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# Integrating Indoor Soundscape Approach into IEQ Research: Acoustic Comfort in Naturally Ventilated Residential Buildings

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## ABSTRACT

*The present study investigates acoustic comfort in naturally ventilated residential buildings through an indoor soundscape approach. Preliminary results from a laboratory listening test are presented, where, in a mock-up living room with a window sight, participants have been exposed to 20 acoustic scenarios, obtained as a combination of 4 indoor sound sources and 5 outdoor urban environments filtered through a window ajar. Participants were asked to rate each exposure condition. Subjective ratings on 6 selected attribute scales related to valence and perceived control are here analyzed in order to: (1) study associations between (psycho)acoustic parameters and subjective judgments, and (2) investigate whether sounds released through natural ventilation could be beneficial to indoor soundscape. Repeated measures correlations showed a general stronger association between subjective ratings and loudness ($N_{10}$). However, considering the effect of outdoor sound type and the interaction between outdoor and indoor sounds on acoustic perception added a fundamental layer of information to indoor soundscape characterization. Under some of the tested conditions, regardless their loudness, outdoor sounds could improve indoor soundscape in terms of increased comfort and reduced annoyance, alleviating feelings of helplessness when in presence of annoying indoor sources or silent indoor environments. Besides confirming the harmful effect of loud heavy traffic noise exposure, the study points out the positive effect of natural sounds on soundscape, and the benefits that can be offered to the indoor soundscape of a residential living room even by urban sounds, such as light traffic noise and human voices from a pedestrian area. The study shows the opportunities for IEQ research to address the apparent conflict between acoustic and ventilation needs from a perceptual, soundscape approach.*

## INTRODUCTION

When dealing with natural ventilation (NV), indoor environmental quality (IEQ) research must address the conflict between acoustic and ventilation needs. Indeed, because of external noise transmitted through ventilation openings, the adoption of NV is often not feasible because it is more difficult to meet the background noise level limits set by acoustic standards and rating protocols compared to the case of sealed mechanically ventilated buildings. Differently from thermal comfort criteria, acoustic design requirements aim at limiting noise annoyance by guaranteeing silent indoor

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spaces without considering different ventilation strategies. Previous studies have already pointed out the weakness of decibel-based levels in effectively characterizing perceived sound quality. Moreover, whether mechanical engineers often assume windows being open for ventilation, acousticians assume windows being closed for noise control, thus leaving the trade-off decision to the final occupants (Harvie-Clark et al. 2019).

In order to tackle the apparent conflict between acoustic comfort and NV from a different, perceptual view, a soundscape approach is proposed. Soundscape research integrates psychological, (psycho)acoustical, physiological, and contextual factors to investigate how people perceive the acoustic environment in order to limit the negative impacts of noise and promote positive sound source types, thus exploiting sound as a design "resource" (Kang et al. 2016; Torresin, Albatici, Aletta, Babich, and Kang 2019).

In this study, results from a laboratory test are presented in which participants have been exposed to several acoustic scenarios, obtained from the combination of indoor sound sources and outdoor urban environments, inside a mock-up living room with a window sight. Subjective ratings here analyzed focus on two main constructs: valence and perceived control. Valence (a pleasure – displeasure continuum) is a fundamental perceptual dimension underlying soundscape assessment (cf. ISO-TS 12913-3:2019), while perceived control is a potential mediator in the association between environmental conditions and perceptual outcomes (Hellwig 2015; Riedel et al. 2018), as already acknowledged by thermal comfort research (Yun 2018).

The study aims at (1) evaluating associations between (psycho)acoustic parameters and subjective judgments, and (2) investigating whether sounds released through NV could be beneficial to indoor soundscape, depending on outdoor urban context and on interaction with indoor sounds. Outcomes will lead to discuss the potential opportunity of an indoor soundscape integration within the IEQ framework.

## METHODS

### Exposure conditions

Listening tests were performed at the UCL IEDE Acoustics Lab in London. The aim was to simulate acoustical scenarios experienced in residential living rooms and to record the subjective states elicited in test participants. Exposure conditions were obtained by combining audio excerpts related to 5 different outdoor urban contexts (Factor A) with audio excerpts related to 4 different indoor sound sources (Factor B) in order to replicate typical indoor acoustic conditions where outdoor sounds filtered through the building façade and ventilation openings (simulated via a display projecting a window view) are mixed with indoor sounds. This resulted in 20 exposure conditions, according to a within-subjects full factorial design experiment. Audio stimuli related to outdoor acoustic environments were recorded in indoor spaces with windows partially open to different urban contexts in the city of London. One-minute audio excerpts were played back from loudspeakers located in the window side of the mock-up living room to simulate the effect of sound entering through a window ajar. Playback was calibrated at the listener position at the authentic A-weighted equivalent continuous sound pressure level ($L_{Aeq}$). Further details can be found in (Torresin et al. 2020).

Binaural recordings of the 20 acoustic conditions resulting from the combination of the two factors were then performed at the listener positions and subjected to acoustic analysis by calculating several acoustic and psychoacoustic parameters, as described in Table 1 and in (Torresin et al. 2020). Factors and levels involved in the full factorial design experiment are described in Table 2. For control conditions (i.e. no added sound), laboratory background noise level is reported.

### Attribute rating scales

Attribute rating scales assessed the affective response to indoor soundscapes. Participants rated attributes by mean of bar sliders on a touchscreen handset by assigning a numeric rating from 0 to 100, indicating how well the attribute could match the perception of the acoustic environment (Axelsson et al. 2010; Torresin et al. 2020). In the present study, results on 6 selected attribute scales are considered. Two attributes were valence-related, namely "comfortable"

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and "annoying, baiting, irritating, troublesome, upsetting" (hereinafter, "annoying"). Four attributes were related to the perceived availability of control: "making you want to open the window more" (hereinafter, "open the window more"), "making you want to close the window" (hereinafter, "close the window"), "under control" and "making you feel helpless". Even if participants were not provided with real control possibilities, these attributes were included to test how perceived control was affected by acoustic conditions in simulated NV conditions.

**Table 1. Table of symbols**

| Symbol | Definition |
|---|---|
| $L_{Aeq,1min}$ | 1-minute A-weighted equivalent continuous sound pressure level (dB) |
| $L_{A10}$-$L_{A90}$ | Difference between A-weighted sound level exceeded for 10% of the measurement period and the A-weighted sound level exceeded for 90% of the measurement period (dB) |
| $L_C$-$L_A$ | Difference between C-weighted and A-weighted equivalent continuous sound pressure levels (dB) |
| $N_{10}$ | Loudness value reached or exceeded in 10% of the measurement period (sone) |
| $N_{10}$-$N_{90}$ | Difference between N10 and N90 values (sone) |
| FS | Fluctuation strength (vacil) |
| R | Roughness (R) |
| S | Sharpness (acum) |

**Table 2. Acoustic characterization of Factor A (outdoor sounds) and Factor B (indoor sounds) and relative levels involved in the full factorial design experiment**

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

## Test procedures

Thirty-five participants took part in the study (17 females, 18 males, mean age: 31.7 yr., s: 7.2 yr.), mainly university students and researchers, all of them self-reporting normal hearing. Participants were told to imagine being at home, relaxing in their living room, while listening to sounds generated indoor and coming from the outside, through a window ajar. Each session started with a one-minute exposure. After that, participants were asked to scale the soundscape they were immersed in, while listening to one-minute repetitions of the sound stimuli previously experienced. Attribute scales were presented in random order across the exposure conditions. After a training session, each participant was singularly exposed to the 20 conditions, presented in random order.

## Statistical analysis

Repeated measures correlation was used (*rmcorr* package in R software) to assess the association between subjective ratings and (psycho)acoustical parameters, a statistical technique for determining the common within-individual association on paired repeated measures data (Bakdash and Marusich 2017). Two-way repeated measures ANOVAs were performed to evaluate the effect of outdoor-generated (Factor A) and indoor-generated sounds (Factor B) on attribute ratings. Greenhouse-Geisser sphericity correction was applied to within-subject factors violating the sphericity assumption. Repeated measure ANOVA is known to be quite robust to normality deviations, for large samples. Ratings in unfavorable conditions (i.e. with heavy traffic), for attributes related to window opening position, showed strongly

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skewed distributions around extreme rating values (0,100). For those conditions, statistical analysis results must be evaluated with more caution. In case of multiple comparisons, Bonferroni correction method was applied.

## RESULTS

A preliminary outlier analysis identified three participants that provided incongruent answers, leading to their exclusion. Therefore, results refer to a final data set on 32 participants.

### Correlation between subjective scores and objective acoustic parameters

Repeated correlation coefficients $r_{rm}$ between subjective ratings and (psycho)acoustical parameters are shown in Table 3. Ratings on "comfortable", "open the window more", and "under control" attributes were negatively correlated with all the considered acoustic and psychoacoustic parameters. In particular, "comfortable" and "under control" ratings were more strongly associated with the loudness parameter $N_{10}$, while ratings for "open the window more" with roughness R. Ratings on "annoying", "close the window", and "making you feel helpless" attributes were positively correlated with all the acoustic and psychoacoustic parameters. The stronger association for "annoying" and "making you feel helpless" ratings was observed for $N_{10}$ parameter, while "close the window" was more strongly associated with $L_{Aeq,1min}$, $N_{10}$, R, and $L_C$-$L_A$ parameters.

**Table 3. Repeated measures correlation coefficients $r_{rm}$ between subjective scores and objective acoustic parameters**

| | Comfortable | Annoying | Open the window more | Close the window | Under control | Making you feel helpless |
|---|---|---|---|---|---|---|
| $L_{Aeq,1min}$ | -0.49 | 0.48 | -0.51 | **0.63** | -0.49 | 0.36 |
| $N_{10}$ | **-0.55** | **0.54** | -0.50 | **0.63** | **-0.53** | **0.45** |
| $L_{A10}$-$L_{A90}$ | -0.43 | 0.43 | -0.50 | 0.60 | -0.46 | 0.30 |
| $N_{10}$-$N_{90}$ | -0.53 | 0.52 | -0.48 | 0.59 | -0.51 | 0.44 |
| FS | -0.16 | 0.17 | -0.25 | 0.23 | -0.13 | 0.11 |
| R | -0.50 | 0.48 | **-0.52** | **0.63** | -0.50 | 0.38 |
| $L_C$-$L_A$ | -0.49 | 0.48 | -0.51 | **0.63** | -0.50 | 0.38 |
| S | -0.23 | 0.26 | -0.24 | 0.26 | -0.20 | 0.26 |

Degrees of freedom: 607; all p-values ≤ 0.001

### Effect of outdoor sound type on subjective scores

A statistically significant interaction was found between outdoor and indoor sounds on "comfortable", $F(7.2, 222.1) = 4.9$, $p < 0.001$, and "annoying" ratings, $F(6.9, 214.5) = 4.7$, $p < 0.001$. Pairwise comparisons using paired t-tests between the control condition (i.e. without sound entering the window) and other outdoor stimuli are indicated in Figure 1. Data are grouped by indoor sound category as, in case of a significant interaction term, the impact of outdoor sounds on subjective ratings depends on indoor sound type.

In the control condition, indoor soundscape was rated significantly more annoying with fan noise (median: 57) than with music (median: 18, $p< 0.001$), and TV sounds (median: 22, $p < 0.01$) and not differently annoying from indoor soundscape with no added sound (median: 31, $p = 0.27$). As regards comfort ratings, in the control condition, fan noise (median: 39) was significantly less comfortable than music (median: 67, $p < 0.001$), TV (median: 59, $p = 0.01$) and indoor soundscape with no indoor sources (median: 58, $p= 0.04$).

Compared to the control condition, heavy traffic caused significantly less comfortable and more annoying indoor soundscapes, regardless indoor sound type. Interestingly, in most cases, comfort and annoyance ratings with light traffic and human voices (i.e. pedestrian area) were not significantly different from those expressed in the control condition, despite their higher sound level. Both light traffic and human voices were significantly more annoying when combined with TV, while light traffic was significantly less comfortable when combined with TV and more annoying

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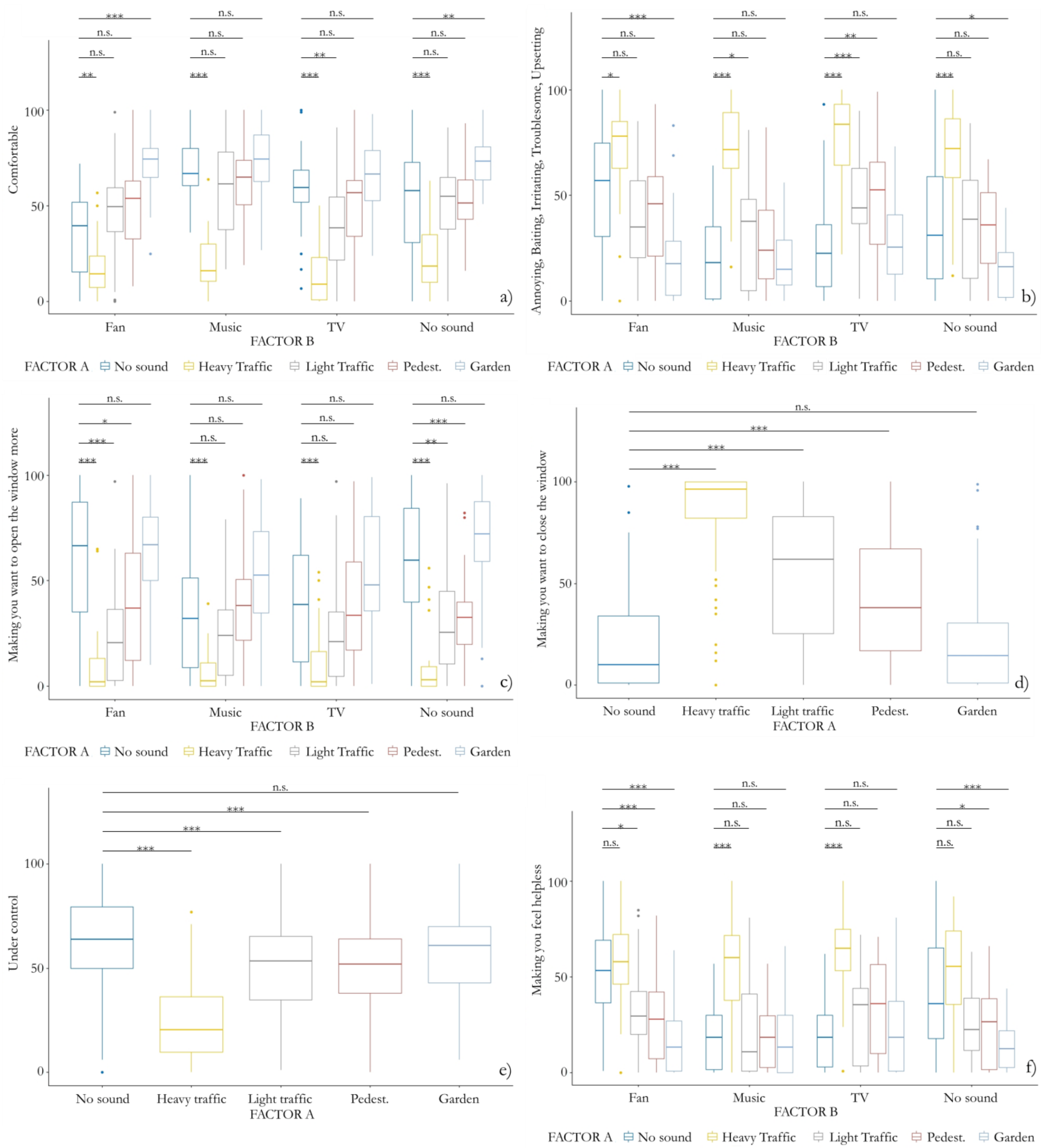


**Figure 1** Boxplots of attribute ratings by type of outdoor sounds (Factor A) and, in case of significant interaction effects, by type of indoor sounds (Factor B) for: (a) "comfortable", (b) "annoying, baiting, irritating, troublesome, upsetting", (c) "making you want to open the window more", (d) "making you want to close the window", (e) "under control", and (f) "making you feel helpless". Pairwise comparisons are shown between the control condition with no sound from outside and other outdoor sound types. n.s.: not significant, * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

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when combined with music. Higher comfort ratings and lower annoyance ratings were observed with natural sounds (i.e. garden) combined with fan noise or no indoor sound. Natural sounds could thus improve indoor soundscape in presence of annoying fan noise, compared to the control condition. The effect of natural sounds was not significantly different from the control condition only when masked by indoor music or TV sounds.

Regarding the ratings for "open the window more", a statistically significant interaction was found between outdoor and indoor sounds, $F(7.1, 219.6) = 3.3$, $p < 0.01$. Compared to the control condition, ratings were significantly lower with heavy traffic, regardless indoor sound type, and with light traffic and voices, when combined with indoor fan noise or no indoor sound source, denoting less desire to open the window further in such conditions. Differently, ratings were not significantly different from control condition when light traffic or human sounds were combined with TV or music, and in presence of natural sounds, regardless indoor sound type.

Higher attribute ratings showed that participants wanted to open the window more in the quietest indoor soundscape (neither indoor nor outdoor sounds), in presence of annoying fan noise not masked by outdoor sound, and in presence of a pleasant outdoor soundscape (i.e. natural sounds), regardless indoor sound type.

Concerning the ratings to "close the window", no significant two-way interaction was found between outdoor and indoor sounds, $F(7.5, 233.7) = 1.1$, $p = 0.39$. Main effect of outdoor sounds on attribute ratings was significant, $F(2.9, 90.0) = 66.1$, $p < 0.001$, indicating that their effect on subjective ratings was independent from indoor sound type. Compared to control condition, ratings were significantly higher with heavy traffic, light traffic and voices from pedestrian area. As expected, rating values for heavy traffic denoted a strong desire to close the window (median: 96). Lower ratings were observed in case of light traffic (median: 62) and human sounds (median: 38), that can be interpreted as people tolerating window in the partially opened position. No significant difference was found between natural sounds and the control condition.

No significant two-way interaction was found between outdoor and indoor sounds on "under control" ratings, $F(12.0, 372.0) = 1.7$, $p = 0.07$. Main effect of outdoor sounds on attribute ratings was significant, $F(3.1, 95.0) = 47.9$, $p < 0.001$. Compared to the control condition, ratings were significantly lower with light traffic, voices from pedestrian area, and particularly with heavy traffic. No significant difference on perceived control was found between indoor soundscapes with natural sounds and the control condition.

Regarding the "making you feel helpless" ratings, a statistically significant interaction was found between outdoor and indoor sounds, $F(7.3, 225.2) = 6.9$, $p < 0.001$. With music or TV sounds, perceived helpless ratings are significantly higher with heavy traffic and not significantly different with light traffic, human sounds or natural sounds compared to the control condition. Interestingly, with indoor fan noise or no indoor sound, helpless ratings assume high values when there is no sound from outside, not significantly different from those with heavy traffic combined with fan noise, or with heavy and light traffic with no indoor sound source. Compared to the control condition, helpless ratings are significantly lower with light traffic, human sounds or natural sounds in combination with fan noise and with human sounds or natural sounds in absence of indoor sources.

## DISCUSSION

### Acoustic comfort in naturally ventilated residential buildings

Repeated measures correlations showed a general stronger association between subjective ratings and loudness ($N_{10}$) than with other indicators, confirming previous findings (Axelsson et al. 2010). Louder indoor soundscapes were associated with less comfortable and more annoying environments, lack of perceived control, stronger feeling of helplessness and desire to close the window. The attribute "making you want to open the window more" had a stronger negative correlation with roughness, a parameter related to the subjective perception of rapid amplitude modulation of a sound, higher in the audio excerpts with heavy traffic noise.

When considering sound type, results showed that indoor soundscape was severely affected by loud heavy traffic in terms of annoyance, comfort, perceived control over the environment and feeling of helplessness. When subjected

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to heavy traffic, participants clearly expressed their desire to close the window in order to reduce noise exposure.

Under extremely quiet outdoor conditions, indoor soundscape was perceived differently depending on the indoor sound source. The lack of outdoor sounds was beneficial when listening to music, most probably as the sound quality of music was not affected, and when watching TV, as the speech intelligibility was not impaired by noise. Differently, the lack of outdoor sounds was detrimental in presence of annoying indoor sources (i.e. fan noise), as no masking opportunity could be provided, and, surprisingly, in absence of indoor sound sources, under the quietest conditions. Indeed, when no sound was released through the window and indoor soundscape was silent or with annoying sources, participants expressed higher feeling of helplessness and the desire to open the window further, despite the stronger perceived control.

Human sounds from pedestrian areas and light traffic sounds generally did not affect comfort and annoyance perception compared to the control condition, despite their higher loudness, while mitigating helpless feelings with annoying fan noise and without indoor sources. Outdoor voices resulted more annoying when watching TV, likely due to the disturbing interference between their informative content and sound level and the perception of the TV speech signal. In presence of light traffic, higher annoyance was reported while listening to music and higher annoyance and lower comfort were expressed while watching TV. Nevertheless, the window in semi-open position was someway tolerated, as participants did not express a strong desire to close it.

Natural sounds could improve comfort and reduce annoyance in case of fan noise or silent indoor spaces, while alleviating the feeling of helplessness compared to the control condition, despite their higher loudness. Sounds from an outdoor garden did not impair comfort conditions while listening to music or watching TV and participants generally expressed a higher desire to open the window further, regardless indoor source type.

Taken together, results showed that, under the tested conditions, outdoor sounds released through a partially open window could in some cases improve indoor soundscape in terms of increased comfort and reduced annoyance, alleviating perceived helplessness in presence of annoying indoor sources or silent indoor environments. Despite the harmful effect of noise exposure for people health and well-being, "the quieter" wouldn´t necessarily mean "the better" in indoor soundscape design. Indeed, besides confirming the positive effect of natural sounds on soundscape (Axelsson et al. 2010), the study points out the benefits that can be offered even by urban sounds, such as light traffic noise and human voices from a pedestrian area, on the indoor soundscape of a residential living room.

As previously reported in urban studies, semantic features of sounds (e.g. sound type) are fundamental in soundscape assessment (Dubois et al. 2006). Moreover, the interaction between outdoor and indoor sounds add a relevant layer of information to indoor soundscape characterization. That is, simple linear associations between subjective judgments and objective metrics are not able to effectively explain the complexity of indoor soundscape experience, thus oversimplifying reality. The knowledge provided by this study could inform acoustic design criteria for naturally ventilated buildings, by taking into consideration "informational aspects" of sounds, beyond sound level.

## Indoor soundscape and IEQ research

The present study reported an application of the indoor soundscape approach to a field that involves different disciplines and IEQ needs, that is NV. The results suggest that, by providing insights into how people perceive the acoustic environment, soundscape research may be able to value acoustic comfort as a potential co-benefit of NV, thus working out the traditional conflict in IEQ research between acoustic and ventilation needs. NV in fact could be exploited as a strategy to transmit, block or adjust outdoor sounds in order to maintain a connection with the outside, allow wanted sounds or mask unwanted ones. Further studies would be needed to investigate the multi-sensory experience of the built environment in NV conditions (e.g. external sound and thermal stimuli in overheating conditions), the connection with the outside and the sense of control over one's environment, that may induce "adaptive acoustic comfort" opportunities (Torresin, Albatici, Aletta, Babich, Oberman, et al. 2019).

By addressing the complexity of the human experience in the built environment beyond a reductive physicalism (Willems et al. 2020), and by aiming at better-than-neutral indoor environments, indoor soundscape approach brings to

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acoustic comfort research many of the trends already experienced in other IEQ research areas. Considering shared methodologies and intents across disciplines, there may be room for indoor soundscape to be integrated into IEQ framework in order to fill the gap between modelled and experienced perception in the built environment, through multi-sensory research and integrated design processes.

## CONCLUSIONS

The main conclusions of the present study are:

1. a general stronger association was observed between subjective ratings and loudness ($N_{10}$), suggesting that louder soundscapes were perceived more negatively by test participants;
2. under some of the tested conditions, regardless their loudness, outdoor sounds could improve indoor soundscape in terms of increased comfort and reduced annoyance, alleviating perceived helplessness when in presence of annoying indoor sources or silent indoor environments. A positive effect on indoor soundscape was observed not only for natural sounds, but also for light traffic and human sounds from a pedestrian area;
3. considering outdoor acoustic context and the interaction between outdoor and indoor sounds is fundamental for indoor soundscape characterization.

## AKNWOLEDGMENTS

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