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Measuring, representing and analysing indoor soundscapes: A data collection campaign in residential buildings with natural and mechanical ventilation in England

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A R T I C L E I N F O

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A B S T R A C T

A model for the assessment of perceived affective quality of indoor residential soundscapes is first applied in a field survey carried out in 61 dwellings in England. Objectives are i) to investigate measurement and indoor soundscape data representation, ii) to characterize soundscape appropriateness for home working and relaxation, iii) to test differences based on the ventilation strategy, and iv) to identify factors predicting indoor soundscapes. In dwellings with natural ventilation (N = 34) the survey was carried out with windows open, while in those with mechanical ventilation (N = 27) with windows closed and the system in operation. Parallel to the administration of the questionnaire, monaural and binaural measurements of the acoustic environments were performed. The study provides examples of data representation in the circumplex space defined by comfort and content dimensions. Soundscapes which are appropriate for work and relaxation are characterized by high comfort and low content, i.e., perceived as private and under control. Indoor soundscapes are strongly related to the perception of traffic noise, window opening, and sound pressure level, especially in the energy content of interference in speech perception through the Speech Interference Level parameter (SIL), factors that lead to reduced comfort and increased saturation of the environment. Moreover, aspects related to psychoacoustics (sharpness), contextual and building-related factors (ownership status and floor level) and cross-modal effects from other sensory modalities (perceived air quality and air temperature) have an impact. A threshold value of 32.7 dB for SIL was identified at which a neutral comfort is attained.

1. Introduction

The acoustic environment surrounding us can influence our cognitive performance (among others [1,2]), mood [3,4], behavior [5,6], health [7,8], and well-being [9,10], according to different pathways. Impacts are not only negative in nature, and related, for instance, to reduced attention, increased annoyance, place avoidance, cardiovascular diseases, and sleep disruption, but can even be positive and lead, for instance, to improved ability to focus, pleasure, prolonged permanence in a place, and restoration. Understanding the potential of the sound environment to generate positive impacts on people through acoustic design is the focus of soundscape research. The soundscape is the acoustic environment as we perceive it in context [11]. The objective of soundscape studies is to identify appropriate descriptors of our acoustic perception in context [11]and to associate these with predictors that can be used as proxies when measuring and managing the perceived acoustic quality of spaces [12]. Soundscape studies have their roots in the planning of urban outdoor spaces [13]. However, since we spend most of our time inside buildings [14], in the indoor built environment the soundscape approach can provide a relevant impact.

In order to improve soundscapes, it is essential to be able to measure them. Listening tests have led to the definition of the perceptual

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dimensions underlying the affective response to the sound environment both in outdoor spaces [15] and indoor residential settings [16]. This can be described by two main dimensions in a circumplex, one related to valence ('pleasantness' [15] or 'comfort' [16]) and one related to the degree of saturation of the environment with sounds and events ('eventfulness' [15] or 'content' [16]). In this two-dimensional orthogonal reference system, a further labelling corresponding to human judgements can be assigned to two additional axes rotated 45° in the same plane (see Fig. 1). These axes vary substantially in the perception pattern of the external and internal soundscapes. In the model developed by Axelsson et al. [15] and taken up in ISO TS 12913-3 [17], with a rotation of 45° with respect to the two main dimensions we find two alternative dimensions representing 'calm' environments versus 'chaotic' ones, and 'vibrant' environments versus 'monotonous' ones (see Fig. 1a). In the model developed by Torresin et al. [16] for residential environments (e.g., a living room), we find two alternative dimensions representing 'private and under-control' versus 'intrusive and uncontrolled' environments, and 'engaging' versus 'detached' environments (see Fig. 1b).

The models provide 8 attributes to be used in 5-value Likert scales for soundscape evaluation, according to ISO/TS 12913-2 [18] (i.e., "*for each of the 8 scales below, to what extent do you agree or disagree that the present surrounding sound environment is …*" pleasant, chaotic, etc. according to the model in Fig. 1a and comfortable, intrusive-uncontrolled, etc. according to the model in Fig. 1b). The eight perceptual attributes can be reduced through trigonometric transformation into a pair of coordinates in the two main axes ('pleasantness' and 'eventfulness' or 'comfort' and 'content'), according to the procedure described in ISO/TS 12913-3 [17]. Affective responses can then be plotted as points in a scatterplot. To effectively analyze standardized assessments and visually compare soundscapes based on specific variables (e.g., different locations or sound levels), it is useful to represent data as probabilistic distribution, e.g., through the 50th percentile contour within the circumplex model and observe the marginal distribution plots as proposed by Mitchell et al. [19].

The two-dimensional reference system is effective in studying factors affecting perceptual dimensions and evaluating the effectiveness of soundscape interventions by comparing the target soundscapes with the achieved ones (*post operam*) [20]. Since the development of Axelsson et al.'s model and its inclusion in the technical specification ISO 12913-3 the methodology has been applied to the evaluation of different outdoor contexts. More recently, a model has been developed to assess the affective response to the indoor soundscapes [16]. The model was first tested in an online questionnaire administered to people working from home in the UK (London area) and Italy during the Covid-19 pandemic and was effective in discerning the appropriateness of the sound environment for work and relaxation at home and in assessing the impact of individual features (e.g., age, gender, noise sensitivity) and building and urban-related factors on the two 'comfort' and 'content' dimensions [10, 21–23]. However, being an online study, the results were limited by the absence of measurements of the physical acoustic environment that could provide recommendations for the design phase.

The present research is the first example of the adoption of the indoor soundscape model in a monitoring campaign in residential buildings to assess the acoustic perception of building occupants. Furthermore, the indoor soundscape data are analysed and visualized in the circumplex for the first time by adapting the methodology proposed by Mitchell et al. [19] for its application to an indoor soundscape dataset.

The main objective of the research is to investigate the main factors influencing indoor soundscapes in residential buildings, through the analysis of its main perceptual dimensions (i.e., 'comfort' and 'content' ratings). In doing so, the study aims to explain acoustic perception as a function of the acoustic characteristics of the environment, characterised through acoustic and psychoacoustic parameters which can be controlled at the design stage. The study constitutes one of the first indoor soundscape studies testing the effectiveness of accurate binaural measurements and related psychoacoustic parameters in predicting occupants' acoustic perception gathered from occupant surveys.

The assessment of the indoor soundscape depends on the specific activity carried out and with reference to which the assessment is made [24]. A lively sound environment could be deemed supportive for one activity, but disturbing for another. The present study assessed indoor soundscapes in relation to relaxation and work-from-home activities, thereby acknowledging the change in work patterns and home use following the COVID-19 pandemic.

Alongside factors related to the acoustic environment and home activities, the characteristics of the built environment (e.g., dwelling size) and the available ventilation system were considered. In dwellings with natural ventilation (NV), air is supplied and removed through ventilation openings (e.g., windows) to and from indoor spaces by relying on buoyancy forces and/or wind pressure differentials [25], without using mechanical devices to drive the air movement (e.g., fans), as it would be the case in dwellings equipped with mechanical ventilation (MV). Ventilation can have a great impact on the indoor acoustic environment, linked to greater or lesser contact with the external environment due to the opening or closing of windows and the presence of additional noise sources related to mechanical ventilation devices (e.g., fans) [26]. Furthermore, it has been hypothesised in the literature that the acoustic perception of the building occupant may be different depending on the ventilation strategy based on a lower expectation of low noise levels, an appreciation of non-acoustic benefits (e.g., the feeling of fresh air) and a different availability of control in naturally ventilated buildings compared to mechanically ventilated ones [27–29]. This would lead to a differentiation of acoustic requirements between mechanically and naturally ventilated buildings in analogy to the adaptive thermal comfort theory. Therefore, in order to test the hypothesis of an adaptive acoustic comfort in naturally ventilated buildings, the socio-acoustic investigations were carried out in two samples of

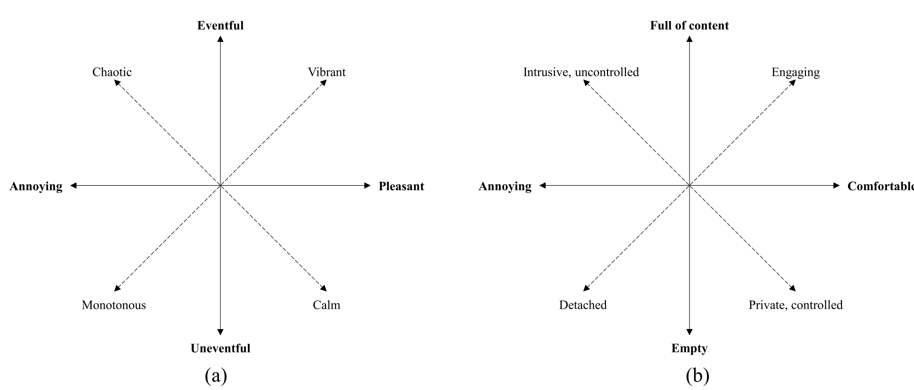

Fig. 1. *Models of perceived affective quality of outdoor (a) and indoor residential (b) soundscapes, adapted from* [16,17].

buildings, naturally and mechanically ventilated.

The study accounted for the multi-sensory nature of human perception. Whereas traditionally occupant surveys focusing on acoustic comfort have mostly measured the physical parameters representative of the acoustic environment, the present study takes a multi-domain perspective [30,31]. Therefore, aspects related to the quality of the outdoor view, perceived air quality and room temperature were recorded as potentially important covariates.

Finally, individual characteristics were considered, such as demographic aspects, personal sensitivity and psychological well-being. Taking England (and, in particular, the London area) as a case study area, the research therefore provides an extraordinary rich dataset on indoor soundscape perception together with a set of possible explanatory variables multi-domain in nature.

The research questions can therefore be summarised as:

- R1. How can quantitative indoor soundscape data be measured and represented?
- R2. What constitutes an appropriate indoor soundscape for working and relaxing at home?
- R3. What are the differences, if any, in the physical and perceived acoustic environment based on the ventilation strategy?
- R4. What are the main factors related to the physical and perceived acoustic environment, non-acoustic environmental domains (i.e., thermal, visual, air quality), building features (notably, ventilation type) and urban environment, and individual traits that influence the indoor soundscape?

In particular, through R4 the hypothesis of adaptive acoustic comfort will be tested: other factors being equal, does the acoustic perception change depending on the type of ventilation strategy *per se*?

The results have the potential to illustrate a methodology for measuring, representing, and analysing the indoor soundscape, and to highlight factors that can be controlled in the design of residential buildings to induce positive outcomes on occupants.

2. Materials and methods

2.1. Monitored dwellings and study area

Socio-acoustic surveys were carried out during the summer period, between 19 June and October 12, 2022, on a one-off basis, in the living rooms of 61 dwellings (or student accommodations), 34 of which were naturally ventilated (NV) and 27 equipped with mechanical ventilation (MV). In this study, dwellings equipped with a continuously mechanical ventilation and extraction system were considered eligible for the subsample of dwellings with MV (cf. system 4, Fig. A-1 in [29]). In this way, eligibility was easily verified by the presence of an air intake/outtake in the living room ceiling, which could be a potential source of noise in the environment where the occupants were invited to provide an assessment of the soundscape. Dwellings only equipped with an extract fan in the bathroom (e.g., coupled with trickle vents in the living room) were not considered (cf. systems 1 and 3, Fig. A-1 in [29]).

The main difficulty encountered during the recruitment campaign was in accessing dwellings equipped with MV. Those are generally fewer in number than those with NV, and often located in prestigious settings, thus less likely to accommodate outsiders for security reasons. Due to the difficulty in reaching the target number of dwellings in London, the survey area was progressively extended to include dwellings in the immediate vicinity of London and in Lincolnshire, thanks to the support and collaboration with North Kesteven District Council. Overall, the homes equipped with NV were located in London (N: 27), Greater London (N: 2), Windsor (N: 1), and Lincolnshire (N: 4). Dwellings equipped with MV were situated in London (N: 19) and in Lincolnshire (N: 8).

2.2. Participants

The study involved one participant per household for a total of 61 participants (31 men [49.2%], 30 women [50.8%]), all of them identifying with a gender that was the same as their sex registered at birth, with a participant age range of 24–72 years (M_{age}: 38.5, SD_{age}: 12.5 years), self-reporting no hearing impairment and good English level. Participants were offered a £10 voucher as a token of appreciation for their time.

2.3. Procedure

The monitoring campaign was conducted on a one-off basis in the participants' living room or, in the absence of a living room, in the space used by the participants for relaxation activities (e.g., the bedroom, the room in student accommodations or the kitchen). The session began with the installation of the measurement equipment (i.e., sound level meter, head-mounted microphone for binaural recordings, temperature data logger). Each participant was provided with a tablet for filling out the questionnaire. Before the beginning of the data collection activities, participants were invited to switch off potential sound sources inside the dwelling (e.g., electrical appliances, mobile phones) and to remain silent during the recording, while completing the questionnaire. In the case of naturally ventilated dwellings, participants were asked to open the windows as usual to ventilate the room. In the case of mechanically ventilated dwellings, the evaluations were conducted with the windows closed and the system in operation. Upon completion of the questionnaire and simultaneous monitoring operations, the researcher took a photograph from the living room window and disassembled the monitoring equipment. The average length of stay in each dwelling was approximately 40 min. The study was approved via the UCL IEDE Ethics departmental procedure on April 28, 2022.

2.4. Questionnaire

Survey data were entered on a touchscreen using REDCap electronic data capture tools hosted at University College London (UCL) [32,33]. The questionnaire consisted of four main parts focusing on: 1) a right-here-right-now assessment of the sound environment in the living room, 2) the evaluation of the typical sound environment in the living room with reference to the month prior to the assessment, 3) building features and ventilation habits and 4) individual characteristics of the participant. An excerpt of the questionnaire used for the online survey is provided in Appendix A. Only the questions that are relevant to the present study have been reported and are described in the following.

In the first section participants were invited to describe the dominance of several categories of sounds as perceived in the living room (Q1). The question was adapted from the ISO/TS 12913-2 (Method A) [18], by including the following sound sources relevant for indoor soundscapes: traffic noise, other noise from outside (e.g. sirens, construction, industry, loading of goods), natural sounds, human beings outside, other human beings present at home, neighbours, building services at home, and building services of neighbours and common areas, as per a previous study [23]. Perceived affective quality responses were collected by adapting questions from the ISO/TS 12913-2 (Method A) [18] with the eight attributes derived in [16] (i.e., Comfortable; Intrusive, uncontrolled; Engaging; Empty; Private, controlled; Annoying; Full of content; Detached, Q2). Participants were then invited to rate the degree of appropriateness of the acoustic environment with respect to relaxation (Q3) and work (Q4) activities.

In the third section, information about the housing context were collected and specifically on: the ownership status (Q5), the dwelling size (Q6), the house typology (i.e., detached single family, semi-detached or terraced house, apartment block, other, Q7), the floor on which the living room was located (Q8), the number of people living at home (Q9), the quality of the view from the window in the living room

(Q10), the satisfaction with the connection between the living room and the external nature (Q11), and the perceived air quality (in a range from "very bad" to "very good", Q12). Given the sample size of buildings investigated, the study of specific building technologies was not included as explanatory variables. Therefore, no specific data e.g., wall and floor composition were collected, being the focus on the link between the acoustic environment (resulting from a combination of factors, including building technologies) and people's perception.

In the last section, information was collected on demographic data and personal characteristics. Noise sensitivity (Q13) was assessed through a reduced number of items extracted from Weinstein's Noise Sensitivity Scale [34], which is able to provide a user profile similar to that of the full scale [35]. Subjective psychological well-being was assessed through the WHO-5 well-being index (Q14) [36]. The WHO-5 is based on five questions covering a time frame of two weeks and has proven to have adequate validity in screening for depression [36]. Finally, demographic information on age, sex and gender was collected (Q15-17).

2.5. Data collection on the physical environment

In addition to data on the 'perceived' environment, data on the 'physical' acoustic, thermal and visual environment were collected in each living room at the same time as the questionnaire was completed.

2.5.1. Sound

Five-minute mono and binaural recordings of the background noise were made in the living room with the window position according to the ventilation strategy. Monaural recordings were performed with a Class 1 NTi Audio XL2 sound level meter calibrated before each measurement session and placed at a height of 1.15 m above the floor, in close proximity to the researcher (see Fig. 2). The binaural audio material was collected with a mobile head-mounted microphone type BHM III.3 by Head Acoustics, worn by the researcher and characterised by a very low inherent noise (15 dBA). At the beginning of the recording, a hand clap was performed to synchronise the two recordings in the post-processing phase. During the completion of the questionnaire, the researcher sat next to the participant, assuming the same orientation (Fig. 2), so that the acoustic environment recorded by the researcher could be as close as possible to that heard by the participant during the completion of the questionnaire.

2.5.2. Temperature

The air temperature (T_{air}) was monitored using a calibrated HOBO U12 data logger. The datalogger was placed on a horizontal surface close to the researcher so as not to be affected by solar radiation.

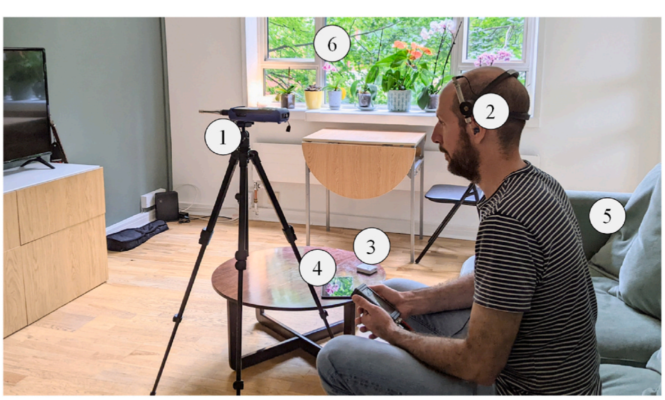

Fig. 2. Setup for the socio-acoustic survey: (1) sound level meter, (2) head-mounted microphone for binaural recordings, (3) temperature data logger, (4) touchscreen for questionnaire administration, (5) positioning of the participant next to the researcher, (6) window opening position according to the ventilation strategy.

2.5.3. Window view

A photo was taken from the window looking outwards in order to consider the quality of what is observed from the living room (i.e., the view content [37]). In the case of several windows in the room, the closest window that framed the outside view from the position of monitoring was considered. The photograph was taken with a Google Pixel 3a phone in a position accessible to the researcher and able to frame the entire aperture. As detailed in section 2.6, the reference framework used is the one developed by Ko et al. to assess the quality of the window view, and which is based on the analysis of view content, accessibility and clarity [37]. In the present study, the photograph was not taken in a standard position as the objective was not to evaluate the overall quality of the window view but only its content, given the main focus on acoustics. Moreover, there is limited time available during measurement sessions, and it is often also impossible to define a "typical" position of the occupant in the living room.

2.6. Data analysis

2.6.1. Affective response

Perceived affective responses were coded from 1 (strongly disagree) to 5 (strongly agree) and transformed into a couple of coordinates in the 'comfort' and 'content' dimensions ranging from −1 to +1, by applying the procedure described in the ISO/TS 12913-3 [17] to the attributes derived from [16], as detailed in [23]:

$$Comfort = [(c - a) + \cos 45^{\circ} \bullet (pc - iu) + \cos 45^{\circ} \bullet (en - d)] \frac{1}{4 + \sqrt{32}}$$

$$Content = [(f - em) + \cos 45^{\circ} \bullet (iu - pc) + \cos 45^{\circ} \bullet (en - d)] \frac{1}{4 + \sqrt{32}}$$

Where *a* is annoying, *c* is comfortable, *d* is detached, *em* is empty, *en* is engaging, *f* is full of content, *iu* is intrusive - uncontrolled, and *pc* is private, controlled.

2.6.2. View content analysis

The quality of visual features seen in the window view (view content, $V_{content}$) was calculated from photographs taken from living rooms (see 2.5.3), according to the framework proposed by Ko et al. [37]. View content is defined as "the sum of the visual features seen in the window view, for example, natural or urban features or the sky" [37]. View content takes a value ranging from 0 (insufficient) to 1 (excellent), depending on the available number of view layers (i.e., sky, landscape, and ground), the depth of external content (i.e., the median distance between the closest and farthest identified objects from the window), the presence of dynamic and natural features in the window view. An example of window views with low and high view content is provided in Fig. 3.

Higher content scores are obtained in the presence of more horizontal layers seen from the window, greater depth of landscape, distant dynamic features, and higher access to nature. The view content score was derived by two authors from observations of the photographs from which the information necessary for scoring was derived (e.g., presence of a certain layer, content distance estimation, percentage of natural feature estimation), following the procedure described in [37]. In the case of discordant ratings by the two evaluators, a secondary collegial discussion was held until consensus was found.

2.6.3. Binaural recordings

Five-minute recording excerpts were selected. In three cases it was necessary to reduce the length of the excerpt to 1 min and in one case to 3 min due to disruptions during recording. ArtemiS SUITE v.10 was used to calculate a set of acoustic and psychoacoustic indicators, related to:

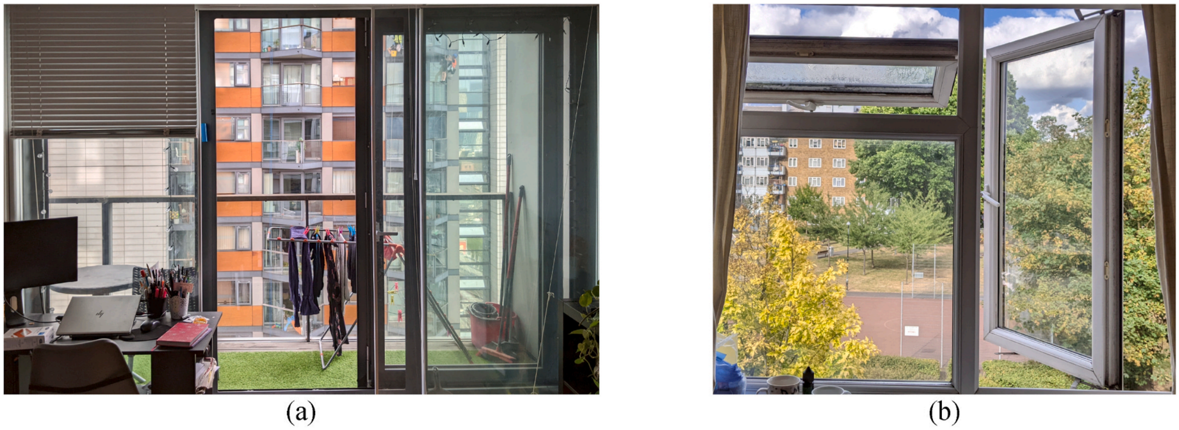

Fig. 3. Examples of window views with a) low view content ($V_{content}$ = 0.125) and b) high view content ($V_{content}$ = 1).

- overall loudness: A-weighted and C-weighted equivalent continuous sound pressure level ($L_{Aeq,5min}$, $L_{Ceq,5min}$); A-weighted sound pressure level measured with a fast time weighting, exceeded 5% ($L_{AF5,5min}$) and 95% of the time ($L_{AF95,5min}$); averaged loudness ($N_{average}$) and root mean cubed loudness (N_{rmc}); loudness exceeded 5% and 95% of the time (N_5, N_{95}) calculated according to Ref. [38] (diffuse soundfield)
- variation over time: 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}); loudness variability (N_5/N_{95}); fluctuation strength exceeded 10% and 50% of the time (FS_{10}, FS_{50}, 1/1 Bark resolution), roughness (ECMA-418-2, 1st edition) exceeded 10% and 50% of the time (R_{10}, R_{50}), relative approach (RA, 1/12 octave, no spectral weighting, 5 ms time weighting, regression method, time pattern)
- spectral content of sound: difference between C and A-weighted sound pressure level (L_{Ceq}-L_{Aeq}, hereinafter L_C-L_A), averaged sharpness ($S_{average}$, aures method with ISO 532-1 loudness method, diffuse field) and sharpness exceeded 5% and 95% of the time (S_5, S_{95})
- interference with speech transmission and intelligibility: articulation index (AI, 6th order filter method, 300 ms time constant), averaged and root mean squared Speech Intelligibility Index ($SII_{average}$, SII_{rms}, 1/3 octave bands, 300 ms time constant, standard speech spectrum with normal vocal effort at 1 m distance), averaged and root mean squared Speech Interference Level ($SIL_{average}$, SIL_{rms}, 500-4k Hz, slow time weighting)
- tonality (T, ECMA-74, 17th/ECMA-418-2, 1st, 20-20k Hz)
- impulsiveness (I, hearing model).

Binaural measurements provide two signals representing the left and right ears of a listener. Therefore, acoustic parameters are calculated separately for both ears. For all metrics considered except for AI and SII (which are expressed as percentages), the higher value of left and right metric values was used as the single representative value of the overall experience. In the case of AI and SII, the average of left and right metric values was considered.

2.6.4. *Statistical analysis*

Mann-Whitney U tests and Wilcoxon signed-rank test were used to test differences between independent groups (i.e., MV vs NV) and paired observations (appropriateness to home working vs. relaxation), respectively. Associations were investigated through the Spearman's rank-order correlation. Analyses were run in IBM SPSS Statistics version 27.

Shrinkage (or regularization) methods have been used to model the effect of perceptual, psychoacoustic, contextual and individual variables on comfort and content dimensions. Indeed, ordinary least squares (OLS) methods (i.e., standard linear models) perform poorly in the case of datasets with a large number of variables relative to the sample size and potentially a high correlation among them. Three models were compared: ridge, lasso and elastic net [39,40]. Ridge regression shrinks the regression coefficients so that independent variables with a smaller contribution to the dependent variable have coefficients close to zero (but never exactly zero). The narrowing of the coefficients is achieved by penalizing the regression model with a shrinkage penalty term, which is the sum of the squared coefficients. The size of the penalty can be fine-tuned using the tuning parameter λ. Lasso (Least Absolute Shrinkage and Selection Operator) shrinks the regression coefficients with a shrinkage penalty term, which forces some of the coefficient estimates to be exactly equal to zero when the tuning parameter λ is sufficiently large, thus performing also variable selection. Elastic Net combines the penalties of ridge regression and lasso to overcome both disadvantages, thus effectively shrinking coefficients like in ridge regression, while yielding to sparse models like in lasso regression. The best model among the three was selected as the one that leads to the lowest average test error (Root mean square error, RMSE) when splitting the sample into a training set (80%) and a test set (20%) 10 times, and performing the tuning of λ on the training set for each model via 10-fold cross-validation. In the case of variable selection (e.g., when a lasso or elastic net model is chosen), the coefficient estimates from an OLS model on these variables are reported rather than the penalised (and therefore somewhat biased) values from lasso or elastic net. The analysis has been performed using the *glmnet* [41] and *caret* packages in R [42].

The prediction was carried out by considering two groups of predictor variables. A first model (M1) considers both perceptual variables (i.e., those linked to the occupant's perception of the environment) and physical variables (i.e, those linked to objectively measurable parameters of the physical environment). Since perceptual and person-related data are not usually available at the design stage, a second model (M2) considered only variables linked to the physical environment and building features. The list of variables included in the two models is detailed in Appendix B.

3. Results

Frequency distributions were computed and relative and absolute frequencies are provided in Table 1. Most of the participants lived in non-owned houses (either rented or not owned and not paying rent, e.g., partner's house), and in dwellings between 40 and 80 m^2, mainly apartments. The living rooms were most often on the ground floor and the dwellings occupied by two people in most of the cases.

The view from the window in the living room was mainly rated as good or very good. According to view content analysis (see 2.6.2), almost half of the homes had excellent view from their living room, while only one had poor view content. It should be noticed that there

Table 1
Frequency distributions of environmental and context-related variables.

Variables	Frequency	
	Relative	Absolute
Ownership status		
Owned	34.4%	21
Not owned	65.6%	40
Dwelling size		
Floor area ≤40 m^2 (430 ft^2)	13.1%	8
40 m^2 (430 ft^2) < Floor area ≤80 m^2 (861 ft^2)	60.7%	37
80 m^2 (861 ft^2) < Floor area ≤110 m^2 (1184 ft^2)	16.4%	10
Floor area >110 m^2 (1184 ft^2)	9.8%	6
Dwelling type		
Apartments	73.8%	45
Detached or semi-detached houses	26.2%	16
Floor		
Ground	26.2%	16
1st	23.0%	14
2nd	13.1%	8
3rd	4.9%	3
4th	11.5%	7
Others: 5th – 26th	21.3%	13
Number of people living at home		
1	26.2%	16
2	39.3%	24
3	11.5%	7
4	8.2%	5
5+	14.8%	9
Quality of the view from the window		
Good or very good	77.0%	47
Neither good, nor bad	19.8%	12
Bad or very bad	3.2%	2
$V_{content}$		
Excellent: $1 \leq V_{content} \leq 0.75$	49.2%	30
Good: $0.75 < V_{content} \leq 0.375$	44.3%	27
Suficient: $0.375 < V_{content} \leq 0.125$	4.9%	3
Poor: $V_{content} < 0.125$	1.6%	1
Satisfaction with the connection between the living room and the external nature?		
Very satisfied or satisfied	59.0%	36
Slightly satisfied, neither satisfied nor dissatisfied, slightly dissatisfied	32.8%	20
Dissatisfied or very dissatisfied	8.2%	5
Perceived air quality		
Very good or good	72.1%	44
Neither good, nor bad	24.6%	15
Bad or very bad	3.3%	2

was no statistically significant correlation between the perceived quality of the view from the window and the $V_{content}$ parameter, r_s (59) = 0.105, p = 0.419. The percentage of natural elements that occupy the visual scene (wf_{nature}, employed in the calculation of $V_{content}$ [37]) was included among the independent variables that are entered into the modelling of indoor soundscape dimensions. Also in this case, the correlation between wf_{nature} and the perception of the window view quality was not statistically significant, r_s (59) = 0.167, p = 0.197.

Almost 60% of participants were satisfied or very satisfied with the contact between the living room and the outdoors. According to a Mann-Whitney *U* test differences in perceived contact with external nature were not statistically significantly different between dwellings with MV (mean rank = 30.67) and NV (mean rank = 31.26), U = 450.0, with a test statistic equal to z = −0.135, and a p-value of p = 0.893. The air quality in the living room was perceived as good or very good by the majority of the participants.

The WHO-5 well-being index averaged 62.16 ± 15.54 (M ± SD), with higher values corresponding to a better psychological well-being. Noise sensitivity index scored on average 63.92 ± 20.01 (M ± SD), with higher scores denoting higher sensitivity to noise.

3.1. Indoor soundscape representation

Affective responses to the indoor acoustic environments are represented in the comfort-content perceptual space using the visualisation tools for the outdoor soundscape developed by Mitchell et al. [19]. All responses from the 61 flats are plotted, resulting in a scatter plot as depicted in Fig. 4a. In the figure, a heatmap of the bivariate distribution (with iso-density curves for each decile) is superimposed on the scatterplot, together with marginal distribution plots of comfort and content ratings. As it can be observed, the indoor soundscape in dwellings varies across the 4 quadrants but the perception in most flats is located along the axis of perceived privacy and control (2^{nd} and 4^{th} quadrants), with a central tendency to be rather comfortable (median: 0.28) and slightly empty (median: 0.04), that is, in the area of perceived privacy and control. This is clearer in Fig. 4b, where the indoor soundscape is represented by its 50^{th} percentile contour containing 50% of the responses.

3.2. Indoor soundscape for home working and relaxation

Acoustic environments were in most cases judged to be appropriate for both relaxation and working from home. Fig. 5 shows indoor soundscapes where data points have been grouped by the perceived appropriateness of the acoustic environment to home working (Fig. 5a) and relaxation (Fig. 5b) (3 categories: not at all & slightly; moderately; very & perfectly). A Wilcoxon signed-rank test was conducted to determine the effect of activity on appropriateness evaluation. The environment was judged significantly more appropriate for working from home (Mdn: 4) than for relaxation (Mdn: 3), with a test statistic equal to z = 1.983, and p-value of p = 0.047.

The appropriateness of the acoustic environment was positively correlated with comfort for both relaxation ($r_s = 0.69$, $p < 0.001$) and working from home ($r_s = 0.73$, $p < 0.001$) and negatively with content, both for relaxation (r_s = - 0.51, $p < 0.001$) and working from home ($r_s = -0.52$, $p < 0.001$).

3.3. Differences in the perceived and physical acoustic environment based on the ventilation strategy

Mann-Whitney U tests were run to determine if there were differences in the perception of sound dominance of specific sound sources, indoor soundscape dimensions, and psycho-acoustic parameters between dwellings with NV and MV. Details are provided in Table 2.

While the perceived dominance of traffic sound in dwellings with NV and MV was not statistically significantly different, other noises from outside (e.g., sirens, construction, industry, loading of goods), natural sounds, and sounds from humans outside were statistically significantly more dominant in homes with NV than in those with MV (see Table 2 and Fig. 6). As regards indoor sounds, the only statistically significant difference was in the perception of sounds from building services in the dwellings, with a higher dominance found in homes with MV than in those with NV. Dominance of sounds from other human beings at home, neighbours, and neighbours' building services were not statistically significantly different in dwellings with MV compared to those with NV (see Table 2).

The appropriateness of the acoustic environment to relaxation and to home working was not significantly different between the two types of ventilation (see Table 2).

The representation of the indoor soundscape through the 50^{th} percentile contour allows the comparison of the soundscape between dwellings with different ventilation strategies, as depicted in Fig. 7. Dwellings with MV are generally located in the pleasant hemispace and mainly perceived as private and under control. The median contour for homes with NV is wider and ranges from perceived annoyance to comfort, with a higher degree of content compared to dwellings with MV. Overall, results of the Mann-Whitney U tests show that difference in comfort is not significantly different between the two subsamples of dwellings, with a tendency for more comfortable acoustic environments in spaces with MV compared to those with NV ($mdn_{MV} = 0.350$; $mdn_{NV} = 0.155$, p = 0.105, see Table 2 and Fig. 8a). As regards the degree of saturation of the acoustic environment, content scores in naturally

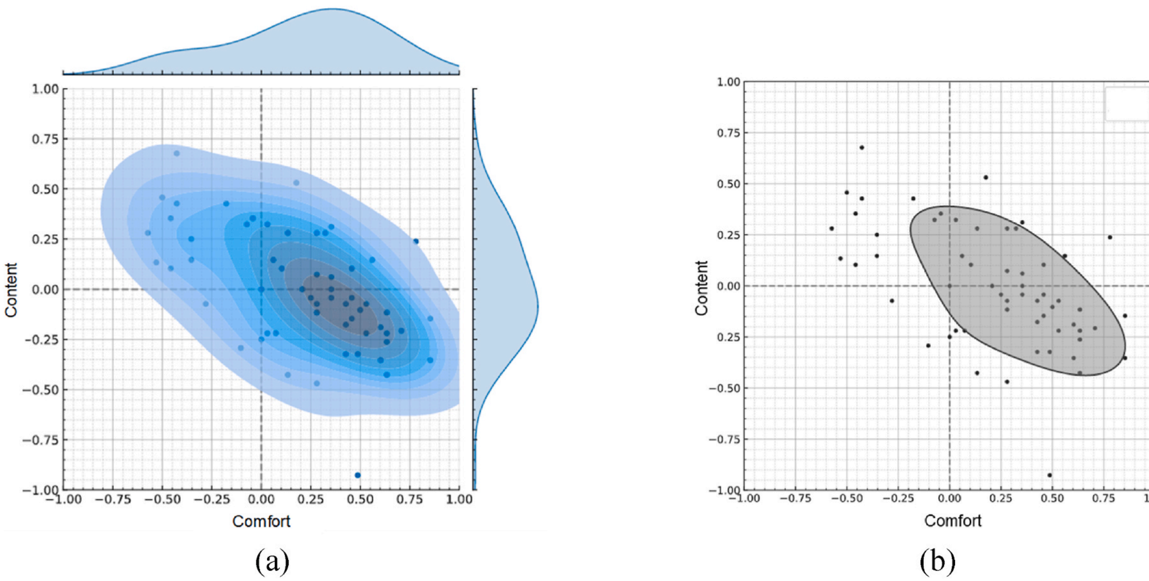

Fig. 4. Indoor soundscape representation. (a) Scatterplot of indoor soundscape perception with decile heatmap of the bivariate distribution and marginal distribution plot for comfort and content. (b) Scatter plot of individual assessments and 50th percentile contour.

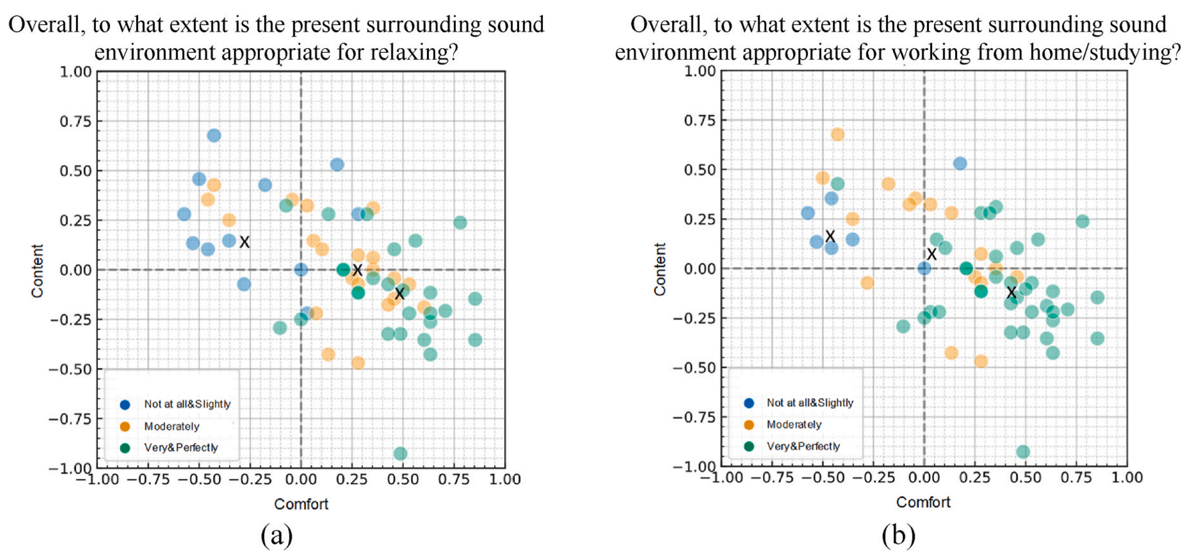

Fig. 5. Indoor soundscapes by soundscape appropriateness to (a) working and (b) relaxation. Crossed dots depict the centroids of the different groups.

ventilated buildings are significantly higher than in mechanically ventilated ones (mdn_{MV} = −0.070; mdn_{NV} = 0.000, p = 0.039, see Table 2 and Fig. 8b).

As far as the physical acoustic environment is concerned, differences between buildings with MV and NV are observed on the A-weighted equivalent sound pressure level (L_{Aeq}) and average loudness ($N_{average}$, N_{rmc}), peak sound pressure levels (L_{AF5}) and loudness (N_5), with significantly higher values in the case of open windows than in the case of closed windows and operating mechanical ventilation (see Table 2, Fig. 8c). Larger temporal variability of sound levels and loudness is found in NV dwellings than in MV ones, with significantly higher L_{A10}-L_{A90}, N_{10}–N_{90}, N_5/N_{95}, FS_{10}, and FS_{50} values (see Table 2, Fig. 8e). The spectral content is significantly different between the two types of ventilation, with higher low-frequency content (represented by L_C-L_A, see Fig. 8d) in mechanically ventilated dwellings than in those with NV. Intelligibility in buildings with MV, assessed through the average Speech Intelligibility Index, is better that in NV buildings, with slightly higher SII values. The noise component relevant to speech intelligibility, evaluated through the Speech Interference Level (average and rms), was significantly higher in dwellings with NV than in MV ones, indicating greater interference in speech reception in the former (see Table 2, Fig. 8f).

3.4. Indoor soundscape modelling

In the following, a comparison of the performance of the ridge, lasso and elastic net models in predicting comfort and content variables is presented, based on the calculation of the prediction error on the test set using models fitted on the training set. Once the best predictive model has been identified, the final regression model is refitted on the entire dataset with a λ-value chosen through cross-validation, and the coefficient estimates are examined on the selected variables.

3.4.1. Comfort

Table 3 reports the average RMSE values with a number of resamples (i.e., train-test splits) equal to 10. In the model considering the full set of

Table 2
Results of Mann-Whitney U tests for the test of median differences in the perceived dominance of sound sources, indoor soundscape dimensions, soundscape appropriateness and psycho-acoustic parameters. *** <0.001, ** <0.01, * <0.05.

Variable	U	z	mean rank MV	mean rank NV	median MV	median NV	p-value
Perceived dominance of sound sources							
Q1.1 Traffic noise from outside	381.5	−1.193	28.13	33.28	2	2	0.233
Q1.2 Other noise from outside	**282.5**	**−2.686**	**24.46**	**36.19**	**1**	**2**	**0.007****
Q1.3 Natural sounds from outside	**177.5**	**−4.335**	**20.57**	**39.28**	**1**	**2**	**<0.001*****
Q1.4 Sounds from human beings from outside	**224.5**	**−3.624**	**22.31**	**37.90**	**1**	**2**	**<0.001*****
Q1.5 Sounds from other human beings at home	528.0	1.135	33.56	28.97	1	1	0.256
Q1.6 Sounds from neighbours	386.5	−1.271	28.31	33.13	1	1	0.204
Q1.7 Sounds from building services at home	**595.5**	**2.158**	**36.06**	**26.99**	**2**	**1**	**0.031***
Q1.8 Sounds from building services of your neighbours	458.5	−0.011	30.98	31.01	1	1	0.991
Indoor soundscape dimensions							
Comfort	570.5	1.621	35.13	27.72	0.350	0.155	0.105
Content	**317.0**	**−2.064**	**25.74**	**35.18**	**−0.070**	**0.000**	**0.039***
Appropriateness							
To relaxation	559.5	1.510	28.04	34.72	4	3	0.131
To WFH	584.5	1.913	27.31	35.65	4	3	0.056
(Psycho)acoustic parameters							
L_{Aeq}	**284.5**	**−2.534**	**24.54**	**36.13**	**32.1**	**36.1**	**0.011***
L_{Ceq}	364.0	−1.379	27.48	33.79	45.6	48.5	0.168
L_{AF5}	**241.5**	**−3.158**	**22.94**	**37.40**	**34.2**	**40.5**	**0.002****
L_{AF95}	371.0	−1.278	27.74	33.59	29.6	30.9	0.201
$N_{average}$	**310.5**	**−2.156**	**25.50**	**35.37**	**1.43**	**1.90**	**0.031***
N_{rmc}	**290.5**	**−2.447**	**24.76**	**35.96**	**1.51**	**2.07**	**0.014***
N_5	**253.0**	**−2.991**	**23.37**	**37.06**	**1.96**	**2.99**	**0.003****
N_{95}	356.5	−1.488	27.20	34.01	1.08	1.33	0.137
L_{A10}-L_{A90}	**159.0**	**−4.356**	**19.89**	**39.82**	**2.6**	**6.4**	**<0.001*****
N_{10}–N_{90}	**131.5**	**−4.756**	**18.87**	**40.63**	**0.57**	**1.21**	**<0.001*****
N_5/N_{95}	**264.5**	**−2.826**	**23.80**	**36.72**	**1.27**	**1.40**	**0.005****
FS_{10}	**225.5**	**−3.391**	**22.35**	**37.87**	**0.0049**	**0.0074**	**0.001****
FS_{50}	**241.0**	**−3.168**	**22.93**	**37.41**	**0.0022**	**0.0030**	**0.002****
R_{10}	436.5	−0.327	30.17	31.66	0.1082	0.1018	0.744
R_{50}	515.0	0.813	33.07	29.35	0.0737	0.0577	0.416
RA	351.0	−1.568	27.00	34.18	2.43	2.88	0.117
L_C-L_A	**630.5**	**2.490**	**37.35**	**25.96**	**11.7**	**8.7**	**0.013***
$S_{average}$	0.977	−0.029	30.93	31.06	1.74	1.68	0.977
S_5	454.5	−0.065	30.83	31.13	2.04	2.06	0.948
S_{95}	464.5	0.080	31.20	30.84	1.37	1.38	0.936
AI	573.5	1.710	35.24	27.63	99.99	99.98	0.087
$SII_{average}$	**674.0**	**3.125**	**38.96**	**24.68**	**99.56**	**99.33**	**0.002****
SII_{rms}	541.0	1.336	34.04	28.59	99.58	99.58	0.182
$SIL_{average}$	**247.5**	**−3.071**	**23.17**	**37.22**	**22.0**	**26.3**	**0.002****
SIL_{rms}	**229.5**	**−3.332**	**22.50**	**37.75**	**23.0**	**27.9**	**0.001****
T	350.5	−1.576	26.98	34.19	0.0322	0.0395	0.115
I	489.0	0.437	32.11	30.12	0.40	0.40	0.662

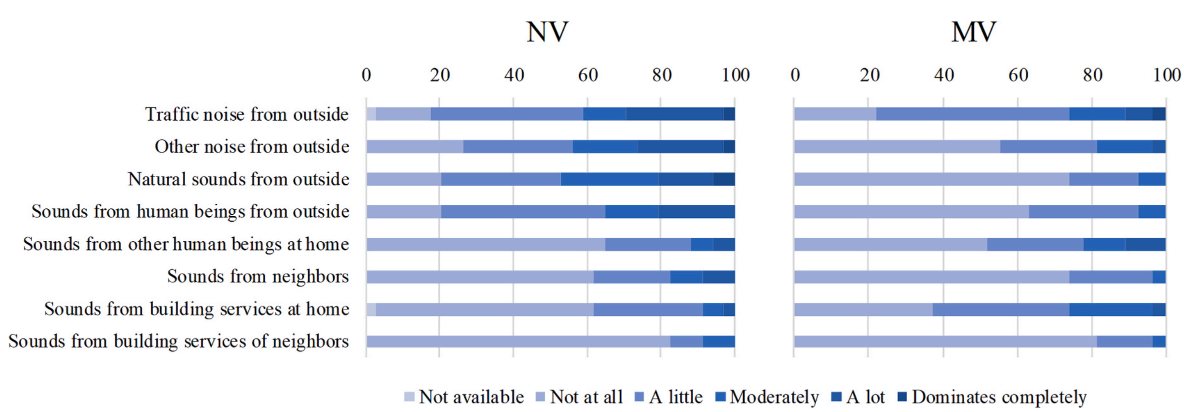

Fig. 6. Perceived dominance of different types of sounds in dwellings with natural ventilation (NV) and mechanical ventilation (MV).

perceptual, building-related, personal and environmental parameters (M1), the lasso model provides a lower root mean square error (RMSE) compared to the ridge and elastic net models. In the model excluding perceptual and person-related parameters (M2) (see Annex B), the best performance is given by the lasso and elastic net models. In the following, the model providing higher sparsity will be considered, i.e., the lasso model. A better performance of the M1 model can be observed (RMSE = 0.285), compared to the M2 model (RMSE = 0.339).

Coefficient estimates from an OLS model on the variables selected by the lasso model are provided in Table 4. As regards M1, the variables selected are related to the perceived acoustic environment (i.e., perceived sound dominance of specific sound types), sound level, ownership status and perceived air quality. In general, higher comfort is related to lower perceived dominance of traffic noise and other external

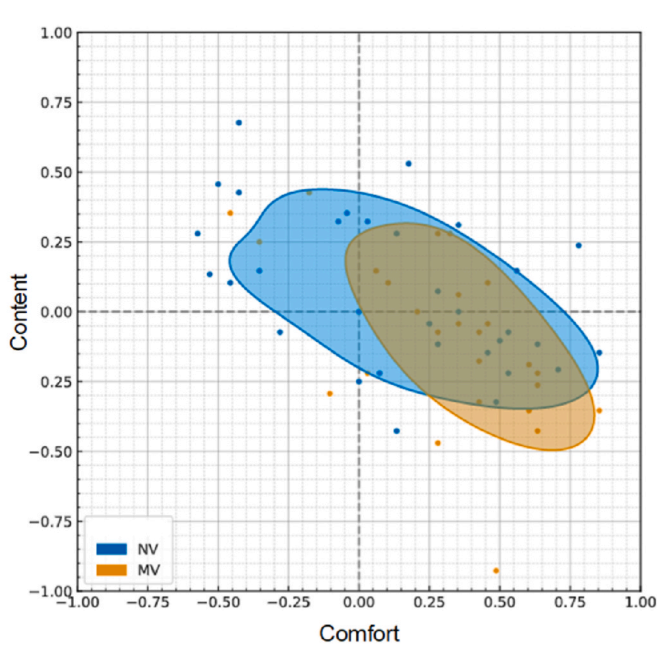

Fig. 7. Comparison of indoor soundscape assessments in dwellings with natural ventilation (NV) and mechanical ventilation (MV) using the 50th percentile contour.

noise (e.g., construction sites, sirens), better perceived air quality in the living room, and owning the dwelling in which one lives. As regards acoustic parameters, better acoustic comfort is associated with lower A and C-weighted equivalent sound pressure levels, higher speech intelligibility ($SII_{average}$) and lower Speech Interference Level values (SIL_{rms}, $SIL_{average}$).

Within the objective parameters considered in M2, the Speech Interference Level was the only parameter selected and lower comfort resulted from a lower $SIL_{average}$ (see Table 4).

A representation of the indoor soundscape as a function of the SIL parameter is shown in Fig. 9, where the threshold parameter is derived from a linear regression model of comfort as a function of $SIL_{average}$, comfort = 0,948–0,029 $SIL_{average}$, $F(1, 59) = 32.1323$, $p < 0.001$, $R^2_{adj} = 0.35$. Neutral comfort values correspond to a SIL equal to 32.7 dB.

As a further example, indoor soundscape representation as a function of the A-weighted equivalent sound pressure level - one of the most commonly used parameters in environmental and building acoustics - is given. The threshold was derived from a linear regression model where comfort is predicted as a function of the equivalent A-weighted sound pressure level L_{Aeq}, comfort = 1,130–0,026 L_{Aeq}, $F(1, 59) = 26.23$, $p < 0.001$, $R^2_{adj} = 0.30$. The L_{Aeq} threshold value for which comfort is neutral (i.e., comfort scores equal to zero) is equal to 43 dB(A). The indoor soundscape representation in the two samples of dwellings is depicted in Fig. 10.

3.4.2. Content

The lasso and elastic net model provided a lower average root mean square error (RMSE) compared to the ridge model (see Table 5) for both M1 and M2 models. In the following, the lasso model will be considered, as it provides higher sparsity. The model including all variables related to the individual, to the building, and to the physical and perceived environment performed better in content prediction (RMSE = 0.227) than the M2 model which excludes person-related and perceptual parameters (RMSE = 0.246).

Coefficient estimates are provided in Table 6. Variables selected by the lasso model for content prediction in M1 are the perceived dominance of outdoor traffic noise and the Speech Interference Level ($SIL_{average}$). Higher content scores result from higher dominance of traffic noise and higher SIL. As regards M2, which excludes perceptive and individual-related variables, the predictors selected by the lasso model are the floor level, sharpness S_5, the Speech Interference Level $SIL_{average}$, the air temperature and ventilation type. Notably, higher content results at higher floor levels, with lower sharpness S_5, higher $SIL_{average}$, higher air temperature and in naturally ventilated buildings compared to mechanically ventilated ones.

4. Discussion

The results are discussed below with reference to the four research questions of the study.

4.1. Indoor soundscape measurement and representation

The study presented a methodology for collecting data on the occupants' experience of the sound environment at home, and provided an example of data representation and analysis. The methodology extends the scope of traditional "socio-acoustic surveys", as per ISO/TS 15666:2021 [43], to assess building occupants' affective response to the sound environment, beyond noise-induced annoyance, and to link perceptual data with data from the physical environment. The methodologies employed in outdoor soundscape studies were applied in the post-occupancy evaluation (POE) of residential buildings in England, adopting perception models that take into account the specificities of the indoor residential context [16]. POEs are methodologies to systematically evaluate the performance of buildings based on user feedback and objective data regarding indoor environmental quality and energy performance [44]. POEs have a long tradition and continue to be a valuable tool included in e.g., building certification protocols. POEs have been questioned recently in relation to their being not only a diagnostic tool for failures in building design and operation from the users' perspective, but also for highlighting successes to be preserved and promoted [45]. If knowledge about causes of dissatisfaction can be a useful source of information for designers and building managers [46], an exclusive focus on dissatisfaction (e.g., noise annoyance) and related causes (e.g., noise sources) can lead to evaluations that are biased by the type of questions included in the survey. Moreover, this focus can leave grey areas in the characterization of occupants' experience of the built environment. As pointed out by Graham and colleagues in their retrospective evaluation of the 20-year application of the CBE's occupant survey [45], the target of PO surveys should change "from surviving to thriving" by accommodating questions about the functional, social and emotional preferences and expectations of users, the goals to be achieved according to the task at hand and the ability of the environment to supports this. Moreover, data on individual user traits (e.g., age, gender, sensitivity) can then help explain why participants give certain ratings. The described methodology of data collection and the use of the indoor soundscape circumplex are thus perfectly aligned with the current trend in research on indoor environmental quality, offering tools for assessing the perceived sound environment and its positive and negative outcomes, thus informing the design of environments that promote more than non-disturbing, but even supportive environments for the well-being and activities of the occupants [47–49].

The present study recognises the multi-sensory nature of humans' experience by measuring aspects related to domains other than acoustics, through measurements of the physical environment (i.e., thermal, and visual environment) and the occupant's perception of other sensory modalities (i.e., perceived indoor air quality). These data can be inserted as covariates to better explain the person-place relationship, and highlight possible cross-modal mechanisms [31,50].

The acoustic environment was investigated through both mono and binaural recordings, deriving acoustic and psychoacoustic parameters, where the latter address several basic auditory sensations, as recommended by the soundscape literature [18,51]. As further discussed in the following sessions, the results of the present study support the use of

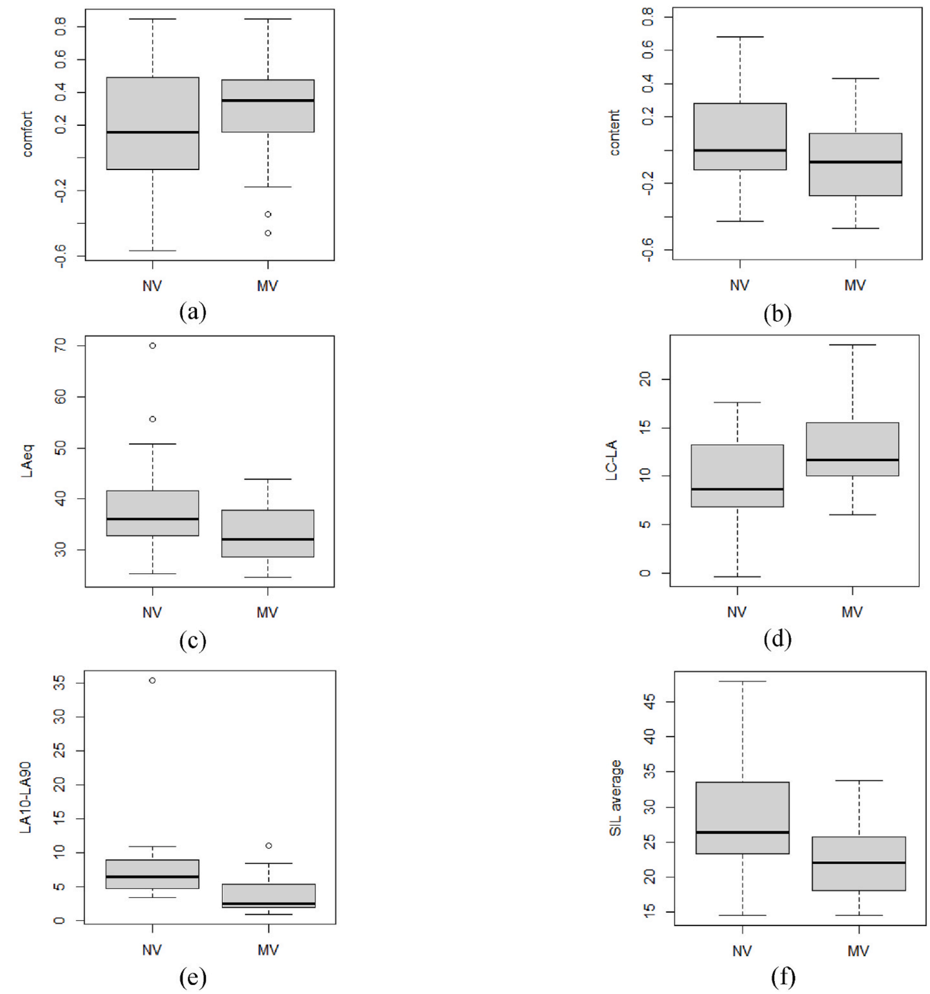

Fig. 8. Boxplots of (a) comfort scores, (b) content scores, (c) L_{Aeq}, (d) L_C-L_A, (e) L_{A10}-L_{A90}, (f) $SIL_{average}$ by type of ventilation strategy (naturally ventilated vs. mechanically ventilated dwellings).

Table 3
Comparison of the average RMSE and standard deviation between the ridge, lasso and elastic net models for comfort, with a number of resamples equal to 10. M1 includes the full set of objective and subjective parameters. M2 excludes perceptual and person-related variables.

	RMSE			
	M1 - Physical and perceptual parameters		M2- Physical parameters	
	M	SD	M	SD
Ridge	0.332	0.068	0.337	0.064
Lasso	**0.285**	0.056	**0.339**	0.066
Elastic Net	0.292	0.079	**0.339**	0.064

Table 4
Variables selected by the lasso model for the comfort variable and unstandardized coefficients from an ordinary least squares model. M1 includes the full set of objective and subjective parameters. M2 excludes perceptual and person-related variables.

Variable	Estimates (OLS)	
	M1	M2
Intercept	0.021	0.948
Q1.1 Perceived dominance of traffic noise from outside	−0.149	
Q1.2 Perceived dominance of other external sources	−0.045	
Q3 Ownership status [owned]	0.097	
Q10 Perceived air quality in the living room	0.108	
L_{Aeq}	−0.003	
L_{Ceq}	−0.004	
$SII_{average}$	0.006	
SIL_{rms}	−0.010	
$SIL_{average}$	−0.003	−0.029

psychoacoustics indices in explaining human acoustic perception, notably in relation to content scores through the parameter sharpness. Moreover, the convenience of representing the indoor soundscape in the circumplex space becomes evident (see Figs. 4, 5, 7, 9 and 10). This type of representation makes it possible to localize the perception of an individual or to compare the perception of different groups of users, based on specific control variables. The comparison is made not only in terms of noise disturbance, but on the basis of the two dimensions (comfort and content) that would underlie a gradient of emotional effects elicited by sound at home, from engagement, to disruption, to perceived privacy and control. In addition, the representational modalities introduced by Mitchell and colleagues [19] allow investigating the distribution of responses on comfort and content, including aspects related to dispersion and skewness, the general shape of the indoor soundscape (through, for example, the 50th percentile contour), and the degree of agreement in soundscape evaluations among participants. The results showed the immediacy of reading the effect of task and ventilation strategy on the indoor soundscape, as further discussed in sections 4.2 and 4.3.

Fig. 10 provided the representation of indoor soundscapes as a function of the A-weighted equivalent sound pressure level, which is one of the most commonly employed parameters measured and controlled in

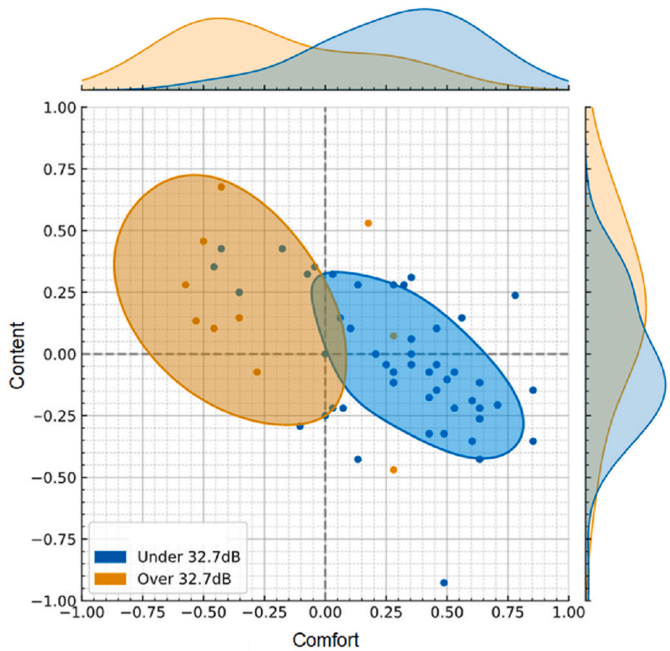

Fig. 9. Comparison for indoor soundscape perception at <32.7 dB $SIL_{average}$ and >32.7 dB.

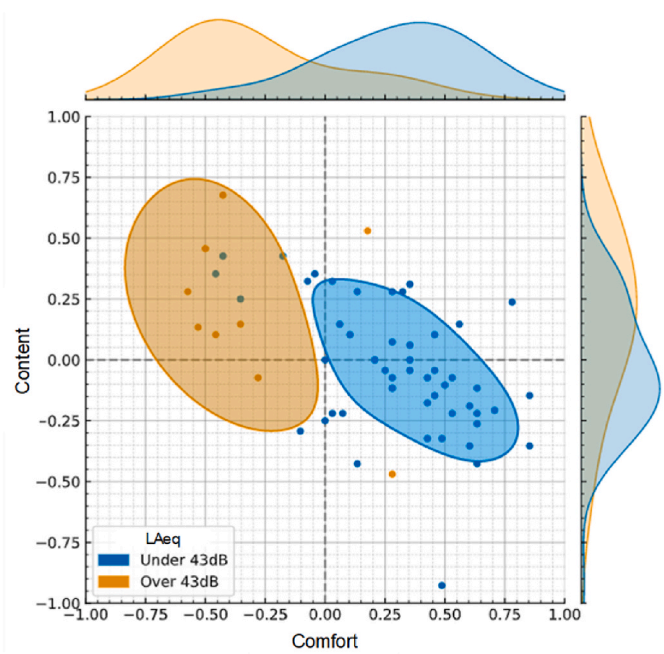

Fig. 10. Comparison for indoor soundscape perception at ≤43 dB L_{Aeq} and >43 dBA

environmental and building acoustics. Despite the limitations of the probabilistic representation due to a small number of cases in the high-noise-level sub-sample, two aspects can be highlighted. First, the representation according to the indoor soundscape circumplex allows effects to be visualized not only on a valence dimension, but also on content, i.e., the saturation of the environment with sound and events. This aspect, as discussed in the following sections, is crucial in understanding, for example, the effect of the sound field on humans depending on specific control variables, such as, ventilation strategy or the task at hand. Second, it can be observed that sound level is effective in

Table 5
Comparison of the average RMSE and standard deviation between the ridge, lasso and elastic net models for content, with a number of resamples equal to 10. M1 includes the full set of objective and subjective parameters. M2 excludes perceptual and person-related variables.

	RMSE			
	M1 - Physical and perceptual parameters		M2- Physical parameters	
	M	SD	M	SD
Ridge	0.237	0.044	0.243	0.047
Lasso	**0.227**	**0.050**	**0.246**	0.044
Elastic Net	**0.227**	**0.050**	**0.246**	0.044

Table 6
Variables selected by the lasso model for the content variable and unstandardized coefficients from an ordinary least squares model. M1 includes the full set of objective and subjective parameters. M2 excludes perceptual and person-related variables.

Variable	Estimates (OLS)	
	M1	M2
Intercept	−0.557	−0.526
Q1.1 Perceived dominance of traffic noise from outside	0.125	
Q8 Floor		0.011
S_5		−0.059
$SIL_{average}$	0.010	0.008
T_{air}		0.019
Vent_type [MV]		−0.127

discriminating against valence at relatively high levels compared to what is often recommended as target design requirement (i.e., most often 30–40 dB, for a review see [27]). At lower levels, factors other than sound level might come into play. For instance, it can be seen from Fig. 11 that the 50th percentile contour including dwellings at L_{Aeq} levels higher than 35 dB is split across the comfort space.

If applied to large samples of buildings and systematically introduced in POEs, the indoor soundscape framework could lead to a validation of new thresholds for sound pressure levels in buildings, on a perceptual basis, as previously discussed in an expert interview ([48], Fig. 3).

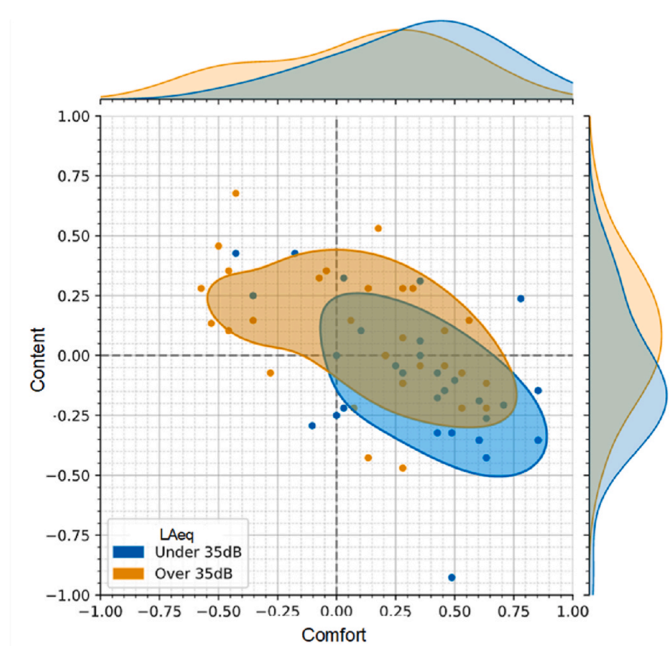

Fig. 11. Comparison for indoor soundscape perception at ≤35 dB L_{Aeq} and >35 dBA

4.2. Indoor soundscape for home working and relaxation

The perception of the acoustic environment generally depends on the task being performed and to which the evaluation refers [22,24]. The results reported in Par. 3.2 showed that acoustic environments were judged more appropriate for working from home than for relaxation activities. The results of an earlier online questionnaire administered in London during the COVID-19 pandemic showed opposite trends, with environments judged more favourably (i.e., more comfortable and appropriate) for relaxation than for working from home [23]. In the present study, environments appropriate to the two activities were comfortable and slightly empty, thus tending towards a condition of perceived privacy and comfort (see Fig. 5). In the study conducted during the lockdown [23] appropriate soundscapes for home-based working were located in the fourth quadrant (i.e., high comfort and low content) while environments ideal for relaxation were located in the positive acoustic comfort hemispace (i.e., on the first and fourth quadrants of the circumplex), and were either engaging or private and under control depending on their content. It should be noted that the results of the present survey, having taken place in the summer of 2022, could include the effects of the post-pandemic period on people's susceptibility. Furthermore, a difference could result from the different evaluation contexts in the two studies. Indeed, in the present study, the evaluations took place in rooms in which only the participant and the researcher were present, thus in a low-dynamic environment. The online questionnaire, on the other hand, could have been filled out in more varied conditions, e.g., in the presence of other persons, as evidenced by the greater number of cases in the first quadrant (i.e., engaging environments) compared to the present study when plotting the survey result in the indoor soundscape circumplex. Future research is called upon to carry out continuous monitoring to assess the physical and perceived sound environment both under conditions where the home is occupied by a single person, and in situations with multiple people, such as possible family members or outside visitors, and during the night-time period, thus populating a database with a greater variety of soundscapes in the four quadrants of the indoor soundscape circumplex and providing a useful reference for the development of predictive indoor soundscape models [12,48].

4.3. Difference in indoor soundscapes based on the ventilation strategy

In naturally ventilated buildings, where the assessment was carried out with the windows open, the perception of external sounds was generally stronger while the perception of noise from building services was significantly weaker than in mechanically ventilated buildings, where the monitoring was performed with the windows closed and the ventilation system running (see Fig. 6 and Table 2). Counterintuitively, the perception of dominance of road traffic noise was not significantly different between the two sub-samples of buildings. However, the appropriateness of the acoustic environment to relaxation and work from home activities was not significantly different according to the type of ventilation, nor was comfort. On the other hand, content was lower in spaces with MV than in those with NV, in keeping with findings from a previous London study carried out during the pandemic [10]: window opening in fact connects the indoor environment with the outdoors, leading to a greater saturation of internal spaces. This is accompanied by higher loudness, greater temporal fluctuation and variability of noise levels, and lower speech intelligibility in homes with NV compared to those with MV (see Table 2). On the other hand, the low-frequency content is higher in the case of mechanically ventilated buildings, most likely due to the low-frequency components of the ventilation systems and the selective attenuation of the closed façade components at higher frequency ranges.

By plotting the 50th percentile contours related to the two types of ventilation strategies, it can be noticed that the general shape of the indoor soundscapes in dwellings with MV is almost entirely in the positive comfort half-space (see Fig. 7). The general shape for buildings with NV is wider and crosses regions of comfort and discomfort, with higher content compared to spaces with MV, as evidenced by its upward placement relative to the contour for mechanical ventilation. This indicates that the indoor soundscape in naturally ventilated buildings tends to be more vulnerable. Depending on the outdoor urban context (e.g., traffic noise), the indoor soundscape may be comfortable, engaging or private and under control, but even strongly intrusive. The results of comfort and content modelling, further discussed in the following section, show that the indoor soundscape is mainly related to the increased perception of traffic noise and the noise component which interferes with speech intelligibility. According to the present study, NV influences acoustic comfort as a function of transmitted sound and related noise levels and not to other factors related to the ventilation strategy *per se* (e.g., availability of control, sense of draught). Since the ventilation strategy is not selected as a predictor variable of comfort (see Table 4), the results of the present study do not currently support the adaptive acoustic comfort hypothesis.

However, two limitations in the data collected should be considered.

The first concerns the sample size. Although the number of dwellings is considerable in relation to the difficulty of accessing private homes, the number of variables involved would require a large sample of buildings in which to replicate the methodology presented here in order to reach conclusive results.

The second aspect concerns the actual degree of understanding and correct use of mechanical ventilation systems by the occupants of buildings equipped with MV systems. Although the investigation of this issue was not among the objectives of the study, in the course of the research, it became apparent that most of the occupants living in dwellings with MV were either i) unaware that they had a mechanical ventilation system installed in their homes, or preferred to rely on windows opening due, for instance, to a ii) lack of understanding of the reasons behind the use of MV, iii) difficulty of use, iv) concern about bill expenses related to the operation of the system, and v) ventilation-related noise. Indeed, when accessing homes with mechanical ventilation, in almost all cases the participants had their windows open, despite the MV system in operation. It is argued that the fact of closing the window with the ventilation system on during the short monitoring period would not be sufficient to represent the actual acoustic perception of occupants who are accustomed to relying on MV alone. In most of the cases, participants living in MV dwellings would rather be accustomed to using their homes as traditionally done in houses with NV, where air exchange occurs through the opening of windows. Therefore, the selected sample of buildings would not be suitable to actually test the hypothesis of adaptive acoustic comfort because behavioural and perceptual patterns that are assumed in people living in buildings with MV (e.g., different degree of environmental control, different acoustic tolerability) would not be present, due to the use of buildings and building systems in a manner that deviates from the design intentions. This could be one of the reasons why the type of ventilation does not appear in this study among the variables influencing acoustic comfort (see Table 4). Observations on the operation of buildings with MV lead to emphasizing the importance of behavioural studies and user-centered design of building services on one side, and proper occupant training and guidance on the other, so that design efforts do not remain in vain and resulting in a performance gap on both energy consumption and user satisfaction between building design and operation [52]. The literature has already shown limitations in the acceptance and effective use by occupants of MV due to inadequate handover, training and understanding on the rationale of MV, and on how to use, operate and control the system [53–56]. Future large-scale studies aimed at further investigating adaptive acoustic comfort opportunities in residential buildings will need to ascertain the actual use of buildings according to the design intent in order to collect data from people who are actually tuned in to that ventilation strategy.

4.4. Factors influencing indoor soundscapes

The comfort and content modelling led to the identification of predictor variables for the two perceptual dimensions. In both cases there is evidence of better performance by models that combine perceptual (e.g., perceived dominance of sound types and air quality) and individual-related variables (e.g., noise sensitivity, age, gender) with objective variables related to the physical environment (e.g., noise levels and psychoacoustic parameters) and context (e.g., home ownership) than by models that exclude individual and perceptual variables (see Tables 3 and 5). Comfort is mainly related to perceived dominance of external noise (i.e., traffic noise, sirens, construction, industry) and is lower as the sound level increases (L_{Aeq}, L_{Ceq}), particularly with regard to energy content interfering with speech intelligibility ($SII_{average}$, SIL_{rms}, $SIL_{average}$). Interestingly, comfort is greater in owned homes than in rented ones. This variable is known to be influential on the indoor soundscape, although the evidence on the direction of the effects based on ownership status is inconclusive [24,57]. Furthermore, the results point to a cross-modal effect of perceived air quality on acoustic comfort: the perception of better air quality corresponds to greater acoustic comfort. Previous reviews on combined and cross-modal effects have shown, in the small number of studies that have addressed the two domains together, no effect in air pollution on noise acceptability or a small effect of odour on noise perception [30,31]. In school settings, Bluyssen and colleagues found a correlation between noise and odour ratings [58]. It must be emphasised, however, that in the present study we are considering the perception of air quality, an aspect that may not necessarily be related to the actual concentration of pollutants in the air and rather to other perceptual and environmental parameters (e.g., temperature, relative humidity [59]) or to socio-personal factors (e.g., occupation and tenure status [60]). In future field studies, it will be important to further investigate this result, assessing whether the relationship with acoustic comfort persists when measuring the concentration of air pollutants, alongside the perceived indoor air quality. In contrast, no effects related to temperature, the perceived connection with the external environment, and the quality of the view from the window on the acoustic comfort were shown.

In the model that excludes perceptual and individual parameters, and thus considers only objective parameters that can be controlled at the design stage, the Speech Interference Level parameter is selected by the lasso model as a comfort predictor. The SIL simply provides the arithmetic mean of the unweighted sound pressure level in octave bands considered to be relevant for intelligibility (500 Hz–4 kHz). As shown in Fig. 9, the parameter at this threshold is able to effectively discriminate indoor soundscapes on the basis of valence (i.e., negative vs positive comfort). It is pointed out that the SIL only considers the noise component in the calculation, but not the speech signal or reverberation characteristics of the environment. Other parameters, such as the Speech Transmission Index [61], lead to a more comprehensive characterization of the influence of the acoustic environment on speech perception, although their measurement is more onerous. Overall, the results highlight how parameters related to speech perception can play an important role in characterizing the indoor soundscape.

As regards content prediction, according to the lasso model M1, a higher saturation of the sound environment is related to greater perception of traffic noise dominance and larger SIL values (Table 6). Therefore, the content dimension is again associated with a variable related to the perception of sound dominance of specific sound sources and a variable related to interference with speech intelligibility. In the model M2 based on physical variables alone, higher content is associated with lower sharpness S_5, higher Speech Interference Level $SIL_{average}$ and natural ventilation. In absence of perceptual variables, the ventilation strategy therefore represents an influential factor in predicting content scores, with higher saturation derived by window opening. A cross-modal effect of the air temperature on content scores is highlighted, with higher perceived saturation at higher temperatures. While previous literature has shown in some cases cross-modal effects of the thermal environment on variables related to acoustic comfort (e.g., annoyance, satisfaction), albeit without a consensus [31], the present results suggest an effect of the thermal environment on the content dimension. No cross-modal effects from other sensory modalities (e.g. perception of air quality or view from the window) on content are reported. Counterintuitively, all else equal, higher content corresponds to higher floors. Future large-scale or laboratory studies focusing on specific variables may help to confirm these associations and understand the mechanisms underlying these influences.

Overall, indoor soundscape is strongly related to the perception of traffic noise, window opening, and sound pressure level, particularly regarding the energy content of interference in speech perception, which are all factors that lead to reduced comfort and increased saturation of the environment. Moreover, psychoacoustic parameters (i.e., sharpness), aspects related to contextual and building-related factors (i.e., ownership status and floor level) and cross-modal effects from other sensory modalities (i.e., perceived air quality and air temperature) further impact on indoor soundscapes. Although not included as an explicit variable in the present study, the presence of a quiet area overlooked by the dwelling -i.e., with low perceived traffic noise and low noise levels - would be crucial, in line with the findings derived from the structural equation modelling of the online survey data in London during the pandemic [10]. Indeed, the presence of a quiet side in the dwelling was associated with greater comfort in remote working and relaxation and reduced content during relaxation [10]. Furthermore, in the previous study [10], an explicit beneficial effect of the perception of natural sounds on comfort was highlighted, which does not appear in the present investigation. In fact, no positive effects on acoustic perception of indoor built environments related to specific types of sounds can be observed in the investigated models. Similarly, in the virtual reality study by Shin et al. [62], it was found that the effect of sounds and smells related to the simulation of window opening had no effect in terms of restoration. In the previous laboratory listening test by Torresin et al. indoor music, natural sounds transmitted by open windows and even sounds of an anthropogenic nature from the outdoors (e.g., voices) could provide ameliorative effects on the indoor soundscape. The results of the thematic analysis of the open-ended questions included in the London survey during the COVID-19 pandemic indicate that music and natural sounds are among the most desired sounds, along with quietness, in an ideal soundscape, with differences depending on the activity [22]. Future studies should investigate indoor soundscapes across a variety of urban and natural contexts in order to ascertain any positive and negative contributions of other types of sounds beyond the urban traffic that prevails in highly urbanised contexts such as London.

5. Conclusions

The present study reports the results of a socio-acoustic survey and monitoring campaign carried out in living rooms of 61 dwellings in England in which data was collected on the physical and perceived acoustic environment, thermal environment and quality of the view from the window, perceived air quality, building and urban context, demographic and individual traits. The study focused on two sub-samples of buildings with different ventilation strategies: in those with natural ventilation the assessment was carried out with the windows open, in those with mechanical ventilation the assessment was made with the windows closed and the system in operation. With reference to the four main research questions that guided the study, the following main outcomes can be highlighted:

- The collection and representation of soundscape data on the indoor soundscape circumplex defined by the comfort and content dimensions proved to be effective in comprehensively representing the perception of individuals and groups of people, based on specific control variables, thus going beyond annoyance-based assessments and highlighting possible positive perceptual outcomes provided by the sound environment.

- Acoustic environments in living rooms were judged more appropriate for working from home than for relaxation. Acoustic appropriateness for working from home and relaxation is characterised by high comfort and low content, and thus tend towards a perception of privacy and control.
- In naturally ventilated environments, outdoor-generated sounds are generally perceived as more dominant, and sound pressure levels and their variability over time are greater. In mechanically ventilated dwellings, sound from building services is perceived as more dominant compared to dwellings with NV, and the low-frequency content of sound and the speech intelligibility are greater. This leads to significantly higher content in buildings with NV. However, the appropriateness of the sound environment to home working and relaxation is not significantly different between the two types of ventilation, as is comfort. In general, indoor soundscapes in dwellings with MV are mainly perceived as comfortable, i.e., the 50^{th} percentile contour in the circumplex space lies in the positive half-space of acoustic comfort. Indoor soundscapes in buildings with NV are characterized by greater vulnerability, crossing regions of positive and negative comfort in the circumplex space, likewise depending on the quality of the outdoor acoustic environment.
- The comfort model (lasso) showed that greater comfort derives from lower perceived dominance of outside traffic and other external noises (e.g., sirens and industry), better perceived air quality in the living room, being owner of the dwelling, being exposed to lower sound pressure levels (L_{Aeq}, L_{Ceq}), especially in the energy component interfering with speech intelligibility (SIL_{rms}, $SIL_{average}$), and from higher intelligibility ($SII_{average}$). By excluding perceptual and individual-related variables that are not usually available at the design stage, the speech interference level (SIL) is selected as a predictor of comfort, with a threshold value for comfort resulting from a SIL = 32.7 dB. The content model (lasso) showed that greater saturation of the environment results from greater perceived dominance of outdoor traffic and greater SIL. According to the model based on only objective variables, higher content is related to natural ventilation, lower sharpness S_5, higher SIL, warmer environments, and higher floor levels. No cross-modal effect of the quality of window view on indoor soundscapes is reported. Both for comfort and content, models that include perceptual and individual parameters outperform.

The results of the present study do not detect an effect of ventilation on acoustic comfort *per se*, related, for example, to a different tolerability, availability of control, and environmental co-benefits related to the ventilation strategy. However, it should be noticed that the usage patterns of the two subsamples of buildings were actually similar, in that in most cases occupants who lived in buildings with MV were either unaware, insufficiently trained or unsatisfied with the ventilation strategy, and typically ventilated their homes in a traditional way (i.e., by opening windows). The results of the study support the use of binaural measurements and employment of psychoacoustic parameters in the prediction of acoustic perception in residential buildings (i.e., the effect of sharpness on content perception), while emphasizing the importance of collecting multi-domain data on the environment in its totality (physical or perceived) to be used as important covariates in explaining people-place relationships and to highlight cross-modal effects. As the present study is based on right-here-right-now assessments and measurements, future campaigns should be conducted on long-term basis, through an objective and perceptual characterization of all the environmental domains.

Overall, the study provides a reference on acoustic and psychoacoustic values measured in residential buildings with different ventilation strategy, and provides a measurement methodology that can be adapted and replicated on a large scale to redefine acoustic requirements towards the design of residential buildings on a perceptual basis.

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CRediT authorship contribution statement

Simone Torresin: Writing – review & editing, Writing – original draft, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Francesco Aletta:** Writing – review & editing, Supervision, Conceptualization. **Tin Oberman:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Veronica Vinciotti:** Writing – review & editing, Formal analysis. **Rossano Albatici:** Writing – review & editing, Supervision. **Jian Kang:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

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

Simone Torresin reports financial support was provided by Autonomous Province of Bolzano - South Tyrol.

Data availability

Data will be made available on request.

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Appendix A. Questionnaire excerpt

ID	Question	Scale	Label
Q1	*To what extent do you presently hear the following types of sounds? Please tick off one response alternative for type of sound. Q1.1 Traffic noise from outside* (e.g., *cars, buses, trains, airplanes); Q1.2 Other noise from outside* (e.g., *sirens, construction, industry, loading of goods); Q1.3 Natural sounds from outside* (e.g., *singing birds, flowing water, wind in vegetation); Q1.4 Sounds from human beings from outside* (e.g., *conversation, laughter, children at play, footsteps); Q1.5 Sounds from other human beings present in your house/accommodation* (e.g., *conversation, music, TV, laughter, children at play, footsteps); Q1.6 Sounds from neighbours* (e.g., *conversation, music, TV, laughter, children at play, footsteps); Q1.7 Sounds from building services of your house/*	Likert	Not available (0); Not at all (1) –Dominates completely (5)

(*continued on next page*)

(*continued*)

ID	Question	Scale	Label
	accommodation(e.g., heating, cooling, ventilation systems, toilet flushes); Q1.8 Sounds from building services of your neighbours/common areas (e.g., heating, cooling, ventilation systems, let flushes, lift)		
Q2	*For each of the 8 scales below, to what extent do you agree or disagree that the present surrounding sound environment is … Please tick off one response alternative per scale. Q2.1 Comfortable; Q2.2 Intrusive, uncontrolled; Q2.3 Engaging; Q2.4 Empty; Q2.5 Private, controlled; Q2.6 Annoying; Q2.7 Full of content; Q2.8 Detached*	Likert	Strongly disagree (1) – Strongly agree (5)
Q3	*Overall, to what extent is the present surrounding sound environment appropriate for relaxing?*	Likert	Not at all (1) – Perfectly (5)
Q4	*Overall, to what extent is the present surrounding sound environment appropriate for working from home/studying?*	Likert	Not at all (1) – Perfectly (5)
Q5	*As regards your house, what is your ownership status?*	-	Rent - not owned (also for student accommodation); Owned; Not owned but not paying rent (e.g., partner's house); Other
Q6	*What is the size of your house/accommodation?*	-	Floor area ≤40 m^2 (430 ft^2); 40 m^2 (430 ft^2) < Floor area ≤80 m^2 (861 ft^2); 80 m^2 (861 ft^2) < Floor area ≤110 m^2 (1184 ft^2); Floor area >110 m^2 (1184 ft^2)
Q7	*What type of house/accommodation do you live in?*	-	Detached single family; Semi-detached or terraced house; Apartment block; Other
Q8	*What floor is your living room on? (In case of a student accommodation this applies to the room you use as living room)*	Integer	[-2; 50]
Q9	*Including yourself, how many people live in your home/accommodation? In case of student accommodation, please refer to your "unit"*	-	1; 2; 3; 4; 5+
Q10	*How would you describe the view from the window present in your living room? (In case of a student accommodation this applies to the room you use as living room)*	Likert	Not applicable (window not present) (0); Very bad (1) – Very good (5)
Q11	*How satisfied are you with the connection between your living room and the external nature? (In case of a student accommodation this applies to the room you use as living room)*	Likert	Very dissatisfied (0) – Very satisfied (7)
Q12	*Overall, how would you describe the present air quality in your living room? (In case of a student accommodation this applies to the room you use as living room)*	Likert	Very bad (1) – Very good (5)
Q13	*Please state to what extent you disagree/agree with the following sentences: Q13.1 I am sensitive to noise; Q13.2 I find it difficult to relax in a place that's noisy; Q13.3 I get mad at people who make noise that keeps me from falling asleep or getting work done; Q13.4 I get annoyed when my neighbours are noisy; Q13.5 I get used to most noises without much difficulty*	Likert	Slider: Totally disagree (0) – Totally agree (100)
Q14	*Please indicate for each of the five statements which is closest to how you have been feeling over the last two weeks. Notice that higher numbers mean better well-being. Q14.1 I have felt cheerful and in good spirits; Q14.2 I have felt calm and relaxed; Q14.3 I have felt active and vigorous; Q14.4 I woke up feeling fresh and rested; Q14.*5 My daily life has *been filled with things that interest me*	Likert	All of the time (5) – At no time (0)
Q15	*How old are you?*	Integer	[18; 90]
Q16	*What is your sex? A question about gender identity will follow later on in the questionnaire*	–	female; male
Q17	*Is the gender you identify with the same as your sex registered at birth? This question is voluntary*	–	y/n

Appendix B. Variables included in comfort and content models (M1 and M2)

Model	Variables
M1	Q1.1 – Q1.8, Q5, Q6, Q7, Q8, Q9, Q10, Q11, Q12, age, sex, NS, WHO-5, L_{Aeq}, L_{Ceq}, L_C-L_A, L_{AF5}, L_{AF95}, L_{A10}-L_{A90}, N_5, N_{95}, $N_{average}$, N_{rmc}, N_5/N_{95}, N_{10}-N_{90}, S_5, $S_{average}$, S_{95}, T, R_{10}, R_{50}, F_{10}, F_{50}, I, RA, AI, SII_{rms}, $SII_{average}$, SIL_{rms}, $SIL_{average}$, T_{air}, wf_{nature}, $V_{content}$, Vent_type
M2	Q6, Q7, Q8, L_{Aeq}, L_{Ceq}, L_C-L_A, L_{AF5}, L_{AF95}, L_{A10}-L_{A90}, N_5, N_{95}, $N_{average}$, N_{rmc}, N_5/N_{95}, N_{10}-N_{90}, S_5, $S_{average}$, S_{95}, T, R_{10}, R_{50}, F_{10}, F_{50}, I, RA, AI, SII_{rms}, $SII_{average}$, SIL_{rms}, $SIL_{average}$, T_{air}, wf_{nature}, $V_{content}$, Vent_type

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