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Factors influencing window opening behavior and mechanical ventilation usage during summertime: A case study in UK dwellings

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ABSTRACT

The study presents findings of a data collection campaign conducted in 61 residential buildings in England during the summer of 2022, aiming to investigate the factors influencing 1) window usage, and 2) activation and deactivation of mechanical ventilation systems, and 3) the correlation between the residential soundscape, landscape, individual noise sensitivity, and the significance attributed to the external acoustic environment in determining window usage. The survey, covering 55 dwellings reliant on windows for ventilation, highlights that window opening is predominantly driven by perceived indoor air quality (PIAQ) and thermal comfort concerns. Conversely, the acoustic factor ranks first in prompting window closure, alongside considerations related to perceived cold, safety concerns, excessive drafts, and insect intrusion. Within the 6 dwellings utilizing manually controlled mechanical ventilation, ventilation needs emerges as the predominant factor triggering system activation, followed by considerations related to thermal comfort and PIAQ. Reasons for system deactivation primarily involve a preference for window opening, excessive drafts, and, secondarily, excessive noise or thermal discomfort, with participant-voiced concerns about operational costs. The significance attributed to the external acoustic environment in determining window usage is mainly independent of perceived sound sources, measured loudness, or soundscape content. However, higher acoustic comfort scores correlate with a greater willingness to open windows for an acoustic contact. Interestingly, noise sensitivity modulates the importance attached to the external acoustic context when interacting with the window (odds ratio: 1.04). The study underscores the need of incorporating noise sensitivity as a relevant individual factor in models simulating window closing behaviour.

1. Introduction

Understanding how building occupants interact with natural ventilation (e.g., windows) and mechanical ventilation systems is crucial due to its impact on indoor environmental quality and building energy consumption [1,2]. This interaction frequently places occupants in the challenging position of having to choose which aspects to prioritize (e.g., thermal comfort or acoustic comfort) when making decisions like opening a window or deactivating the mechanical ventilation system, with cascading effects on their health, well-being, and productivity. Moreover, the way people interact with ventilation-related interfaces can result in an energy performance gap between the building's design and actual operation due to unintended occupant behaviours (e.g., opening windows instead of relying on the mechanical ventilation).

Regarding interaction with mechanical ventilation systems, previous studies have often investigated reasons for disabling them, citing concerns about operational costs, discomfort due to drafts and noise, and a general lack of understanding about these systems [3]. Noise, in particular, is frequently implicated as a reason for disabling and turning off mechanical ventilation systems [4–7].

Factors driving window interaction are diverse and encompass psychological (e.g., thermal preference), physiological (e.g., age, gender), social (e.g., smoking habits, occupancy), physical environment-related (e.g., relative humidity, indoor and outdoor temperature, CO_2 levels, solar radiation, wind speed), and contextual aspects (e.g., apartment and room type, orientation, building service type, season, time of day, insect presence, safety and privacy concerns) [2,8–15]. Most studies have focused so far on the impact of environmental factors on window

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opening and closing behaviour, as they can easily be incorporated into predictive building energy models [9]. However, non-environmental factors play a significant role in understanding the complexity of human-building interactions and existing literature calls for more research in this domain [9]. Additionally, among the environmental factors influencing window interaction, the acoustic factor is underrepresented, as highlighted in the literature [8,12]. Acoustic monitoring is rarely conducted, and aspects of acoustic perception (e.g., participants' noise sensitivity) are often omitted from surveys assessing window opening behaviour [8].

Building upon these gaps in the existing research, the present study examines the drivers of interaction with natural and mechanical ventilation devices based on socio-acoustic monitoring conducted in the living room of 61 homes [16]. The study is conducted within the (climatic, acoustic, and socio-cultural) context of England, during summertime. The research questions are as follows.

- RQ1) What factors influence the opening and closing of windows?
- RQ2) What factors drive occupants to turn on and off ventilation systems?

Building on the detailed acoustic and psychoacoustic data gathered during the data collection campaign (see Section 2.4), we investigate whether behavioural drivers are dependent on sound-related environmental variables, personal sensitivity to noise, and the indoor soundscape (i.e., the physical acoustic environment as perceived by occupants in the context defined by the building [17,18]). Noise sensitivity is recognized as a key factor in determining noise annoyance, with individuals who are more noise-sensitive experiencing greater annoyance when exposed to particular noise sources [19–21]. In a prior study conducted during the COVID-19 pandemic, which involved individuals working from home, it was observed that noise sensitivity played a moderating role in the connection between the perceived prominence of certain noise sources (such as neighbour noise) and acoustic comfort and well-being [22,23]. Although noise sensitivity significantly impacts acoustic comfort, no prior research on window-opening modelling has explored and included its influence. Furthermore, it is important to consider the quality of the view from the window in studies concerning window opening behaviour, given the interactions with the auditory [24] and thermal sensory modalities [25]. Indeed, sensory modalities are not independent [26], with audio-visual interactions already reported in the literature [27] that can potentially influence the interaction with the window. Findings from an online survey conducted during the COVID-19 pandemic indicated that individuals in Italy who had a view of more vegetation from their windows were more likely to keep their windows open while working from home [28]. In order to control for this, a quantitative approach to defining the quality of a window view was adopted, an approach not previously employed in examining window operation. Therefore, by adopting a multi-domain perspective [29], the present study seeks to explore how acoustic-related factors influencing window and ventilation device operation correlate with individual noise sensitivity, acoustic and psychoacoustic parameters, the perception of specific sound sources and the visual outdoor environment (RQ3).

2. Methods

The study adopts a Convergent Multi-Methods Design, which combines multiple data collection types and analysis within the same framework [30]. Notably, it integrates survey data with objective environmental data, as described below. This design is particularly useful as it allows us to explore the complex relationship between environmental factors and human behavior from multiple perspectives, in line with the approach of data and methodological triangulation in soundscape studies [31].

2.1. Sample

Socio-acoustic surveys were conducted during the summer, between June 19th and October 12th, 2022, as a one-time assessment in the living rooms of 61 dwellings, including student accommodations, located in London (46), Lincolnshire (12), Greater London (2), Windsor (1), as depicted in Fig. 1. The study is exploratory in nature and relied on convenience sampling, which involves selecting participants who are readily accessible and willing to participate [32]. This method was chosen due to the practical challenges of recruiting participants from private homes, given the concerns residents have about hosting strangers. While convenience sampling does not aim for representativeness, it facilitates the collection of rich, detailed data under realistic conditions. For this purpose, we targeted around 30 homes per type of ventilation. Dwellings equipped with continuous mechanical ventilation and extraction systems were deemed eligible for the sub-sample. This eligibility was confirmed by the presence of an air intake/outtake in the living room ceiling, where occupants were asked to assess the soundscape. Out of the 61 involved dwellings, 34 had natural ventilation (NV), and 27 were equipped with mechanical ventilation (MV).

The study involved one participant per household, totaling 61 participants (31 men [49.2 %], 30 women [50.8 %]). All participants identified with the gender corresponding to their birth sex, and their ages ranged from 24 to 72 years (average age: 38.5, standard deviation: 12.5 years). Participants self-reported no hearing impairments and a good level of English proficiency. A token of appreciation in the form of a £10 voucher was offered to each participant for their time. The investigation followed the principles of informed consent. The study received approval through the UCL IEDE Ethics departmental procedure on April 28, 2022.

2.2. Procedure

The study conducted a single monitoring campaign within participants' residences, utilizing their living rooms or alternative relaxation spaces like bedrooms, or kitchens if a living room wasn't available (e.g., in student accommodations). The process commenced with the setup of measurement tools, including a sound level meter, a head-mounted microphone for binaural recordings, and a temperature data logger. Each participant was provided with a tablet for questionnaire administration. Prior to data collection, participants were briefed to switch off potential noise sources like electrical appliances and mobile phones and to maintain silence during the recording while completing the questionnaire.

For naturally ventilated residences, participants were instructed to open windows as they typically would for ventilation. In mechanically ventilated homes, assessments were conducted with windows shut and the ventilation system running. Following questionnaire completion and concurrent monitoring, the researcher captured a photograph from the living room window and dismantled the monitoring equipment. On average, each visit to a residence lasted approximately 40 min.

2.3. Questionnaire

Survey responses were collected using a touchscreen interface through the REDCap electronic data capture tools, which are hosted at University College London (UCL)) [33,34]. The questionnaire was structured into four main sections, each focusing on specific aspects: i) evaluation of the immediate sound environment in the living room during the survey; ii) assessment of the typical sound environment in the living room, referencing the month before the survey; iii) collection of housing context information; iv) gathering of demographic and personal characteristics. Only information pertinent to the present study is discussed here, while a more detailed description is available elsewhere [16].

Participants were tasked with evaluating the prominence of various

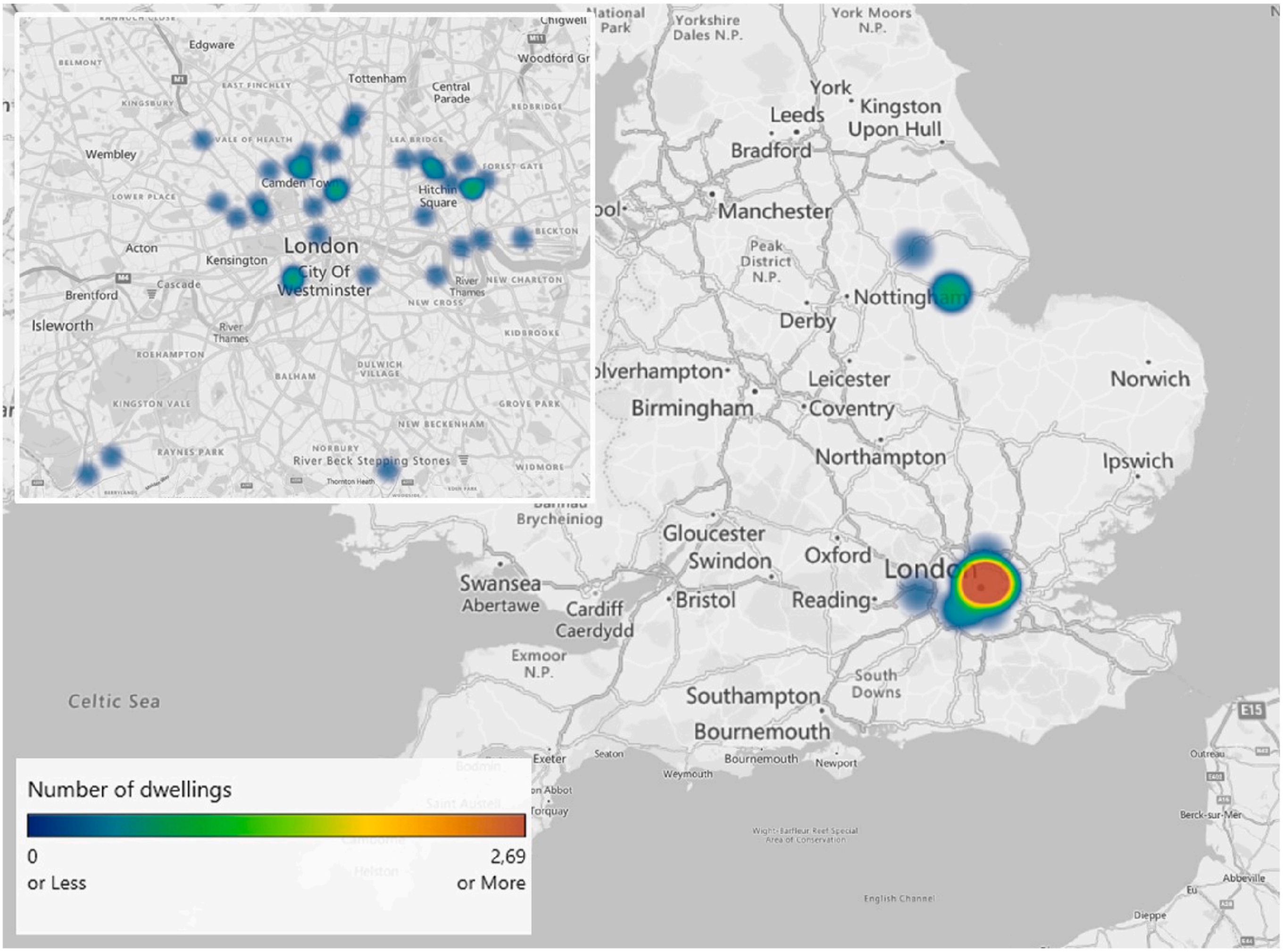

Fig. 1. – Heat map of surveyed dwellings in England, with a zoom on the London area (N: 61).

sound categories perceived in their living rooms over the previous month. This inquiry was adapted from ISO/TS 12913-2 (Method A) [35], one of the most commonly used methods in soundscape research [36]. Relevant indoor soundscape sources encompassed traffic noise, other external noises, natural sounds, people outside the building, other individuals within the home, neighbours, home building services, and neighbours' building services [22].

The perceived affective quality of the domestic soundscape was assessed by adapting questions from ISO/TS 12913-2 (Method A) [35] and utilizing the eight attributes derived in a prior study [17]. Ratings from these attributes were then condensed into two coordinates on the comfort and content axes, representing the primary perceptual dimensions in a bi-dimensional coordinate system underlying the affective response to the soundscape in residential living spaces (referred to as an indoor soundscape circumplex) [37]. Comfort and content scores are computed from ratings collected on the eight attributes (*a*: annoying, *c*: comfortable, *d*: detached, *em*: empty, *en*: engaging, *f*: full of content, *iu*: intrusive - uncontrolled, and *pc*: private, controlled), as:

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

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

The comfort dimension spans a continuum between comfort and annoyance, while the content dimension expresses the level of saturation of the environment with sounds and events. In the third section, participants were invited to describe the quality of the view from their living room window and their home ventilation strategies. Those who ventilated by opening windows were asked to rank the importance of various factors influencing their decision to open or close the windows, divided into two separate questions, each referring to the previous week. Participants also had the option to include additional factors using the "other" option.

For participants using a mechanical ventilation system, they were asked to specify the type of system (e.g., centralized or displaced) and the level of control they had over its operation. Respondents with manually operated ventilation systems were queried about the importance of different factors related to turning the system on and off.

In the final section, noise sensitivity was assessed using a shortened version of the Weinstein's Noise Sensitivity Scale [38,39]. Subjective psychological well-being was evaluated through the WHO-5 well-being index [40]. Demographic information, including age, sex, and gender, was also collected.

The questions and response options are listed in Appendix A in Supplementary Materials.

2.4. Environmental data

In addition to data regarding the "perceived" environment, measurements of the "physical" acoustic and visual environment were concurrently collected in each living room as the participants completed the questionnaire.

Background noise in the living room was recorded for 5 min in both monaural and binaural formats, with the window position aligned with the ventilation strategy. Throughout the questionnaire completion process, the researcher sat beside the participant, maintaining the same orientation, to ensure that the acoustic environment recorded closely matched what the participant experienced during the questionnaire. Binaural measurements enable the derivation of psychoacoustic parameters, which are essential for describing fundamental auditory sensations. These parameters are derived from the temporal and spectral structure of sound, providing insights that go beyond what can be gleaned from sound pressure levels alone [41].

A photograph was taken from the window to evaluate the quality of the view from the living room (i.e., the view content). A Google Pixel 3a phone was used to capture the photograph from a location accessible to the researcher, ensuring the entire view was framed. The assessment of window view content followed the framework introduced by Ko et al., which defines view content as the sum of the visual features visible through the window, encompassing both natural or urban features and the sky [42]. The view content score ranges from 0 (insufficient) to 1 (excellent). Further details on audio recordings and view content calculation are provided in Ref. [16].

2.5. Data analysis

Statistical analyses were run in IBM SPSS Statistics version 27. Frequency distributions were processed in order to explore categorical and ordinal variables. The Mann-Whitney *U* test was utilized to evaluate differences between two groups (e.g., difference in sound source dominance across ventilation type). Bonferroni correction was adopted in case of multiple comparisons. Two cumulative odds ordinal logistic regressions with proportional odds were run to determine the effect of perceived dominance of different sound sources, window view content, measured loudness, noise sensitivity, comfort and content scores on the importance attributed to sound and noise in determining, respectively, window opening and closing. In order to avoid multicollinearity issues, we opted for a single parameter representing ambient sound level. Specifically, we chose the loudness parameter over the equivalent continuous sound pressure level based on its stronger association with evaluations of acoustic comfort in prior research [17]. Moreover, indoor air temperature was not included in the model, for the sake of model parsimony and fit. In a previous study on the same dataset, temperature was not found to be influential for acoustic comfort [16]. Therefore, while it is expected that temperature affects window interaction, it is reasonable to assume that it does not influence the importance attributed to outdoor acoustic conditions in this interaction. The assumptions on proportional odds and absence of multicollinearity have been verified. The statistical significance threshold was set at 0.05.

3. Results

The perception of dominance of different sound sources with reference to the month before the questionnaire administration is depicted in Fig. 2, based on the ventilation type (i.e., natural and mechanical ventilation). A trend can be observed toward lower dominance of sounds from external sources (i.e., sirens, natural sounds, human noises) in mechanically ventilated buildings compared to naturally ventilated ones (Mann-Whitney, $p > 0.05$). Furthermore, there is a trend for greater dominance of noise from building services and noise from other people at home in mechanically ventilated buildings compared to naturally ventilated ones, although not substantiated by statistical significance. No differences in perceived sound dominance are observed in the perception of traffic noise and noises from neighbours.

Higher sound pressure levels and loudness [43] were observed in naturally ventilated buildings when measurements were conducted with windows open (median, Mdn L_{Aeq} = 36.1 dB, N_{avr} = 1.90 sone), in contrast to mechanically ventilated buildings where measurements were made with windows closed and the system in operation (Mdn L_{Aeq} = 32.1 dB, N_{avr} = 1.43). As regards the comfort scores with reference to the indoor soundscape circumplex space, higher comfort resulted in dwellings with MV ($Comfort_{MV}$ = 0.350), compared to those with NV ($Comfort_{NV}$ = 0.155). Moreover, naturally ventilated spaces were more saturated with sound events, resulting in higher content scores ($Content_{NV}$ = 0.000) compared to those with MV ($Content_{MV}$ = −0.070). The indoor air temperature averaged 24.1 ± 2.3 °C (mean ± standard deviation), ranging between 17.4 °C and 29.3 °C. The quality of window view from living rooms was good in most of the surveyed dwellings. 77 % of participants rated the view from the window as good or very good (N: 47), and an excellent window view content (i.e., $1 \leq V_{content} \leq 0.75$) was obtained in 49.2 % of cases. Variability of external conditions was ensured, with view content scores ranging from 0 to 1. A detailed description of the acoustic environments as well as of other environmental variables during the questionnaire administration and residential context is available in Ref. [16].

Fig. 2. Perceived dominance of different types of sounds in dwellings with natural ventilation (NV) and mechanical ventilation (MV) with reference to the month before the questionnaire was administered (N: 61).

Participants' noise sensitivity ranged from a minimum of 26 to a maximum of 100, with a median value of 63, with higher scores resulting in higher sensitivity to noise. Among the 61 homes involved in the study, 90.2 % of them relied on window opening for ventilation (N = 55). It's noteworthy that this practice was common even in homes equipped with mechanical ventilation systems (N = 21). As discussed in Ref. [16], many participants were either unaware of having a mechanical ventilation system at home, didn't understand its operation, or simply preferred using window opening for ventilation. 31.1 % used the mechanical ventilation system for ventilation (N = 19). Four dwellings had a centralized system serving the whole building (in case of apartment blocks), 12 dwellings had a centralized system dedicated to the housing unit, while 3 dwellings were equipped with a displaced ventilation system. The mechanical ventilation system was operated mainly automatically, accounting for 68.4 % of cases (N = 13). In 31.6 % of cases, the system was manually operated, meaning occupants decided when to turn it on or off (N = 6). Considering the small sample size of participants with a manually controlled mechanical ventilation system, research question 3 will only focus on the impact of both acoustic and non-acoustic factors on the parameters that guide window interaction, as described in Section 3.3.

3.1. Factors driving window opening and closing behaviour

Out of the 55 participants who indicated that they ventilate their living room by opening the windows, the primary reason for doing so is to ventilate the room (Mdn: 5, in a scale of importance from 1, "not at all important", to 5, "extremely important"), followed by feeling warm (Mdn: 4), the desire for a breeze (Mdn: 3), perceiving the environment as smelly (Mdn: 3), wanting to feel connected to the outside world (Mdn: 3), and, lastly, wishing to hear sounds from the outdoors (Mdn: 2). The distribution of importance ratings for the various window-opening factors is illustrated in Fig. 3. Among the other reasons for opening the window specified by the participants is the prevention of moisture buildup in the house.

The primary reason for closing the window is excessive noise from outside (Mdn: 4), followed by concerns about feeling cold (Mdn: 4), security (e.g., when leaving the home) (Mdn: 3), the presence of excessive drafts (Mdn: 3), the potential entry of insects (Mdn: 2), and the intention to save energy (e.g., when using air conditioning) (Mdn: 2). Fig. 4 illustrates the distribution of importance ratings for various window-closing factors. Another reason reported by the respondents is the fear of birds (e.g., pigeons) entering.

3.2. Factors driving occupants to turn on and off ventilation systems

Out of the 6 participants with access to a mechanical ventilation system and control over its activation and deactivation, the main reason for switching it on is the need for room ventilation (Mdn: 4.5), followed by sensing the room as smelly (Mdn: 4.5), a desire for a bit of draught (Mdn: 4), feeling warm (Mdn: 3), not wanting to waste energy by opening the window (Mdn: 1.5), and, lastly, a preference for some background noise (generated by the system) (Mdn: 1). The distribution of importance ratings for the factors that guide the activation of the mechanical ventilation system is reported in Fig. 5.

The primary factor leading occupants to deactivate the mechanical ventilation system is their preference for opening the window (Mdn: 4), followed by the presence of excessive drafts (Mdn: 3), the system's excessive noise (Mdn: 1.5), and, lastly, feeling cold (Mdn: 1.5), as showed in Fig. 6. Another reason for deactivating the system, as mentioned by one participant, is the intention to save energy by turning off the ventilation system.

3.3. Influence of personal and environmental noise-related variables on acoustic-related factors influencing window opening and closing behaviour

A cumulative odds ordinal logistic regression with proportional odds was run to determine the effect of perceived sound source dominance, window view content, comfort and content scores, measured loudness and individual noise sensitivity on the importance attributed to the external sound environment when opening the windows. There were proportional odds, as assessed by a full likelihood ratio test comparing the fitted model to a model with varying location parameters, $\chi^2(26) = 32.119$, $p = 0.189$. The final model statistically significantly predicted the dependent variable over and above the intercept-only model, $\chi^2(13) = 23.478$, $p = 0.036$. An increase in acoustic comfort was associated with an increase in the odds of considering external sound an important driver for window opening (Table 1). The more the soundscape was perceived as comfortable, the greater the importance attributed to the sound component in the window-opening behaviour. This can be observed in Fig. 7, where the importance attached to the desire to hear external sounds when opening windows is noticeably higher in the high comfort soundscape compared to the low comfort soundscape (as defined by the median comfort value).

Moreover, a tendency can be observed towards greater significance attributed to external sounds when opening windows in areas with higher window view content scores computed from pictures (i.e., with better views) and when the living room is less exposed to outdoor anthropogenic noise, such as voices (see Table 1). The perceived dominance of sound sources, content scores, and the loudness computed from binaural recordings with open windows did not emerge as significant variables (see Table 1). A trend can be observed in Fig. 8a, where the low noise sensitivity group, defined relative to the median noise sensitivity value, appears to attribute greater importance to the connection with the outdoor acoustic environment in influencing window-opening behaviour compared to the high sensitivity group. However, this relationship was not substantiated by statistical significance (Table 1).

A second model was calculated on the importance attributed to external noise in determining the closing of windows. View content was excluded for model fit. The assumption of proportional odds was met, according to a full likelihood ratio test comparing the fitted model to a model with varying location parameters, $\chi^2(36) = 48.340$, $p = 0.082$. The final model statistically significantly predicted the dependent variable over and above the intercept-only model, $\chi^2(12) = 24.026$, $p = 0.020$. There was no significant association between the importance attributed to excessive external noise and the dominance of sounds typically heard when the living room windows are open, the loudness measured during the monitoring campaign, soundscape comfort, and content (Table 2). Interestingly, higher noise sensitivity was associated

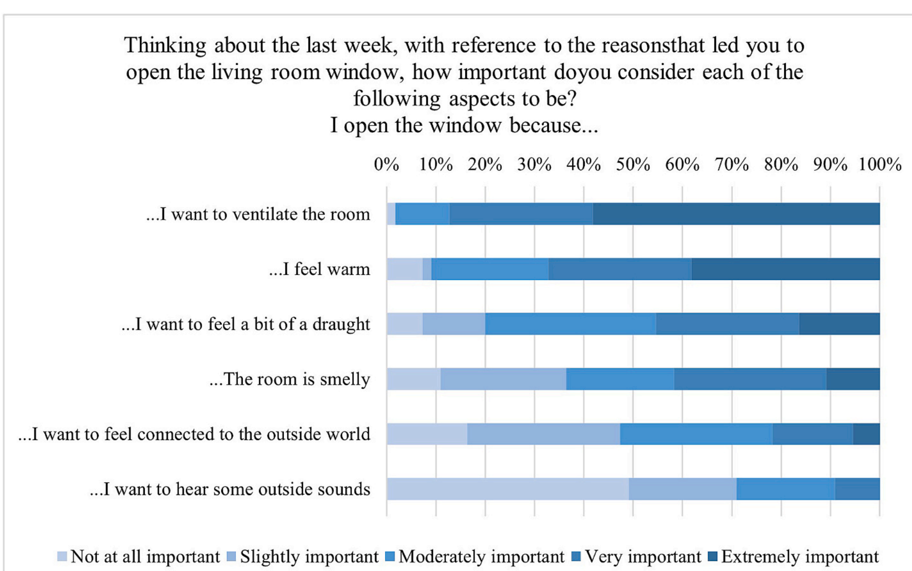

Fig. 3. Distribution of importance ratings for factors driving window opening (N: 55).

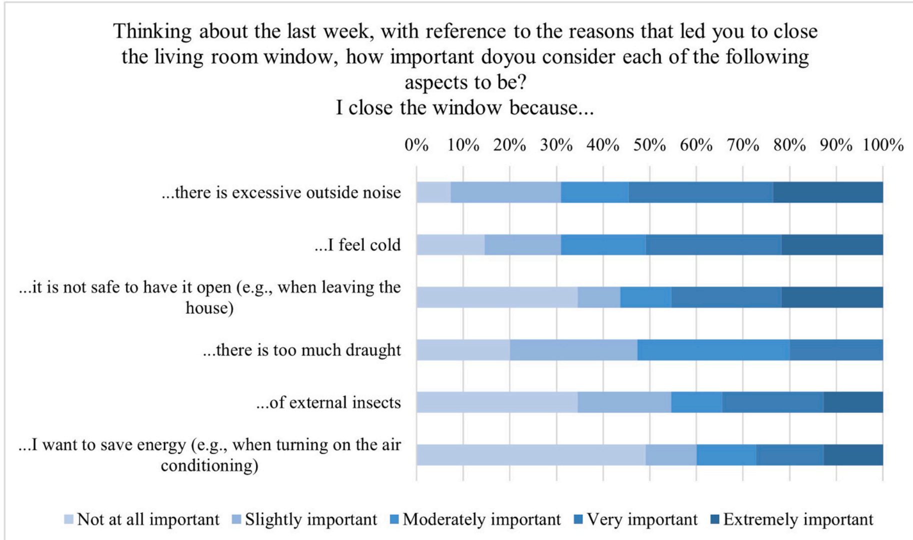

Fig. 4. Distribution of importance ratings for factors driving window closing (N: 55).

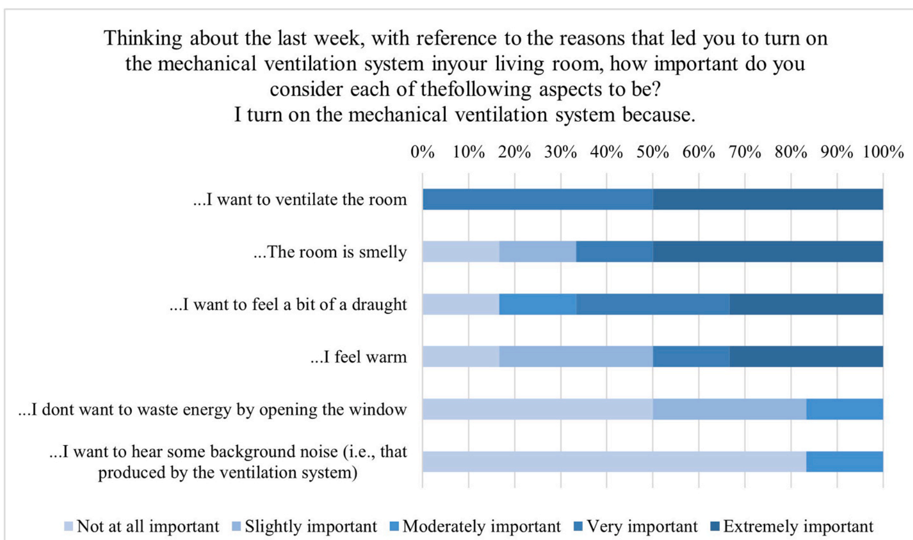

Fig. 5. Distribution of importance ratings for factors driving the activation of the mechanical ventilation system (N: 6).

with an increase in the odds of considering external noise an important driver for window closing (Table 2). This is particularly evident in Fig. 8b, where the high noise sensitivity group attributed higher importance to external noise in closing the windows. It should be noticed that similar results in the two models are obtained by characterising the acoustic environment through the A-weighted sound pressure level L_{Aeq}.

4. Discussion

4.1. Factors influencing building occupants' interaction with windows

This study delved into the motivations behind opening and closing windows in residential buildings during the summer period. Although the term “window opening behaviour” is often used to refer to both the opening and closing of windows, it’s important to note that the factors driving these two behaviours can be different, as previously reported in the literature [14].

The opening of windows is primarily associated with aspects related to perceived air quality and thermal comfort. The factors to which greater importance is attributed are the need to ventilate the room, cool it down, feel a breeze, and the perception of the room as smelly. Findings align with existing literature reporting that window opening behaviour in residential environments is mainly linked to indoor and outdoor temperature, CO_2 concentration, as well as time of the day [9,11,13,14,44].

Differently, when assessing the importance attributed to the factors contributing to window closure, it is noticeable that excessive external noise stands out as a significant reason for closing windows, besides thermal discomfort (i.e., feeling too cold). While literature does not consistently report the effect of noise on window usage in buildings [8], this study highlights different effects of sound stimuli in influencing the opening and closing of windows.

The connection with the external world, including auditory contact facilitated by open windows, is often valued in residential environments, as reported in studies conducted during the COVID-19 pandemic in London [22,45]. Indeed, windows can function not just as pathways for disruptive noises but also for sounds, be they natural or sometimes

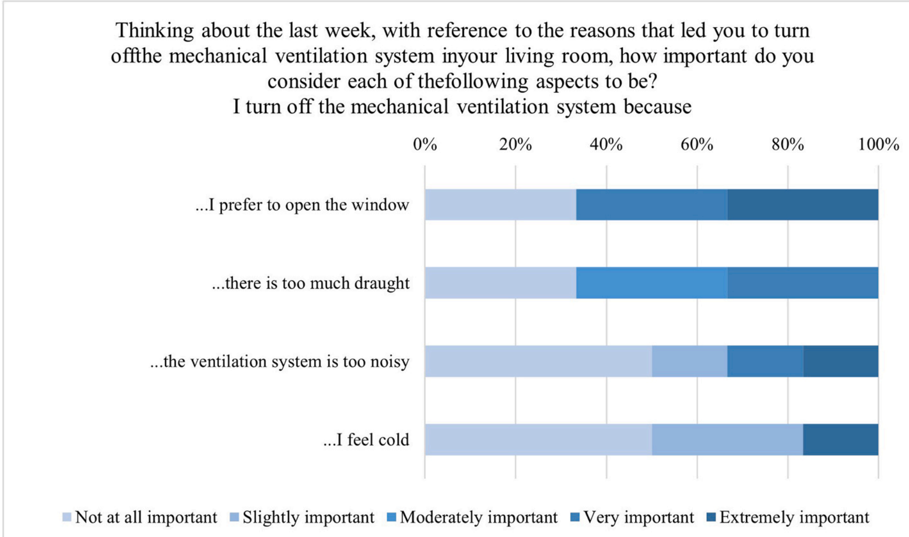

Fig. 6. Distribution of importance ratings for factors driving the deactivation of the mechanical ventilation system (N: 6).

urban, capable of fostering positive indoor soundscapes, restoration and building a sense of place [17,45]. In a study conducted in an office building in Washington, the addition of noise was reported as one of the reasons for opening windows in summer [15]. However, in the present study, connection with outdoor sound stimuli doesn't seem to be a significantly influential factor prompting action, i.e., the decision to open windows, at least according to the occupants' responses. Excessive noise, on the other hand, emerges as a notable factor in the decision to close windows, as reported by participants. While studies on window opening behaviour mainly focus on thermal comfort and air quality aspects [8,12], it is crucial to place greater emphasis on the characterization of the impacts provided by the acoustic environment on window usage. Further research in this direction is needed.

Moreover, the study confirms the multifaceted nature of the factors involved in window opening behaviour. In addition to environmental aspects, demographic, psychological, social, and contextual factors play important roles. For example, findings have highlighted among the reasons that lead to the closing of windows, factors related to safety and concerns about the entry of insects and birds, aligning with previous findings in the literature [10,46].

4.2. Factors influencing building occupants' interaction with mechanical ventilation systems

The primary triggers for activating the ventilation system when automatic control is available are related to perceived indoor air quality and thermal comfort. Activation occurs when there is a need to ventilate the space, detect unpleasant odours, facilitate air circulation, or address excessive room temperature. To a lesser extent, there are energy-saving considerations associated with the use of the system in comparison to opening windows (an aspect that might be more relevant in the heating season), or the intention to provide some background noise intentionally.

Conversely, the deactivation of the system is primarily driven by occupants' preference for using windows for ventilation and the presence of inconvenient drafts. This is followed by annoyance caused by excessive noise and thermal discomfort associated with feeling cold. Additionally, participants added reasons such as concerns about the operational costs of system. A survey on satisfaction in buildings in the UK equipped with MVHR (Mechanical Ventilation with Heat Recovery) revealed that, among the reasons for deactivating the system, concerns about operational costs were prevalent, with noise and drafts and a lack of understanding of the system being contributing factors to a lesser extent [3]. A significant portion of users did not know how to use, operate, control, and maintain the system, a facet substantiated by the present study. Indeed, during the monitoring, occupants in many of the homes we visited equipped with a mechanical ventilation system were either unaware of its presence or simply did not know how to use it and how to take advantage of it. The lack of training and comprehension regarding the use of the ventilation system could underlie the preference for using windows and concerns about operating costs. Proper training increases occupants' satisfaction [47] and makes design efforts worthwhile. Drafts [3] and excessive noise [3,5,6] are common reasons for deactivating the system that are found both in the present study and in the literature.

4.3. The influence of view from window, indoor-outdoor soundscapes and individual noise sensitivity on window opening behaviour

The study results indicate that the importance attributed to the external acoustic environment in the process of opening and closing windows is generally not influenced by the type of heard sources, be it prevalent traffic noise or natural sounds, nor by the psychoacoustic loudness or the saturation of the environment with sound events (i.e., content scores). A trend was observed towards a decrease in the odds of opening the window for external acoustic contact in the presence of human sounds outdoor, such as voices (Table 1). However, the result was not substantiated by statistical significance.

Furthermore, a tendency is reported towards a greater importance attached to the outdoor acoustic environment as a driver for window opening in contexts with a better view outdoors, assessed through photo analysis using the view content parameter. This recalls the results from an online study conducted during the COVID-19 pandemic where, in the Italian subset, a higher frequency of window opening resulted where vegetation was more visible from windows [28]. However, this was not the case for the London subset in the mentioned study [28], which reported that the frequency of window opening did not depend on the view from the window, whether dominated by buildings, vegetation, or the sky, or the presence of a noisy or quiet urban external environment. This is likely due to the fact that the motivations regulating window opening behaviour are primarily rooted in aspects related to air quality and thermal comfort, as showed in the present study.

Results have highlighted an association between acoustic comfort, evaluated based on the circumplex model of indoor soundscapes, and the significance attributed to perceiving external sounds when opening windows. The more comfortable the soundscape - assessed with

Table 1
Cumulative odds ordinal logistic regression with proportional odds of importance attributed to acoustic-related factors for window opening based on perceived dominance of different sound sources, loudness, window view content, noise sensitivity, comfort and content scores (N: 55).

	B	*SE*	*p*	Odds Ratio	95 % CI for Odds Ratio	
					Lower	Upper
Dominance of traffic noise from outside	0.51	0.55	0.358	1.66	0.56	4.88
Dominance of other noise from outside"	−0.06	0.52	0.907	0.94	0.34	2.62
Natural sounds from outside (e.g., singing birds, flowing water, wind in vegetation)	0.25	0.38	0.506	1.28	0.61	2.68
Sounds from human beings from outside (e.g., conversation, laughter, children at play, footsteps)	−0.91	0.5	0.069	0.40	0.15	1.07
Sounds from other human beings present in your house/ accommodation (e.g., conversation, music, TV, laughter, children at play, footsteps)	0.08	0.36	0.831	1.08	0.53	2.19
Sounds from neighbours (e.g., conversation, music, TV, laughter, children at play, footsteps)	0.33	0.41	0.423	1.39	0.62	3.08
Sounds from building services of your house/ accommodation (e.g., heating, cooling, ventilation systems, toilet flushes)	−0.28	0.46	0.538	0.75	0.30	1.86
Sounds from building services of your neighbours/common areas (e.g., heating, cooling, ventilation systems, let flushes, lift)	0.09	0.40	0.826	1.09	0.50	2.38
N_{avr}	0.27	0.19	0.161	1.31	0.90	1.90
View content	2.67	1.62	0.099	14.47	0.60	346.83
Noise sensitivity	−0.02	0.02	0.173	0.98	0.95	1.01
Comfort	**3.88**	**1.43**	**0.007**	**48.44**	**2.95**	**794.68**
Content	0.78	1.46	0.595	2.18	0.12	38.33

windows open - the more the contact with the external sound environment encourages window opening.

Moreover, the present study emphasizes the relevance of noise sensitivity in determining the importance assigned to the acoustic factor when interacting with windows. Fig. 8a illustrates a trend: individuals who are more sensitive to noise tend to be less inclined to open windows for acoustic engagement with the external surroundings. This trend is statistically significant in terms of window-closing behavior (Fig. 8b), indicating that individuals more sensitive to noise are more influenced by external noise when deciding to close windows. In a previous study, it was found that more noise sensitive individuals tended to keep their windows open less frequently, with a difference of 4–29 % in locations with sound levels above 47–51 dB during nighttime outside bedroom windows [48]. This individual parameter is generally not included nor considered in studies on window opening behaviour [2,9], despite its significance in determining the relevance of the external acoustic environment to window closing habits. Future studies should include noise

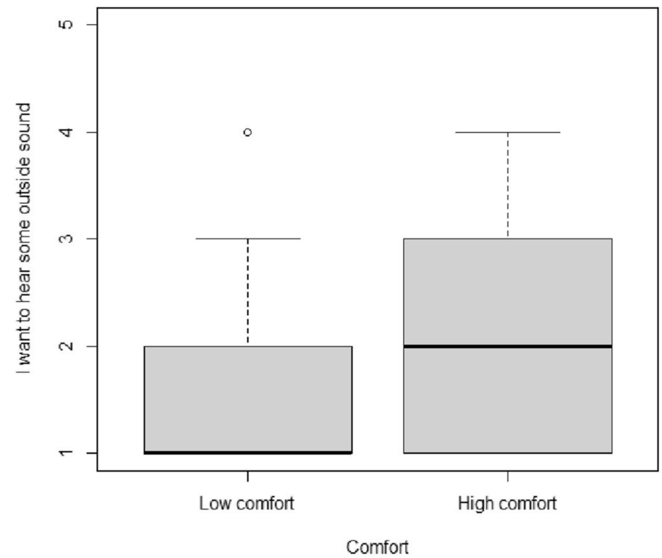

Fig. 7. – Difference in the importance assigned to acoustic-related factors in driving window opening behaviour from 1 (not at all important) to 5 (extremely important) for the low and high comfort groups. N: 55.

sensitivity in models of window opening and closing behaviour, an aspect that could be crucial, for instance, in buildings housing occupants particularly sensitive to noise, as in the case of neuroatypical individuals [49,50].

5. Limitations

The results of the present study must be considered in light of certain limitations. Firstly, the sample of buildings with controlled mechanical ventilation was rather limited (N = 6) and, for this reason, statistical analyses where confined to the sample of buildings with NV (N = 55). Secondly, given the exploratory nature of the investigation and the challenges in accessing private homes, the sample of buildings cannot be considered representative of the geographical area under study. While not claiming generalizability in our study, we do assert transferability [51]. This concept refers to the extent to which the findings can be applied to other contexts or groups. It is achieved by providing detailed descriptions of the research context and participants, allowing others to judge the relevance of the findings to their own settings. Our findings, such as the significance of collecting data on noise sensitivity in studies analysing window opening behaviour, can guide future large-scale studies that aim for statistically representative samples, also allowing for better model fitting and narrower confidence intervals. Furthermore, the study relies on occupants' self-assessment of the factors influencing window opening and closing or the activation and deactivation of ventilation systems, rather than observing their actual habits. Participants may not be fully aware of the reasons guiding their behaviours, potentially leading to inaccurate reporting. Moreover, some of the collected information are retrospective in nature and people may not always be accurate in recalling past experiences [52]. The study is contextualized within the English context. While many of the factors mentioned align with findings in international literature, variations in socio-cultural aspects may introduce different patterns in the way occupants interact with windows and mechanical ventilation systems according to the geographical context. Lastly, the study reported results collected at a single point in time, specifically during the summer season. In addition to the aspects touched upon here, the literature highlights the importance of seasonality and time of day and night in determining window opening behaviour [2]. Future large-scale longitudinal studies are needed to incorporate aspects related to seasonality, socio-cultural background, and time of day.

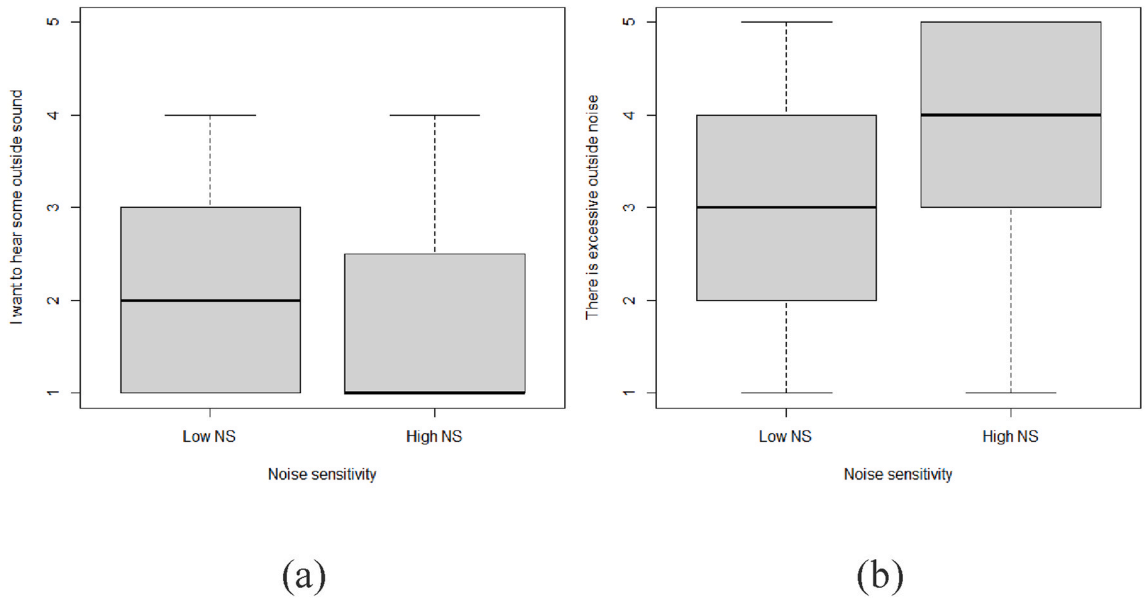

Fig. 8. – Difference in the importance assigned to acoustic-related factors in driving window opening (a) and window closing (b) behaviour from 1 (not at all important) to 5 (extremely important) for the low and high noise sensitive groups. N: 55.

6. Conclusions

The study presents findings from a data collection campaign in residential buildings in England. The research aimed to explore 1) the factors influencing the opening and closing of windows, 2) the drivers of activation and deactivation of mechanical ventilation systems, and 3) the correlation between the physical and perceived acoustic environment, the quality of the external view, individual noise sensitivity, and the importance attached to contact with the external acoustic environment in determining the opening and closing of windows.

1) The survey results on 55 dwellings relying on windows for ventilation, revealed that, concerning window opening, greater importance is given to the need for ventilation, the perception of warmth, the desire for airflow, and the perception of the room as odorous. The desire to feel connected to the outside, even from an auditory perspective, is considered secondary. Conversely, the acoustic factor plays a key role in triggering window closure, followed by the perception of cold, safety concerns, excessive drafts, concern for insect intrusion, and the desire to save energy, particularly when ventilation or air conditioning systems are activated.
2) Within the 6 dwellings employing a manually controlled mechanical ventilation system, the predominant factor triggering system activation is the necessity for ventilation. This is followed by considerations such as perceiving the environment as smelly, a desire for increased airflow, and a sensation of warmth. Less important factors include the willingness to save energy (by avoiding window opening) and the intention to create background noise. Reasons for system deactivation primarily include a preference for window opening, excessive drafts, and, secondarily, perceiving the system as too noisy or the environment as too cold. Additionally, a participant highlighted concerns about the operational costs of the system.
3) The importance attached to contact with the external acoustic environment (whether positive or negative) in relation to window opening and closing does not depend on the type of perceived sound sources when the window is open, nor on the measured sound levels in the home (i.e., psychoacoustic loudness), or the degree of ambient sound saturation (soundscape content). Only a trend was observed indicating a greater significance of contact with the external sound environment in driving window opening in the presence of a better outdoor view and reduced external noise from voices. Interestingly, environments with better acoustic comfort were associated with a greater willingness to open the window to experience the external acoustic environment. Furthermore, window closing behaviour depends on individual noise sensitivity: individuals more sensitive to noise attach greater importance to the presence of excessive external noise when deciding to close the window, with an odds ratio of 1.04 (95 % CI, 1.01 to 1.07), $p = 0.003$.

The research confirms the complexity and multifactorial nature of the interaction with windows or mechanical ventilation devices. Moreover, the study contributes to investigating the influence of acoustic factors on window opening behaviour and the use of mechanical ventilation systems. It underscores the importance of incorporating noise sensitivity as an individual factor in models simulating window opening behaviour. This aspect might be crucial for inclusive housing designed for populations with heightened sensitivity to noise, such as neuroatypical individuals.

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CRediT authorship contribution statement

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

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. If there are other authors, they

Table 2
Cumulative odds ordinal logistic regression with proportional odds of importance attributed to acoustic-related factors for window closing based on perceived dominance of different sound sources, loudness, noise sensitivity, comfort and content scores (N: 55).

	B	*SE*	*p*	Odds Ratio	95 % CI for Odds Ratio	
					Lower	Upper
Dominance of traffic noise from outside	0.25	0.42	0.558	1.28	0.56	2.94
Dominance of other noise from outside	−0.04	0.39	0.910	0.96	0.45	2.05
Natural sounds from outside (e.g., singing birds, flowing water, wind in vegetation)	−0.06	0.33	0.855	0.94	0.49	1.81
Sounds from human beings from outside (e.g., conversation, laughter, children at play, footsteps)	−0.01	0.40	0.996	1.00	0.45	2.20
Sounds from other human beings present in your house/ accommodation (e.g., conversation, music, TV, laughter, children at play, footsteps)	−0.01	0.31	0.965	0.99	0.53	1.83
Sounds from neighbours (e.g., conversation, music, TV, laughter, children at play, footsteps)	0.09	0.36	0.796	1.10	0.54	2.23
Sounds from building services of your house/ accommodation (e.g., heating, cooling, ventilation systems, toilet flushes)	0.15	0.42	0.721	1.16	0.51	2.67
Sounds from building services of your neighbours/common areas (e.g., heating, cooling, ventilation systems, let flushes, lift)	−0.13	0.33	0.691	0.88	0.46	1.68
N_{avr}	−0.08	0.15	0.586	0.92	0.69	1.23
Noise sensitivity	**0.04**	**0.01**	**0.003**	**1.04**	**1.01**	**1.07**
Comfort	−0.90	1.14	0.426	0.40	0.04	3.75
Content	0.19	1.15	0.866	1.21	0.13	11.53

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2024.111880.

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