix E. The first component (PC1) was best explained by “comfortable”, “relaxed”, and “agreeable, pleasant”, (sorted in descending order of loading value) on the positive side and by “inconvenient”, “annoying, baiting, irritating, troublesome, upsetting”, and “disagreeable, disharmonious, unpleasant” on the negative side (cf. Figure 3). PC1 was thus labelled *Comfort*. The second component (PC2) was best explained by “lively, full of content, full of life”, “living”, and “energetic” on the positive side and by “dead, lethargic, lifeless”, “empty”, and “without contrast” on the negative side (cf. Figure 3 and Figure 4). PC2 was therefore labelled *Content*. The third component (PC3) was best explained by “common”, “commonplace”, and “unsophisticated” on the positive side and by “sophisticated”, “impressive” and “unreal” on the negative side (cf. Figure 4). PC3 was hence labelled *Familiarity*.

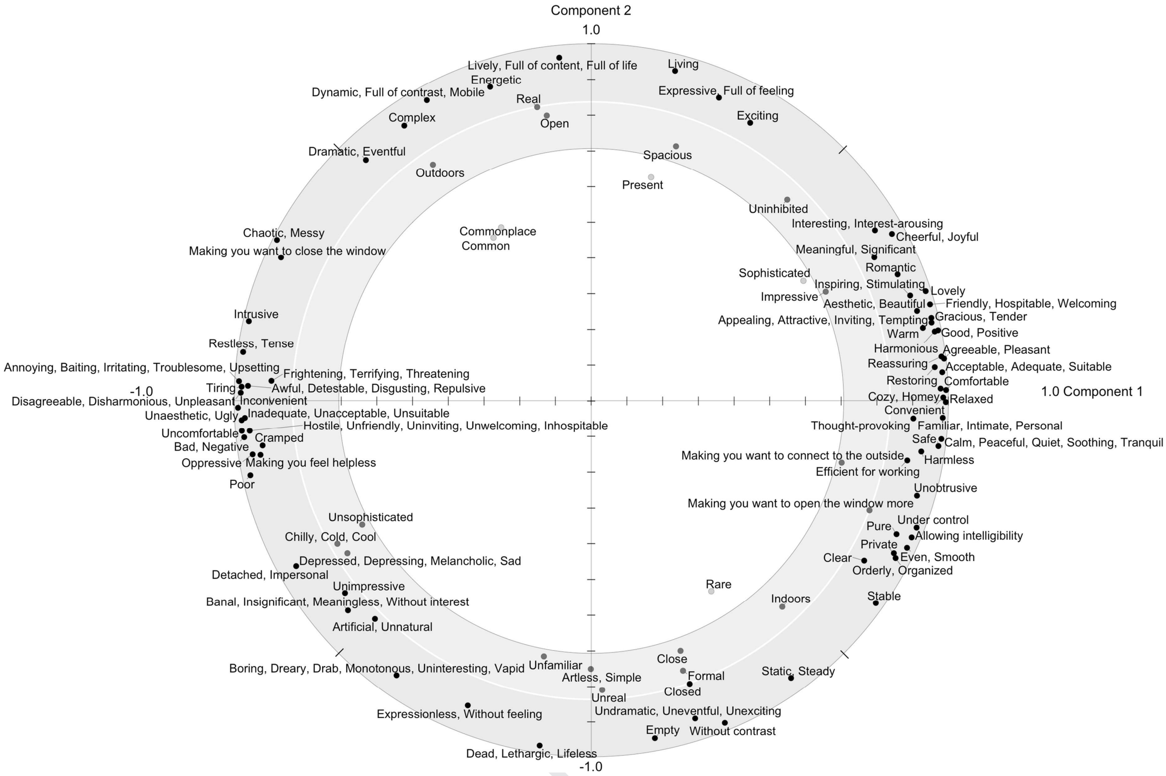

Figure 3 – PC1 – PC2 plot. Three areas are depicted in the figure according to the length of the vectors of the 97 attributes from the origin (v_a, distance from the center of the plot): Zone 1, $v_a^2 < 0.50$ (light grey circles); Zone 2, $0.50 \leq v_a^2 < 0.70$ (dark grey circles); Zone 3, $v_a^2 \geq 0.70$ (black circles), where v_a^2 represents the amount of variance in the attribute explained by PC1 and PC2.

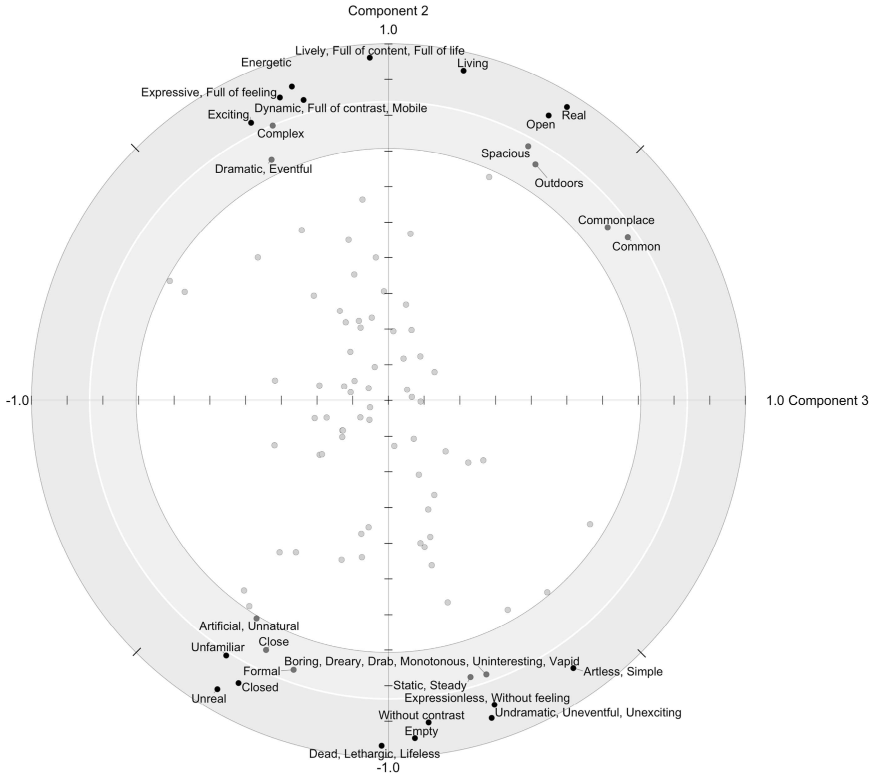

Figure 4 – PC3 – PC2 plot. Three areas are depicted in the figure according to the length of the vectors of the 97 attributes from the origin (v_a, distance from the center of the plot): Zone 1, $v_a^2 < 0.50$ (light grey circles); Zone 2, $0.50 \leq v_a^2 < 0.70$ (dark grey circles); Zone 3, $v_a^2 \geq 0.70$ (black circles), where v_a^2 represents the amount of variance in the attribute explained by PC2 and PC3.

To verify whether the PCA results (i.e. the extracted factors and their composition) were the same across two independent samples of subjects, the original sample of subjects was divided in two halves and each of the two halves has been subjected to PCA. Component loadings were extracted from both data sets and intercorrelated (cf. [38]). Spearman's rank correlation coefficients between the component loadings of these two new solutions were 0.98, 0.97, and 0.89 and for PC1, PC2, and PC3 respectively ($p < 0.001$), thus showing that the three-PCs model was reliable across the two subgroups of individuals.

3.2 Relationships between principal components, acoustic indicators and sound-categories

Repeated measures correlation coefficients r_{rm} are presented in Table 3. The *Comfort* scores were negatively correlated with all the considered acoustic and psychoacoustic parameters. The correlation was moderate with $L_{Aeq,1min}$, N_{10}, L_{A10}-L_{A90}, N_{10}-N_{90}, R, L_C-L_A, and weak with FS and S. Notably, *Comfort* was more strongly associated with the loudness parameter N_{10}. The *Content* scores were positively correlated with all the computed acoustic and psychoacoustic parameters. Correlation coefficients indicated a moderate correlation with $L_{Aeq,1min}$, N_{10}, L_{A10}-L_{A90}, N_{10}-N_{90}, R, L_C-L_A, and a weak correlation with FS and S. In particular, *Content* was more strongly associated with level variability over time (L_{A10}-L_{A90}). The *Familiarity* scores were negatively correlated with all the computed acoustic and psychoacoustic parameters. The correlation was generally weak ($L_{Aeq,1min}$, N_{10}, L_{A10}-L_{A90}, N_{10}-N_{90}, R, L_C-L_A), and moderate with FS and S. Specifically, *Familiarity* scores exhibited a stronger association with sharpness S.

Table 3 – Repeated measures correlation coefficients r_{rm} between PC scores and acoustic parameters. In bold are the strongest correlations. df: 607. All p-values ≤ 0.001.

	PC1 ***Comfort***	**PC2** ***Content***	**PC3** ***Familiarity***
$L_{Aeq,1min}$	-0.54	0.38	-0.15
N_{10}	**-0.61**	0.33	-0.19
L_{A10}-L_{A90}	-0.49	**0.44**	-0.16
N_{10}-N_{90}	-0.58	0.32	-0.25
FS	-0.18	0.14	-0.34
R	-0.56	0.38	-0.14
L_C-L_A	-0.55	0.40	-0.17
S	-0.22	0.24	**-0.51**

LMMs with a single acoustic parameter were developed for all the chosen (psycho)acoustic parameters and then compared based on the AIC parameter (the smaller, the better the fit). Table 4 describes the selected models, reporting the AIC values, the marginal coefficient of determination R_m^2, the conditional coefficient of determination R_c^2, and the estimates of regression coefficients. *Comfort* was best explained by loudness N_{10}, confirming the negative trend observed in the correlation analysis (cf. Table 3). Louder stimuli (i.e. heavy traffic in the tested conditions) resulted in less comfortable indoor soundscapes. *Content* was best predicted by level variability over time L_{A10}-L_{A90}, with a positive trend. Soundscapes exhibiting larger temporal variability (i.e. heavy traffic, TV and music in the tested conditions) resulted richer in *Content*. *Familiarity* was best explained by sharpness S, with sharper soundscapes (i.e. heavy traffic, music and TV) resulting less familiar.

In the presented models, participants have been considered as random-effects terms. Model comparison based on likelihood ratio test showed the suitability of random-intercept and random-slope models, thus taking into account that the effects of loudness, level variability and sharpness respectively on *Comfort, Content,* and *Familiarity* scores were different for each participant and that each participant responded differently at varying levels of N_{10}, L_{A10}-L_{A90} and S.

Sound categories and demographic data (i.e. gender, age) were added to the previous models with a stepwise procedure aimed at identifying significant predictors. For the sake of simplicity, interaction terms were not included in the final models.

Natural, technological sounds and music added significant contribution to *Comfort* prediction (cf. Table 4). At equal loudness values, the presence of natural sounds and music were found to increase *Comfort* scores, whereas technological sounds caused a *Comforts* reduction. Human and TV sounds, participant´s age and gender didn´t contribute significantly to *Comfort* explanation. By including sound category variables, the proportion of the total variance explained by the fixed effects (R_m^2) increased from 35% to 52%.

Regarding the *Content* model, natural, human, TV sounds and music were added as significant predictors. Supposing equal L_{A10}-L_{A90} values, *Content* was found to increase in presence of natural, human sounds and music and to decrease in presence of TV sounds (cf. Table 4). Technological sounds, participant´s age and gender didn´t contribute significantly to *Content*. The inclusion of significant sound category variables increased the proportion of the total variance explained by the fixed effects (R_m^2) from 18% to 43%.

Natural, human, technological and TV sounds added significant contribution to *Familiarity* prediction (cf. Table 4). In particular, at equal sharpness values, natural, human and technological sounds were found to reduce *Familiarity*, while TV sounds to increase *Familiarity* perception. Music, participant´s age and gender were not retained as significant *Familiarity* predictors. By including sound category variables, the proportion of the total variance explained by the fixed effects (R_m^2) increased from 14% to 17%. It should be noticed that sound categories and acoustic parameters could explain only a reduced amount of variance in *Familiarity* scores, that increased substantially when accounting for the variability of responses related to individualities (from 60 to 64%).

The interpretation of the presented regression models is sometimes not straightforward. For instance, TV sounds contributed negatively to *Content* scores based on their sound category but positively due to their high temporal variability (L_{A10}-L_{A90}) in the tested conditions. Differently, loud heavy traffic sounds contributed to *Content* through their high L_{A10}-L_{A90} values, even without a significant contribution through their sound category. Regression models allow to control for the effect of acoustic parameters, so that the effect of a sound category can be evaluated while holding all the other variables constant. However, acoustic features are sometimes inherently embedded in a sound category, so that it´s not always possible to differentiate meaningfully the effect of sound type from the effect of the acoustic parameter.

The combined effects of different sound types and their acoustic features were tested in ANOVA analysis, as described in the following paragraph.

Table 4 – LMMs of PC1, PC2, and PC3 scores. For each perceptual dimension, two models are presented: one with a single acoustic parameter and one with both acoustic parameters and sound categories as predictors. For each model, the Akaike Information Criterion (AIC) value, the marginal coefficient of determination R_m^2, the conditional coefficient of determination R_c^2 and the estimates of regression coefficients are reported.

Model	**AIC**	**R^2_m**	**R^2_c**	**Fixed-effect terms**	**Estimates**	**t-value**
Comfort	4449.0	0.35	0.40	Intercept	6.08	11.59
				N_{10}	-0.80	-14.52
	4231.1	0.52	0.59	Intercept	4.14	6.63
				N_{10}	-0.65	-11.16
				Natural	6.86	10.62
				Technological	-3.16	-5.49
				Music	4.55	7.77
Content	4117.5	0.18	0.25	Intercept	-8.41	-8.93
				L_{A10}-L_{A90}	0.18	8.23
	3857.6	0.43	0.53	Intercept	-14.22	-14.24
				L_{A10}-L_{A90}	0.25	11.18
				Natural	7.27	15.06
				Human	6.08	12.43
				Music	1.08	2.31
				TV	-2.62	-5.41
Familiarity	3581.6	0.14	0.60	Intercept	17.61	9.50
				S	-11.40	-11.71

	3527.5	0.17	0.64	Intercept	15.89	8.46
				S	-9.84	-9.85
				Natural	-0.65	-3.34
				Human	-0.97	-5.02
				TV	0.32	2.00
				Technological	-1.15	-7.07

3.3 Effect of outdoor and indoor sound type on principal components

Differently from previous LMMs, two-way repeated measures ANOVAs didn´t control for the effects of acoustic parameters as covariates (e.g. sound level or loudness) as it was intended to test the global effects of different sound stimuli in their sound composition and realistic acoustic features. Indeed, when testing for the effect of natural sounds from a garden against traffic noise from a busy street we were considering the global effect of different sound types, together with their different levels, temporal and spectral features that were representative for those sound categories [55,56]. In addition, technological sounds were here differentiated according to the different experimental categories (i.e. fan noise, heavy traffic and light traffic).

As far as *Comfort* scores is concerned, a statistically significant interaction was found between outdoor context and indoor sounds, thus indicating that the impact of one factor depended on the category of the other factor (cf. Table 5).

Table 5 – Summary of main and interaction effects of the type of outdoor acoustic environment (Factor A) and the type of indoor-generated sounds (Factor B) on PC1, PC2, and PC3 scores from repeated measures ANOVAs. The table presents the mean value of component scores, the degrees of freedom in the numerator DFn, the degrees of freedom in the denominator DFd, the test statistic F, the p-values and the generalized eta squared values η_G^2

PC	**Effect**	**Category**	**Mean**	**DFn**	**DFd**	**F**	**p**	**η_G^2**
Comfort	Factor A	No sound	2.80	2.58	79.97	100.71	$p < 0.001$	0.53
		Heavy traffic	-12.11					
		Light traffic	-0.85					
		Pedestrian area	1.56					
		Garden	8.57					
	Factor B	Fan	-1.94	2.33	72.33	14.73	$p < 0.001$	0.08
		Music	3.04					
		TV	-1.41					
		No sound	0.28					
	Interaction			6.83	211.58	8.98	$p < 0.001$	0.08
Content	Factor A	No sound	-7.00	3.13	97.10	61.37	$p < 0.001$	0.41
		Heavy traffic	3.45					
		Light traffic	-1.57					
		Pedestrian area	1.74					
		Garden	3.38					
	Factor B	Fan	-1.36	2.02	62.70	18.31	$p < 0.001$	0.10
		Music	2.67					
		TV	-0.19					
		No sound	-1.11					
	Interaction			6.01	186.22	19.53	$p < 0.001$	0.17
Familiarity	Factor A	No sound	-2.15	4.00	124.00	24.84	$p < 0.001$	0.09
		Heavy traffic	-1.32					
		Light traffic	2.50					
		Pedestrian area	0.61					
		Garden	0.42					
	Factor B	Fan	2.17	2.15	66.78	33.19	$p < 0.001$	0.09
		Music	-1.81					
		TV	-1.24					
		No sound	0.93					
	Interaction			7.04	218.17	7.63	$p < 0.001$	0.04

Table 6 – Summary of simple main effects of one factor (indicated in the first column) for each category of the second factor (indicated in the second column) on PC1, PC2, and PC3 scores from repeated measures ANOVAs. The table presents the degrees of freedom in the numerator DFn, the degrees of freedom in the denominator DFd, the test statistic F, the p-values and the generalized eta squared values η_G^2

	Effect	**Category**	**DFn**	**DFd**	**F**	**p**	η_G^2
Comfort	Factor A	Fan	2.9	89.80	61.00	$p < 0.001$	0.54
		Music	3.07	95.20	55.10	$p < 0.001$	0.56
		TV	3.16	97.80	66.10	$p < 0.001$	0.56
		No sound	2.74	84.90	49.80	$p < 0.001$	0.54
	Factor B	No sound	3.00	93.00	20.30	$p < 0.001$	0.35
		Heavy traffic	3.00	93.00	2.10	$p = 0.53$	0.01
		Light traffic	2.46	76.10	7.73	$p = 0.002$	0.11
		Pedestrian area	2.17	67.30	11.60	$p < 0.001$	0.12
		Garden	2.25	69.90	3.40	$p = 0.17$	0.06
Content	Factor A	Fan	4.00	124.00	56.80	$p < 0.001$	0.59
		Music	4.00	124.00	2.18	$p = 0.30$	0.04
		TV	3.12	96.80	37.30	$p < 0.001$	0.37
		No sound	2.61	81.00	60.00	$p < 0.001$	0.61
	Factor B	No sound	2.01	62.40	39.40	$p < 0.001$	0.48
		Heavy traffic	3.00	93.00	0.44	$p = 1.00$	0.00
		Light traffic	2.27	70.50	12.30	$p < 0.001$	0.18
		Pedestrian area	3.00	93.00	2.25	$p = 0.44$	0.03
		Garden	2.23	69.10	2.03	$p = 0.66$	0.03
Familiarity	Factor A	Fan	4.00	124.00	8.96	$p < 0.001$	0.08
		Music	3.11	96.50	6.90	$p < 0.001$	0.06
		TV	4.00	124.00	5.70	$p = 0.001$	0.05
		No sound	2.44	75.70	26.40	$p < 0.001$	0.25
	Factor B	No sound	2.40	74.30	13.40	$p < 0.001$	0.17
		Heavy traffic	2.05	63.40	7.57	$p = 0.005$	0.04
		Light traffic	2.47	76.60	26.00	$p < 0.001$	0.19
		Pedestrian area	3.00	93.00	21.30	$p < 0.001$	0.10
		Garden	3.00	93.00	12.20	$p < 0.001$	0.10

Simple main effects of indoor-generated sounds were analyzed at each type of outdoor sound (cf. Table 6). Pairwise comparisons between the control condition (i.e. without indoor sound sources) and other indoor sound stimuli are indicated in Figure 5a. In case of no sound transmitted from the window, compared to the case without internal sources, *Comfort* scores were higher with music, lower with fan noise, and not significantly different with TV sounds. It should be noticed that in the completely silent condition (i.e. no sound neither from outside nor from inside) subjective responses exhibited a high variability (Figure5a). In presence of heavy traffic or natural sounds (i.e. the garden condition), the effect of indoor sound type was not significant (cf.). With light traffic, *Comfort* scores were not significantly different from the control condition depending on indoor sound type. In presence of human sounds from the outside (i.e. the pedestrian area), compared to the control condition, music significantly improved *Comfort* scores, while other indoor sources didn´t result in significant differences.

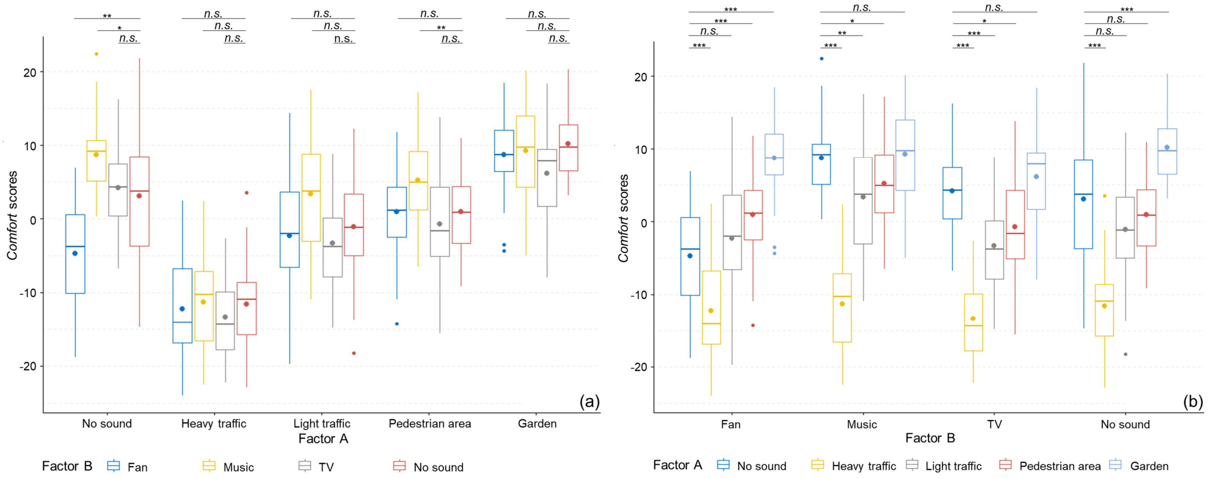

Figure 5 – Boxplots of *Comfort* scores by type of outdoor sounds (Factor A) and by type of indoor sounds (Factor B). On the left (a), data are grouped by Factor A and pairwise comparisons are shown between the control condition with no indoor sound source and other indoor sound types. On the right (b), data are grouped by Factor B and pairwise comparisons are shown between the control condition with no sound from the outside and other outdoor sound types. Inside the boxes, the central line is the median value, and the point is the mean value. *n.s.*: not significant, * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

Simple main effects of outdoor context were significant at each type of indoor sound (cf. Table 6). Pairwise comparisons between the control condition (i.e. without sounds from the outside) and other outdoor conditions are indicated in Figure5b. Compared to the control condition, *Comfort* was strongly and negatively affected by heavy traffic in combination with all indoor sound sources. In presence of fan noise, *Comfort* was not significantly different from the control condition with light traffic and improved with human voices and natural sounds. Similarly, in the condition with no internal source, compared to the control condition, light traffic and human voices resulted in non-significantly different *Comfort* scores, while natural sounds improved indoor soundscape. With music or TV, *Comfort* was significantly higher with no sound from outside or with natural sounds, with no significant difference between the two conditions, and significantly lower with light traffic and human voices, compared to the control condition. Notably, light traffic and human voices had a stronger detrimental effect on *Comfort* while watching TV

($\text{median}_{\text{Light\_traffic}}$: -3.83; $\text{median}_{\text{Pedestrian\_area}}$: -1.71), than while listening to music ($\text{median}_{\text{Light\_traffic}}$: 3.71; $\text{median}_{\text{Pedestrian\_area}}$: 4.91), $p < 0.001$.

When looking at effect size statistics (cf. Table 5 and 6), the magnitude of the effect that outdoor sounds had on *Comfort* scores was larger compared to that of indoor sounds or their interaction. Effect size was larger for indoor sounds only when not masked by outdoor sounds (i.e. in the control condition).

Regarding *Content* scores, a statistically significant interaction was found between outdoor context and indoor sound type (cf. Table 5).

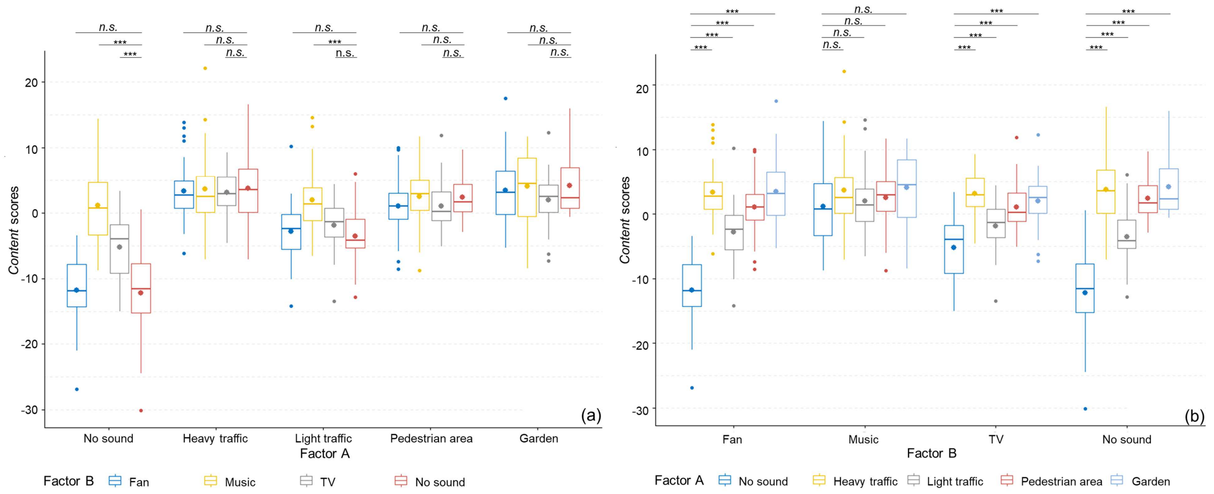

Figure 6 – Boxplots of *Content* scores by type of outdoor sounds (Factor A) and by type of indoor sounds (Factor B). On the left (a), data are grouped by Factor A and pairwise comparisons are shown between the control condition with no indoor sound source and other indoor sound types. On the right (b), data are grouped by Factor B and pairwise comparisons are shown between the control condition with no sound from outside and other outdoor sound types. Inside the boxes, the central line is the median value, and the point is the mean value. *n.s.*: not significant, * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

Figure 6a shows pairwise comparisons between the control condition (i.e. without indoor sound sources) and other indoor sound stimuli. Simple main effects of indoor sound type were not significant when combined with heavy traffic, pedestrian area and garden conditions (cf. Table 6). In the condition with no sound from the outside, compared to the control condition, *Content* scores were higher with TV and music and not significantly different with fan noise. In case of light traffic, compared to the control condition, fan noise and TV sounds provided non-significantly different *Content* scores, while music resulted in higher *Content* scores.

Simple main effects of outdoor context were not significant with music (cf. Table 6). Pairwise comparisons between the control condition (i.e. without sound from the outside) and other outdoor conditions are indicated in Figure 6b. With fan noise, TV and no indoor source, *Content* scores were significantly lower in the control condition than with heavy traffic, light traffic, human or natural sounds. Notably, heavy traffic resulted in higher *Content* scores compared to light traffic (p < 0.001) and not significantly different compared to pedestrian area and garden conditions.

The magnitude of the impact outdoor sound had on *Content* scores was larger compared to that of indoor sounds or their interaction, except when indoor soundscape was already saturated with music (cf. Table 5 and 6). Effect size for indoor sounds assumed larger values in the control condition, in absence of outdoor sounds.

Regarding *Familiarity* scores, a statistically significant interaction was found between outdoor context and indoor sound type (cf. Table 5).

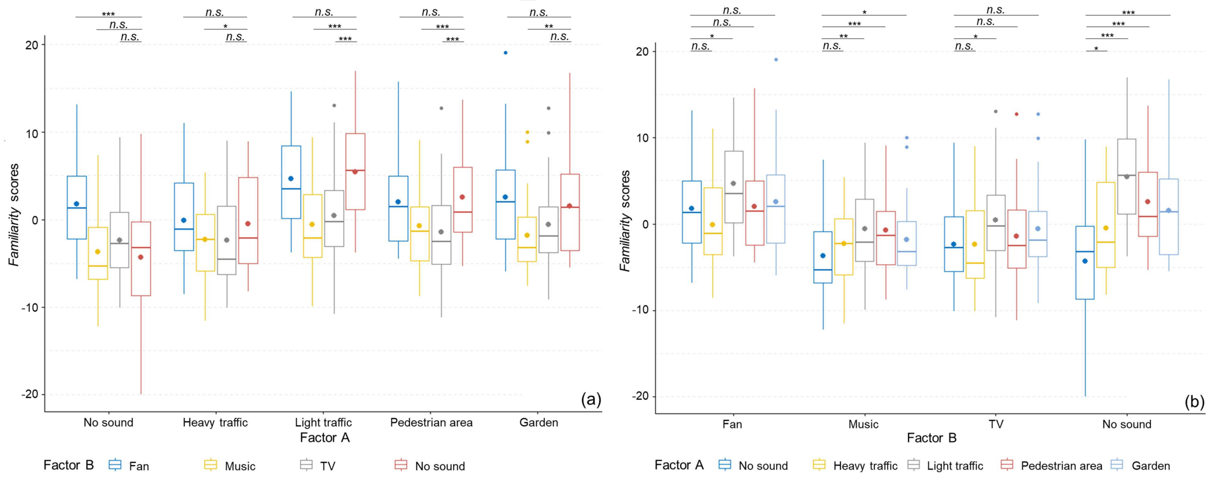

Figure 7 – Boxplots of *Familiarity* scores by type of outdoor sounds (Factor A) and by type of indoor sounds (Factor B). On the left (a), data are grouped by Factor A and pairwise comparisons are shown between the control condition with no indoor sound source and other indoor sound types. On the right (b), data are grouped by Factor B and pairwise comparisons are shown between the control condition with no sound from outside and other outdoor sound types. Inside the boxes, the central line is the median value, and the point is the mean value. *n.s.*: not significant, * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

Simple main effects of indoor sound type on *Familiarity* were significant at each type of outdoor context (cf. Table 6). Pairwise comparisons between the control condition with no indoor sources and other indoor sound stimuli are presented in Figure 7a. In the silent condition without played indoor and outdoor sounds, *Familiarity* scores exhibited a high variability in subjective scores. Compared to the control condition, *Familiarity* was not significantly different with music or TV, and higher with fan noise. When combined with natural sounds or heavy traffic, music was significantly less familiar, while other indoor sources exhibited no significant differences compared to the control condition. In presence of light traffic or human sounds from the pedestrian area, compared to the control condition, *Familiarity* scores were lower with music or TV sounds and not significantly different with fan noise.

Simple main effects of outdoor type on *Familiarity* were significant at each type of indoor sound (cf. Table 6). Figure 7b shows the pairwise comparisons between the control condition with no sound from the outside and other outdoor conditions. Interestingly, compared to the control condition, *Familiarity* scores were significantly higher with light traffic, regardless indoor sound type. In case of no internal source, the control condition was significantly less familiar compared to conditions with other outdoor stimuli. Notably, light traffic was more familiar than heavy traffic ($p < 0.001$), pedestrian sounds ($p = 0.005$), and natural sounds ($p < 0.001$). With fan noise or TV sounds, conditions other than light traffic were not differently familiar from the control condition. When combined with music, compared to the control condition, indoor soundscapes were significantly more familiar with light traffic, human and natural sounds, and not significantly different with heavy traffic.

Effect sizes were generally low for *Familiarity* scores (cf. Table 5 and 6). The impact of outdoor sounds was higher when combined with no indoor source, while the impact of indoor sounds was higher in case of no outdoor sounds or light traffic.

4. Discussion

PCA results showed that the affective response to indoor soundscapes can be described by three main components: *Comfort*, *Content*, and *Familiarity*. Insights on component meaning can be drawn from the association between component scores, attribute loadings, (psycho)acoustic measures and sound categories. The analysis of the three perceptual dimensions is followed by a discussion on the model applicability in building design and on study limitations.

4.1 Dimensions of acoustic perception in indoor residential living rooms

4.1.1 *Comfort* and *Content*

Taken together, *Comfort* and *Content* explained 83% of total variance of the attribute ratings. The main component, *Comfort*, ranked soundscapes according to a "comfortable – annoying" continuum and was found to explain 58% of the variance in indoor soundscape evaluation. This component aligned with previous research on visual atmosphere [57], emotions [39], environmental psychology and urban soundscapes [36–38] (cf. Figure 8) that identified *Coziness*, *Valence* or *Pleasantness* as a fundamental dimension underlying affective responses. Looking at the attributes that loaded positively on this first dimension, aspects underpinning (acoustic) comfort in residential buildings can be derived, such as relax, pleasantness, intimacy, coziness, but also tranquility, safety, restoration and suitability (cf. Figure 3). Interestingly, safety appeared as one of the aspects contributing to *Comfort*. According to Andriga and Lanser, safety would be the key factor of pleasant soundscapes as it enables the freedom of mind-states for mental restoration and proactive behavior, without forcing people to attend and address the "here and now" [58]. Safety would be particularly relevant in indoor residential contexts, in keeping with the concept of ontological security that is sought at home as opposed to a world that is threatening and out of control [59,60]. In the present study, appropriateness (expressed by the attribute "acceptable, adequate, suitable") was another aspect highly correlated with *Comfort*. While Axelsson proposed *Appropriateness* as a dimension independent from *Pleasantness* and *Eventfulness* [42], our results agree with previous studies that reported *Appropriateness* and *Pleasantness* (or *Comfort*) to be overlapping dimensions [31]. Furthermore, in the present study the concepts of calmness and tranquility emerged on a shared dimension with *Comfort*, as aspects almost unrelated to *Content* (cf. Figure 3). Previous urban soundscape research generally indicated *Calmness* as a diagonal dimension in the *Pleasantness* – *Eventfulness* space [13,33] (see Figure 8), whilst other studies recently reported *Calmness* and *Pleasantness* to be overlapping [30,31].

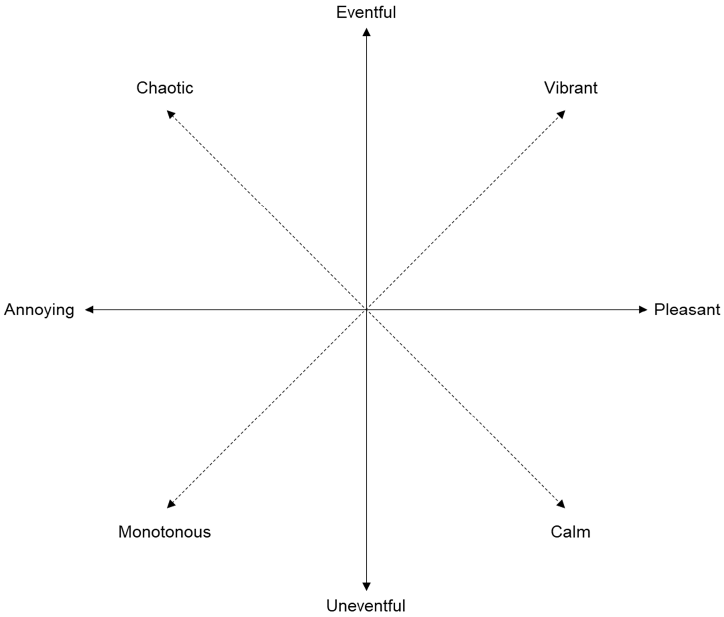

Figure 8 – Model of affective response to outdoor soundscapes from ISO/TS 12913-3:2019 [41] (adapted from [38])

The second component, *Content*, ordered soundscape excerpts on a "full of content – empty" continuum and explained 25% of the total variance. By expressing how much the environment is saturated, *Content* aligns with the concepts of *Liveliness* [57], *Activity* [29] and *Eventfulness* [36–38], which are in turn related to *Arousal* [39,61]. Indeed, Ward and Russel reported that although *Arousal* and *Activity* are correlated, arousing environments may result from factors other than *Activity*. In the present study, the term *Content* was chosen to represent a dimension orthogonal to *Comfort*. Interestingly, the attribute "eventfulness" appeared not to be neutral with respect to *Comfort* (cf. Figure 3). In the context of indoor soundscapes, the attribute "dramatic, eventful" resulted to have a negative valence connotation, while the term "undramatic, uneventful, unexciting" was found to have a positive valence connotation.

Among the tested acoustic and psychoacoustic parameters, *Comfort* was best explained by loudness N_{10}. Indoor soundscapes dominated by louder sounds were generally perceived as less comfortable, in agreement with previous urban soundscape results [38]. Nevertheless, the predictive power of a linear *Comfort* model based solely on loudness was quite limited. The inclusion of informational properties of sounds (i.e. sound categories) sensibly improved *Comfort* predictability (with R^2 values in line with [38]), thus confirming the important contribution of semantic features of sounds (e.g. sound type) in soundscape evaluations [14]. At constant loudness, *Comfort* was found to increase with natural sounds and music, and to be reduced by technological sounds. Further insights on the extracted perceptual dimensions were gained by investigating the interactions between internal and external sound types and by discriminating between different technological sound types.

In the tested conditions, in presence of a simulated semi-open window, *Comfort* was mainly influenced by outdoor sounds. The effect size of indoor sound type was relevant only when no sound was transmitted through the window, as it may occur in highly insulated facades. In absence of outdoor sounds, compared to a silent indoor environment or in presence of TV sounds, indoor soundscape was perceived as more annoying with fan noise and more comfortable with music. Regarding the effect of outdoor sounds on *Comfort*, loud heavy traffic noise resulted always detrimental for indoor soundscape quality, regardless indoor sound type. Compared to the condition with no sound from outside, human sounds could improve comfort conditions in presence of annoying fan noise and natural sounds provided a more comfortable indoor environment when combine with indoor fan noise or no indoor sound source. While listening to music or watching TV, *Comfort* was higher with natural sounds and without sounds entering the environment and lower with traffic sounds or human voices. This was likely due to the fact that the sound quality of music was slightly affected by outdoor sounds and TV speech intelligibility was reduced due to the informative content of voices and sound level of light traffic (around 500 – 4k Hz, cf. Figure 2), thus resulting less comfortable.

Soundscape literature reported people generally liking natural sounds and disliking mechanical and transportation sounds [16,38,62,63]. Human sounds were reported to be either pleasant [16,62,63] or valence neutral [38]. Taken together, in the tested conditions, noise exposure to heavy traffic resulted highly annoying. Despite their higher loudness compared to a silent indoor environment, light traffic and human sounds generally provided neutral comfort conditions, while natural sounds proved highly beneficial for indoor soundscape quality.

As far as *Content* is concerned, this perceptual dimension was best explained by level variability over time (L_{A10}-L_{A90}). Understandably, soundscapes with more level variation (i.e. technological sounds, TV and music) resulted in higher *Content*. The proportion of total variance explained by L_{A10}-L_{A90} was unimportant and increased when sound categories were included as predictors in the LMM, with R^2 values in line with [38]. While holding constant L_{A10}-L_{A90}, *Content* was found to increase with music, human and natural sounds and to decrease with TV sounds.

The effect size of outdoor sounds on *Content* was larger compared to that provided by indoor sounds, except when indoor soundscape was saturated with music. In presence of fan noise, TV or no indoor source, indoor soundscape was higher in *Content* with heavy traffic, human and natural sounds. Lower *Content* resulted in conditions with no outdoor sounds or light traffic. The effect size of indoor sound type on soundscape *Content* was larger only in the condition with no sound from the outside. Pairwise comparisons between the tested exposure conditions showed that higher content was provided by music (in absence of outdoor sounds or with light traffic) and by TV sounds (with light traffic).

In the two-dimensional space defined by *Comfort* and *Content*, many of the 97 attributes employed to measure indoor soundscapes didn´t cluster around the two main axes but were organized in a meaningful circular arrangement (cf. Figure 3), as in the Russell´s circumplex model of affect [39] and in the soundscape model by Axelsson et al. [38]. According to the circumplex model structure, indoor soundscape attributes may be interpreted as a combination of *Comfort* and *Content*. Further labelling corresponding to affective responses could then be applied to two additional axes rotated 45° on the same *Comfort – Content* plane (cf. Figure 9).

By referring to the attributes that loaded approximately equally comfortable and full of content, items describing an *engaging* indoor soundscape can be observed (e.g. “Exciting” and “Interesting, interest-arousing” , cf. Figure 3). Imagine for instance listening to music in your living room with a background of natural sounds coming from the outside (cf. Figure 9). On the opposite side, a *detached* soundscape may be view as a “mix” of an empty and annoying soundscape. This *engaging – detached* axis aligns well with the *Vibrancy* or *Excitement* perceptual construct that already emerged from previous soundscape literature [13,38,64].

A comfortable and empty soundscape was described by attributes that express a static, stable and organized environment, allowing for a sense of privacy and control (labelled as *private, controlled* in Figure 9). Imagine the private situation of watching TV in your living room, having control of the acoustic conditions (cf. Figure 9). On the opposite side, a full of content and annoying soundscape may be interpreted as dramatic, unexpected and, as such, *intrusive* and *uncontrolled*. Previous research reported that perceived noise control may be considered as a mediator between noise exposure and noise annoyance [65], and suggested its contribution to the restoration process [66]. The *Privacy* and *Control* dimension thus relates to home as a private place where inhabitants perceive control over their environment.

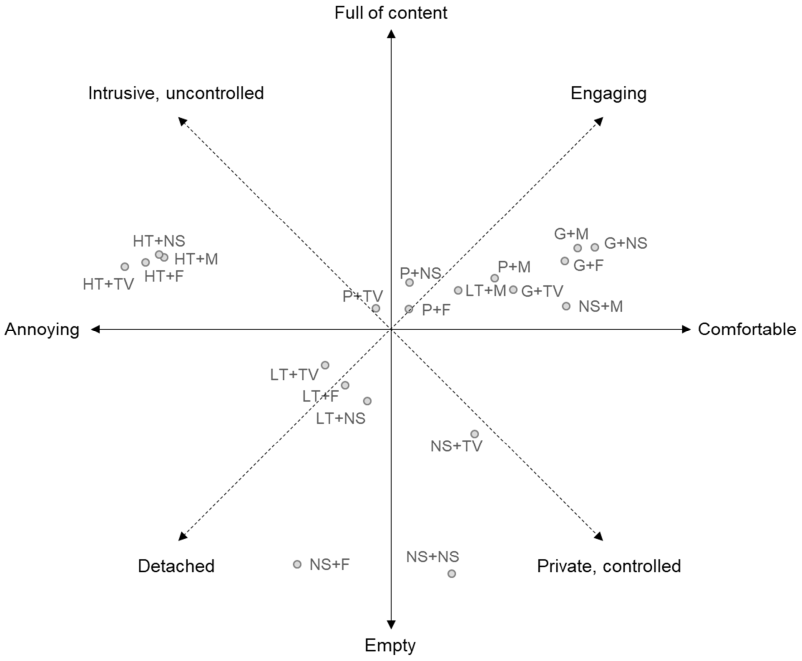

Figure 9 – Component scores of the 20 indoor soundscapes on the *Comfort* – *Content* plot. Each point represents an exposure condition, resulting from the combination of an outdoor context (NS: no sound, HT: heavy traffic, LT: light traffic, P: pedestrian area, G: garden) and an indoor sound type (F: fan, M: music, TV: TV, NS: no sound).

According to the model proposed in Figure 9, an *engaging* and *private* and *controlled* indoor soundscape may be equally comfortable but differ in their content. Likewise, a *private* and *controlled* and a detached indoor soundscape may be equally empty but differ in their perceived comfort. The tested acoustic conditions managed to cover the four quadrants of the two-dimensional space defined by *Comfort* and *Content* as main axis, and *Privacy-Control* and *Engagement* as secondary axis. It should be noticed that no exposure condition scored extremely high in content, situation that may occur when the living room is filled with people (e.g. in a party situation).

4.1.2 Familiarity

The third component, *Familiarity*, was found to explain 7% of indoor soundscape ratings, and ordered the soundscape excerpts according to a “common – uncommon” continuum. This dimension aligns with findings from previous soundscape studies [29,38].

Familiarity was best explained by sharpness, with sharper sounds resulting less familiar. Nevertheless, *Familiarity* predictability by LMMs based on sharpness was rather low, regardless the inclusion of sound categories as predictors. A high proportion of total variance was explained by subject variability instead, likely due to the individual interpretation of sound familiarity according to different experiential backgrounds.

Effect sizes of outdoor or indoor sound type were generally low for *Familiarity* scores, and this may be due to the fact that all the soundscape excerpts were quite realistic and related to everyday life sounds. Among indoor sound type, fan noise and no indoor sounds were the most familiar, while TV and music were the most unfamiliar, most probably due to the fact that it was the first time participants watched and listened those sound and video stimuli. Interestingly, among outdoor sound types, light traffic was generally perceived the most familiar, thus reflecting the urban context in which the experiment took place. On the contrary, in absence of indoor sound sources or in presence of indoor music, the condition with no sound from outside was the less familiar. It should be noticed that the completely silent condition (without both internal and external sources) was experienced very differently between the test participants, as showed by high variability in comfort and familiarity scores for this condition. The atypically and unrealistic silent condition for a living room with a semi open window may have elicited different responses (e.g. relax or anxiety [67]) according to participants´ living contexts and general preferences.

4.2 Model application to building design

The proposed model identified the dimensions underlying the acoustic perception in living rooms. The model can be intended as an adjustment of soundscape models developed by urban soundscape research and proposed by ISO 12913 series in order to address the peculiarities of the acoustic experience indoor. Such model provides a reference for indoor soundscape research and practice by indicating which perceptual constructs are to be measured in buildings, how to measure them through a set of attribute scales and how to promote high-quality indoor soundscapes through a useful combination of indoor and outdoor sound sources.

Current design criteria mainly focus on blocking out external "noises", in order to limit noise annoyance by reducing dB sound levels. The present study showed how external sounds released through the facade and internal sounds could be combined to improve soundscape quality, regardless the overall sound level, based on the meaning attributed to sounds and on masking opportunities.

POE surveys are often limited to the assessment of annoyance or dissatisfaction caused by noises and to the identification of disturbing sound sources [7]. The two-dimensional space defined by *Comfort* and *Content* (cf. Figure 9) suggests that there is a much broader affective space to explore through indoor soundscape design than the negative *Comfort* axis pointing towards annoyance. Soundscape surveys should focus on sound impact on all the relevant perceptual dimensions (*Comfort*, *Content*, *Engagement*, *Privacy*, *Control* and *Familiarity*), by adapting existing soundscape collection methods [43,68] to indoor peculiarities. POE surveys integrating soundscape methodologies (cf. [69]) could thus inform practices oriented towards the design of better-than-neutral indoor soundscapes [16], with positive outcomes on people health, well-being and quality of life [17,20,21,66,70,71]. Following the proposal by Cain et al. [13], existing and target indoor soundscapes could be plotted in the perceptual space showed in Figure 9, in order to understand how specific design interventions can "move" soundscape position along certain perceptual dimensions and in order to assess the effectiveness of design actions in terms of perceptual outcomes. In doing so, the effect of materials, space layout, and building technologies can be evaluated in terms of soundscape outcomes, thus providing a perceptual perspective to building and room acoustics. This perceptual approach would provide designers and acousticians with a wider range of design solutions. For instance, ventilation devices may be reinterpreted as systems to transmit, block or adjust external sounds to provide a connection with the external context, release wanted sounds, and mask unwanted sounds [24]. This would change the way in which acoustic design requirements are defined beyond setting noise level limits, the needs that natural ventilation solutions (e.g. active noise control or automated openings) are required to meet and the way in which those solutions would be assessed. The present study confirmed the limited predictive power of objective acoustic parameters taken in isolation and encouraged for the acknowledgement of sound categories in modelling acoustic perception. Based on the proposed model of indoor soundscape perception, predictive indices may be developed to guide the design stage [72,73], thus filling the gap between expected and experienced acoustic perception in buildings.

4.3 Limitations

Given the experimental settings and the chosen exposure conditions, the proposed model is intended to be applied to living rooms and in general to spaces dedicated to daily activities, such as relaxing, listening to music and watching TV. The use among the audio stimuli of a TV video with speech content extends model applicability to socialization activities that normally occur in living rooms (e.g. talking to other people in person or by phone). Nevertheless, no exposure condition resulted extremely full of content and future studies may investigate situations in which the space is occupied by more than one human subject. The present work was limited to the relaxing task (e.g. reading, watching TV, listening to music) and further research would be needed to investigate the combined effect of sound type (indoor and outdoor) and intelligibility conditions on affective responses, in presence of more cognitive demanding tasks, as would be the case in schools or offices. Furthermore, it must be noticed that the model does not apply to bedrooms, where sleep disturbance may occur, leading to immediate and long-term effects on cardiovascular and mental health [74].

One limitation of the present study is represented by the number of tested exposure conditions (n = 20), also in relation to the number of variables (p = 97). Indeed, PCA should ideally rely on large sample sizes in order to minimize errors and maximize the probability that components extracted from the sample reflect the underlying population [75]. The application of PCA in cases where $n \ll p$ is not unusual [38,76], even if sub-optimal. In such cases, lower order PCs can be expected to be more stable across different samples (i.e. PC1, PC2, …), while the higher order PCs capture a large part of data variation (i.e. noise dimensions) [75]. In general, by relying on small sample sizes there is the risk that different PCs can emerge from different samples, so that the extracted model is not generalizable anymore. The design of the present experiment had to find a trade-off between the number of attributes and the number of conditions to assess, in order to keep each experimental session within reasonable time limits. As described in Appendix C, a large number of attributes (i.e. 97) was selected in order to comprehensively cover the many possible affective states that an indoor acoustic environment can elicit and that might have resulted in potentially relevant perceptual dimensions. Besides the number of observations itself (i.e. 20), it is foundational to consider how those conditions have been selected in order to be representative of scenarios typically experienced in indoor living rooms, as explained in Section 2.2. Consequently, the extracted perceptual dimensions can be expected to be stable across different samples of indoor acoustic conditions in dwellings.

In order to limit test duration, some of the factors that may affect indoor soundscapes in residential buildings have not be included in the present experiment and may be investigated in future laboratory and field research. Studies would be useful to verify how the sound of neighbors position indoor soundscapes in the *Comfort – Content* space, likely in the *intrusive – uncontrolled* area, and how they interact with outdoor sounds. Many acoustic and non-acoustic factors that affect acoustic perception in residential buildings may be integrated in indoor soundscape models, such as building features, the urban context, the personal traits, the socio-economic, situational and environmental factors [16,77]. In any case, established soundscape models [38,41], confirmed through both laboratory and field studies, corroborate the general validity of the proposed model as in both the cases (i.e. outdoor and indoor environments) the lower order PCs (i.e. PC1, PC2 and PC3) reflect a similar structure (cf. Figure 8 and Figure 9).

5. Conclusions

The present study investigated the affective response to indoor soundscapes in residential buildings, in order to: (i) identify, interpret and analyze the dimensions underlying acoustic perception in indoor residential living rooms and (ii) discuss potential implications in building design practice.

Regarding the first research question, the main conclusions are:

(1) Three main perceptual dimensions were extracted from the assessment of 20 acoustic conditions on 97 attribute rating scales: *Comfort*, *Content*, and *Familiarity*. The first two dimensions explained together 83% of total variance. In the two-dimensional space defined by the orthogonal components *Comfort* and *Content*, attributes were organized in a meaningful circular fashion, according to a “circumplex” model. In this perceptual space, an *engaging* indoor soundscape would be both comfortable and full of content, a *detached* soundscape would be annoying and empty, an *intrusive* and *uncontrolled* soundscape would be annoying and full of content, whilst a *private* and *controlled* indoor soundscape would be both comfortable and empty;

(2) *Comfort* was negatively associated with loudness N_{10}, *Content* was positively associated to sound level variability L_{A10}-L_{A90}, and *Familiarity* was negatively associated with sharpness S. LMMs based on single objective acoustic parameters had limited predictive power on the three perceptual dimensions, that increased when sound categories (i.e. technological, human, natural, music and TV sounds) were included as predictors. Age and gender were not significant contributors;

(3) *Comfort* was mainly influenced by outdoor sounds. Indoor soundscapes dominated by heavy traffic sounds were found to be annoying, indoor soundscapes with light traffic sounds or human sounds coming from the outside were found to provide neutral comfort conditions, and indoor

soundscape with natural sounds were found to be highly comfortable. The effect size of indoor sound type was larger only when no sound was transmitted through the window, with music resulting in more comfortable and fan noise resulting in more annoying indoor soundscapes, compared to TV or no indoor sound sources. Interestingly, in presence of annoying indoor sound sources or no indoor sound source, outdoor sounds (e.g. human voices and natural sounds) can result in improved indoor soundscapes in terms of indoor comfort, despite higher overall loudness;

(4) *Content* was mainly affected by outdoor sound type compared to indoor sound type, except when indoor soundscape was saturated with music. In general, indoor soundscape dominated by heavy traffic, human and natural sounds were fuller of *Content*. The effect size of indoor sound type on *Content* was larger only in the condition with no sound from the outside, with higher content generally provided by music and by TV sounds;

(5) Effect sizes of outdoor or indoor sound type were generally low for *Familiarity* scores. Among indoor sound types, the conditions with fan noise and no indoor sounds resulted the most familiar. Among outdoor sound types, light traffic was generally the most familiar.

Regarding the second research question, the main conclusions are:

(1) A measurement system of indoor soundscape perception is proposed, consisting of a two-dimensional space defined by two main orthogonal axis, *Comfort* and *Content*, and two additional axis, *Engagement* and *Privacy – Control*, rotated 45° on the same plane. The model represents an adjustment of previous soundscape models developed for outdoor urban environments (cf. ISO/TS 12913 – 3 [41] and Axelsson et al. [38]) to account for perceptual aspects occurring in indoor spaces;

(2) The model suggests the perceptual constructs to be measured (e.g. in post-occupancy evaluations), the attribute scales to be employed and actions to improve indoor soundscape quality.

Acknowledgments

The authors would like to thank dr. Stawinoga Agnieszka Elzbieta (Eurac Research) for her advice on the statistical analysis. The authors gratefully acknowledge the UCL IEDE Acoustics Group for its collaboration in the pilot survey and the Bartlett Real Estate Institute for kindly sharing part of the furniture used in the laboratory setup.

Funding

This work was supported by the Programma di cooperazione Interreg V-A Italia-Svizzera 2014– 2020, project QAES [ID no. 613474]; and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme [grant agreement No. 740696].

References

[1] A. Santoni, J.L. Davy, P. Fausti, P. Bonfiglio, A review of the different approaches to predict the sound transmission loss of building partitions, (2020) 1–27. https://doi.org/10.1177/1351010X20911599.

[2] A. Arjunan, C.J. Wang, K. Yahiaoui, D.J. Mynors, T. Morgan, M. English, Finite element acoustic analysis of a steel stud based double-leaf wall, Build. Environ. 67 (2013) 202–210.

[3] A. Arjunan, C. Wang, M. English, M. Stanford, P. Lister, A computationally-efficient numerical model to characterize the noise behavior of metal-framed walls, Metals (Basel). 5 (2015) 1414–1431.

[4] ISO 16283-1:2014 Acoustics — Field measurement of sound insulation in buildings and of building elements — Part 1: Airborne sound insulation, (2014).

[5] ISO 717-1:2013 Acoustics — Rating of sound insulation in buildings and of building elements — Part 1: Airborne sound insulation, (2013).

[6] L. Zagreus, C. Huizenga, E. Arens, D. Lehrer, Listening to the occupants : a Web-based indoor environmental quality survey Practical implications, Indoor Air. 14 (2004) 65–74.

[7] L.T. Graham, T. Parkinson, S. Schiavon, Where do we go now? Lessons learned from 20 years of

CBE’s Occupant Survey, (2020) 0–23. https://escholarship.org/uc/item/8k20v82j.

[8] N.G. Vardaxis, D. Bard, K. Persson Waye, Review of acoustic comfort evaluation in dwellings—part I: Associations of acoustic field data to subjective responses from building surveys, Build. Acoust. 25 (2018) 151–170. https://doi.org/10.1177/1351010X18762687.

[9] N. Vardaxis, D. Bard, Review of acoustic comfort evaluation in dwellings : part II — impact sound data associated with subjective responses in laboratory tests, (2018). https://doi.org/10.1177/1351010X18772026.

[10] N.G. Vardaxis, D. Bard, Review of acoustic comfort evaluation in dwellings: Part III—airborne sound data associated with subjective responses in laboratory tests, Build. Acoust. 25 (2018) 289–305. https://doi.org/10.1177/1351010X18788685.

[11] D. de la Prida, A. Pedrero, M.Á. Navacerrada, A. Díaz-chyla, An annoyance-related SNQ for the assessment of airborne sound insulation for urban-type sounds, Appl. Acoust. 168 (2020) 107432. https://doi.org/10.1016/j.apacoust.2020.107432.

[12] V. Hongisto, M. Maria, Satisfaction with sound insulation in residential dwellings - The effect of wall construction, 85 (2015). https://doi.org/10.1016/j.buildenv.2014.12.010.

[13] R. Cain, P. Jennings, J. Poxon, The development and application of the emotional dimensions of a soundscape, Appl. Acoust. 74 (2013) 232–239. https://doi.org/10.1016/j.apacoust.2011.11.006.

[14] D. Dubois, C. Guastavino, M. Raimbault, A cognitive approach to urban soundscapes: Using verbal data to access everyday life auditory categories, Acta Acust. United with Acust. 92 (2006) 865–874.

[15] B. Berglund, M.E. Nilsson, On a tool for measuring soundscape quality in urban residential areas, Acta Acust. United with Acust. 92 (2006) 938–944.

[16] S. Torresin, R. Albatici, F. Aletta, F. Babich, J. Kang, Assessment methods and factors determining positive indoor soundscapes in residential buildings: A systematic review, Sustain. 11 (2019) 5290. https://doi.org/10.3390/su11195290.

[17] S. Altomonte, J. Allen, P. Bluyssen, G. Brager, L. Heschong, A. Loder, S. Schiavon, J. Veitch, L.

Wang, P. Wargocki, Ten questions concerning well-being in the built environment, Build. Environ. (2020) 106949. https://doi.org/10.1016/j.buildenv.2020.106949.

[18] ISO 12913-1:2014 - Acoustics - Soundscape Part 1: Definition and conceptual framework, ISO, Geneva, 2014.

[19] J. Kang, F. Aletta, T.T. Gjestland, L.A. Brown, D. Botteldooren, B. Schulte-Fortkamp, P. Lercher, I. van Kamp, K. Genuit, A. Fiebig, J.L. Bento Coelho, L. Maffei, L. Lavia, Ten questions on the soundscapes of the built environment, Build. Environ. 108 (2016) 284–294. https://doi.org/10.1016/j.buildenv.2016.08.011.

[20] F. Aletta, T. Oberman, J. Kang, Associations between positive health-related effects and soundscapes perceptual constructs: A systematic review, Int. J. Environ. Res. Public Health. 15 (2018) 2392. https://doi.org/10.3390/ijerph15112392.

[21] H. Ma, S. Shu, An Experimental Study: The Restorative Effect of Soundscape Elements in a Simulated Open-Plan Office, Acta Acust. United with Acust. 104 (2018) 106–115. https://doi.org/10.3813/AAA.919150.

[22] J. Kang, B. Schulte-Fortkamp, Soundscape and the built environment, CRC press Boca Raton, FL, USA:, 2016.

[23] F. Aletta, A. Astolfi, Soundscapes of buildings and built environments, Build. Acoust. 25 (2018) 195–197. https://doi.org/10.1177/1351010X18793279.

[24] S. Torresin, R. Albatici, F. Aletta, F. Babich, T. Oberman, J. Kang, Acoustic design criteria in naturally ventilated residential buildings: New research perspectives by applying the indoor soundscape approach, Appl. Sci. 9 (2019) 1–25. https://doi.org/10.3390/app9245401.

[25] U.B. Ercakmak, P.N. Dokmeci Yorukoglu, Comparing Turkish and European Noise Management and Soundscape Policies : A Proposal of Indoor Soundscape Integration to Architectural Design and Application, Acoustics. 1 (2019) 847–865. https://doi.org/https://doi.org/10.3390/acoustics1040051.

[26] K.W. Ma, H.M. Wong, C.M. Mak, A systematic review of human perceptual dimensions of sound:

Meta-analysis of semantic differential method applications to indoor and outdoor sounds, Build. Environ. 133 (2018) 123–150. https://doi.org/10.1016/j.buildenv.2018.02.021.

[27] C.E. Osgood, The nature and measurement of meaning, Psychol. Bull. 49 (1952) 197.

[28] C.E. Osgood, On the whys and wherefores of E, P, and A, J. Pers. Soc. Psychol. 12 (1969) 194.

[29] K. Kawai, T. Kojima, K. Hirate, M. Yasuoka, Personal evaluation structure of environmental sounds: Experiments of subjective evaluation using subjects' own terms, J. Sound Vib. 277 (2004) 523–533. https://doi.org/10.1016/j.jsv.2004.03.013.

[30] J.Y. Jeon, J.Y. Hong, C. Lavandier, J. Lafon, Ö. Axelsson, M. Hurtig, A cross-national comparison in assessment of urban park soundscapes in France, Korea, and Sweden through laboratory experiments, Appl. Acoust. 133 (2018) 107–117. https://doi.org/10.1016/j.apacoust.2017.12.016.

[31] C. Tarlao, D. Steele, C. Guastavino, Investigating factors influencing soundscape evaluations across multiple urban spaces in Montreal, INTER-NOISE 2019 MADRID - 48th Int. Congr. Exhib. Noise Control Eng. (2019).

[32] D.A. Hall, A. Irwin, M. Edmondson-Jones, S. Phillips, J.E.W. Poxon, An exploratory evaluation of perceptual, psychoacoustic and acoustical properties of urban soundscapes, Appl. Acoust. 74 (2013) 248–254. https://doi.org/10.1016/j.apacoust.2011.03.006.

[33] D. Welch, D. Shepherd, K. Dirks, M.Y. Tan, G. Coad, Use of creative writing to develop a semantic differential tool for assessing soundscapes, Front. Psychol. 9 (2019) 1–16. https://doi.org/10.3389/fpsyg.2018.02698.

[34] B. Yu, J. Kang, H. Ma, Development of indicators for the soundscape in urban shopping streets, Acta Acust. United with Acust. 102 (2016) 462–473. https://doi.org/10.3813/AAA.918965.

[35] J. Kang, M. Zhang, Semantic differential analysis of the soundscape in urban open public spaces, Build. Environ. 45 (2010) 150–157. https://doi.org/10.1016/j.buildenv.2009.05.014.

[36] C.E. Mediastika, A.S. Sudarsono, L. Kristanto, G. Tanuwidjaja, R.G. Sunaryo, R. Damayanti, Appraising the sonic environment of urban parks using the soundscape dimension of visually

impaired people, Int. J. Urban Sci. 0 (2020) 1–26. https://doi.org/10.1080/12265934.2020.1713863.

[37] J.Y. Hong, J.Y. Jeon, Influence of urban contexts on soundscape perceptions: A structural equation modeling approach, Landsc. Urban Plan. 141 (2015) 78–87. https://doi.org/10.1016/j.landurbplan.2015.05.004.

[38] Ö. Axelsson, M.E. Nilsson, B. Berglund, A principal components model of soundscape perception, J. Acoust. Soc. Am. 128 (2010) 2836–2846. https://doi.org/10.1121/1.3493436.

[39] J.A. Russell, A circumplex model of affect, J. Pers. Soc. Psychol. 39 (1980) 1161–1178. https://doi.org/10.1037/h0077714.

[40] J. Posner, J.A. Russell, The circumplex model of affect : An integrative approach to affective neuroscience , cognitive development , and psychopathology, (2005) 715–734.

[41] ISO TS 12913-3:2019 - Acoustics - Soundscape part 3: Data analysis, ISO, Geneva, 2019.

[42] Ö. Axelsson, How to Measure Soundscape Quality, Euronoise 2015. (2015) 1477–1481. http://www.conforg.fr/euronoise2015/proceedings/data/articles/000067.pdf.

[43] ISO TS 12913-2:2018 - Acoustics - Soundscape part 2: Data collection and reporting requirements, ISO, Geneva, 2018.

[44] C.J. Yu, J. Kang, Soundscape in the sustainable living environment: A cross-cultural comparison between the UK and Taiwan, Sci. Total Environ. 482–483 (2014) 501–509. https://doi.org/10.1016/j.scitotenv.2013.10.107.

[45] S.M. Alam, L.S. Eang, A. Tan, T.S. Tiong, An investigation of community noise in high-rise residential environments, J. Acoust. Soc. Am. 127 (2010) 3511–3518. https://doi.org/10.1121/1.3409477.

[46] M. Romanowska, The Warsaw soundscape - Structure and specifics, Misc. Geogr. 18 (2014) 5–16. https://doi.org/10.2478/mgrsd-2014-0021.

[47] R. Bernhaupt, M. Obrist, A. Weiss, E. Beck, M. Tscheligi, Trends in the Living Room and Beyond : Results from Ethnographic Studies Using Creative and Playful Probing, Comput.

Entertain. 6 (2008) 1–23. https://doi.org/http://doi.acm.org/10.1145/1350843.1350848.

[48] EN-ISO, 3382-2: 2008, Acoust. Meas. Room Acoust. Parameters. Part. 2 (2008) 3382.

[49] ISO, 532-1. Acoustics - Methods for Calculating Loudness - Part 1: Zwicker Method, Int. Stand. (2017).

[50] BS 8233:2014 Guidance on sound insulation and noise reduction for buildings, (2014).

[51] C. Guastavino, B.F.G. Katz, J.D. Polack, D.J. Levitin, D. Dubois, Ecological validity of soundscape reproduction, Acta Acust. United with Acust. 91 (2005) 333–341.

[52] R.C. Team, others, R: A language and environment for statistical computing, (2013).

[53] H.F. Kaiser, The application of electronic computers to factor analysis, Educ. Psychol. Meas. 20 (1960) 141–151.

[54] R.B. Cattell, The scree test for the number of factors, Multivariate Behav. Res. 1 (1966) 245–276.

[55] M. Rychtáriková, G. Vermeir, Soundscape categorization on the basis of objective acoustical parameters, Appl. Acoust. 74 (2013) 240–247. https://doi.org/10.1016/j.apacoust.2011.01.004.

[56] K. Sun, B. De Coensel, K. Filipan, F. Aletta, T. Van Renterghem, T. De Pessemier, W. Joseph, D. Botteldooren, Classification of soundscapes of urban public open spaces, Landsc. Urban Plan. 189 (2019) 139–155. https://doi.org/10.1016/j.landurbplan.2019.04.016.

[57] I. Vogels, Atmosphere Metrics: a tool to quantify perceived atmosphere, in: J.H.D.M. Westerink, M. Ouwerkerk, T.J.M. Overbeek, W.F. Pasveer, B. de Ruyter (Eds.), Probing Exp., Springer, Dordrecht, 2008: p. https://doi.org/https://doi.org/10.1007/978-1-4020-6593-4_3.

[58] T.C. Andringa, J.J.L. Lanser, How pleasant sounds promote and annoying sounds impede health: A cognitive approach, Int. J. Environ. Res. Public Health. 10 (2013) 1439–1461. https://doi.org/10.3390/ijerph10041439.

[59] A. Dupuis, D.C. Thorns, Home, home ownership and the search for ontological security, Sociol. Rev. 46 (1998) 24–47.

[60] A. Kearns, R. Hiscock, A. Ellaway, S. Macintyre, “Beyond four walls”. The psycho-social benefits of home: Evidence from West Central Scotland, Hous. Stud. 15 (2000) 387–410.

https://doi.org/10.1080/02673030050009249.

[61] L.M. Ward, J.A. Russell, The psychological representation of molar physical environments, J. Exp. Psychol. Gen. 110 (1981) 121–152. https://doi.org/10.1037/0096-3445.110.2.121.

[62] C. Guastavino, The ideal urban soundscape: Investigating the sound quality of French cities, Acta Acust. United with Acust. 92 (2006) 945–951.

[63] W.J. Davies, N.S. Bruce, J.E. Murphy, Soundscape reproduction and synthesis, Acta Acust. United with Acust. 100 (2014) 285–292. https://doi.org/10.3813/AAA.918708.

[64] F. Aletta, J. Kang, Towards an Urban Vibrancy Model: A Soundscape Approach, Int. J. Environ. Res. Public Health. 15 (2018) 1712. https://doi.org/10.3390/ijerph15081712.

[65] N. Riedel, H. Köckler, J. Scheiner, I. van Kamp, R. Erbel, A. Loerbroks, T. Claßen, G. Bolte, Home as a place of noise control for the elderly? A cross-sectional study on potential mediating effects and associations between road traffic noise exposure, access to a quiet side, dwelling-related green and noise annoyance, Int. J. Environ. Res. Public Health. 15 (2018). https://doi.org/10.3390/ijerph15051036.

[66] I. Van Kamp, R. Klaeboe, A.L. Brown, P. Lercher, Soundscapes, human restoration and quality of life, in: J. Kang, B. Schulte-Fortkamp (Eds.), Soundscape Built Environ., CRC Press, Boca Raton, FL, USA, 2016: pp. 43–68. https://doi.org/10.1201/b19145-4.

[67] T. Stockfelt, Sound as an existential necessity, J. Sound Vib. 151 (1991) 367–370. https://doi.org/10.1016/0022-460X(91)90533-P.

[68] M.S. Engel, A. Fiebig, C. Pfaffenbach, J. Fels, A Review of Socio-acoustic Surveys for Soundscape Studies, Curr. Pollut. Reports. 4 (2018) 220–239. https://doi.org/10.1007/s40726-018-0094-8.

[69] A.A.M. Aburawis, P.N. Dokmeci Yorukoglu, An integrated framework on soundscape perception and spatial experience by adapting post-occupancy evaluation methodology, Build. Acoust. 25 (2018) 3–16. https://doi.org/10.1177/1351010X18758478.

[70] S. Shu, H. Ma, Restorative Effects of Classroom Soundscapes on Children's Cognitive

Performance, Int. J. Environ. Res. Public Health. 16 (2019) 293. https://doi.org/10.3390/ijerph16020293.

[71] J.J. Alvarsson, S. Wiens, M.E. Nilsson, Stress recovery during exposure to nature sound and environmental noise, Int. J. Environ. Res. Public Health. 7 (2010) 1036–1046. https://doi.org/10.3390/ijerph7031036.

[72] F. Aletta, J. Kang, Ö. Axelsson, Soundscape descriptors and a conceptual framework for developing predictive soundscape models, Landsc. Urban Plan. 149 (2016) 65–74. https://doi.org/10.1016/j.landurbplan.2016.02.001.

[73] J. Kang, F. Aletta, T. Oberman, M. Erfanian, M. Kachlicka, M. Lionello, A. Mitchell, Towards soundscape indices, in: Int. Congr. Acoust. - ICA, 2019: pp. 2488–2495. https://www.researchgate.net/publication/335661596_Towards_soundscape_indices.

[74] World Health Organization Regional Office for Europe, Night noise guidelines for Europe, World Heal. Organ. (2009) 154.

[75] J.W. Osborne, A.B. Costello, Sample size and subject to item ratio in principal components analysis Sample size and subject to item ratio in principal components analysis, Pract. Assessement, Res. Eval. 9 (2004).

[76] I.T. Jolliffe, J. Cadima, J. Cadima, Principal component analysis : a review and recent developments Subject Areas, Phil.Trans.R.Soc.A. 374 (2016) 1–16.

[77] S. Torresin, G. Pernigotto, F. Cappelletti, A. Gasparella, Combined effects of environmental factors on human perception and objective performance: A review of experimental laboratory works, Indoor Air. 28 (2018). https://doi.org/10.1111/ina.12457.

Highlights

(1) Laboratory listening tests reproduced indoor soundscapes in living rooms.

(2) *Comfort*, *Content* and *Familiarity* are the main dimensions of acoustic perception.

(3) *Privacy-Control* and *Engagement* are at a 45° rotation from *Comfort* and *Content*.

(4) Sound categories are fundamental predictors of indoor soundscape quality.

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: