DOI: 10.61782/fa.2025.0256

FORUM ACUSTICUM EURONOISE 2025

CROSS-MODAL EFFECTS ON ASSESSMENTS OF SOUNDSCAPE AND IAQ IN UNIVERSITY CLASSROOMS

Matteo Pellegatti[1*] **Chiara Visentin**[1] **Simone Torresin**[2]
Francesco Babich[3] **Pawel Wargocki**[4] **Nicola Prodi**[1]
[1] Department of Engineering, University of Ferrara, Italy
[2] Department of Civil, Environmental and Mechanical Engineering, University of Trento, Italy
[3] Institute for Renewable Energy, Eurac Research, Italy
[4] Department of Environmental and Resource Engineering, Indoor Environment, Technical University of Denmark, Denmark

ABSTRACT

Ensuring adequate indoor environmental quality (IEQ) in educational settings is essential for safeguarding students' well-being and optimizing learning. Despite the importance of this issue, limited research has examined the cross-modal effects of acoustics and indoor air quality (IAQ). In this laboratory study, 29 university students were tasked with assessing soundscapes and evaluating IAQ under two CO_2 concentrations (800 and 3000 ppm) and four acoustic conditions (quiet, babble noise, mechanical ventilation noise, and birdsongs). Soundscape data were analysed using linear mixed-effects models, while IAQ assessments were analysed with general linear mixed models. All models accounted for the effects of the sounds, CO_2 concentrations, and their interactions. The results revealed that soundscape evaluations were influenced solely by the acoustic conditions, with birdsongs being perceived as pleasant, quiet and calm, mechanical ventilation as monotonous, and babble noise as chaotic. In contrast, IAQ evaluations were affected only by the CO_2 concentration, with poorer air quality leading to worse perceptions. In conclusion, for the conditions tested in this experiment, each assessment was independently influenced by its respective domain, suggesting an absence of cross-modal effects.

[*] ***Corresponding author***: matteo.pellegatti@unife.it.

Keywords: *Students, Soundscape, Ventilation Sounds, IAQ.*

1. INTRODUCTION

Maintaining a high Indoor Environmental Quality (IEQ) in indoor environments is fundamental for creating a comfortable setting that ensures adequate individual well-being. Only recently have the four IEQ domains, namely thermal, acoustic, air quality, and visual comfort, been studied together; however, few studies have addressed acoustics and air quality [1], particularly in educational settings. The joint investigation of these two domains is also valuable for informing the choice between natural and mechanical ventilation. In this study, therefore, we sought to investigate the cross-modal interaction effects of air quality and ventilation sounds on evaluations of the soundscape and air quality, adopting the terminology by Chinazzo et al. [2].

2. METHODS

An experiment was conducted at the field lab of the DTU Sustain Indoor Environment Section. The laboratory was equipped with two tables, two chairs and a partition. A total of 29 students participated in the experiment and were remunerated for their two hours commitment with a voucher worth 300 DDK (40€) for the university bookshop. Participants were asked to assess both the air quality and the soundscape while being exposed to four auditory stimuli associated with natural and mechanical ventilation, namely

quiet, babble noise, mechanical ventilation and birdsong, and at two CO_2 concentrations obtained via bio-effluents, namely 3000 ppm (poor IAQ) and 800 ppm (good IAQ). The sound stimuli were recorded binaurally: those from natural ventilation were recorded with the left ear directed towards an open window, whereas those from mechanical ventilation were recorded inside a laboratory fitted with an HVAC system operating at 160 l/s. The sounds were then reproduced with headphones at 47 dBA. For each auditory stimulus, the students first completed the IAQ evaluations followed by the soundscape assessments. Each exposure was interspersed with a 5-minute break outside the testing laboratory to prevent accumulated CO_2 exposure. The students first completed the entire experiment for one CO_2 concentration and then for the second concentration. At the end of the experiment, participants completed a questionnaire on noise sensitivity [3]. The combinations of exposure conditions and CO_2 concentrations were balanced using a Latin square design. Specifically, the air quality questions comprised a descriptive multiple-choice item in which participants had to indicate whether the environment was humid, dry, fresh, stuffy, smelly, or odourless, and three 4-point Likert scale items assessing the acceptability of the indoor air quality, the ventilation, and the extent of air pollution. For the analysis of these responses, participants who provided contradictory air quality evaluations for the same listening condition (for example, rating the air as both "stuffy" and "fresh") were excluded. Additionally, responses for "dry" and "humid" were excluded, as they were considered inconsistent. All responses were recoded into dichotomous values (0, 1): for the descriptive items, a single descriptor was retained (stuffy/fresh and malodorous/odourless), while for the Likert scales data were transformed into two values: acceptable vs. not acceptable and polluted vs. not polluted. Subsequently, mixed generalized linear models (GLMM) were developed, incorporating the auditory stimulus, the CO_2 concentration, and their interaction as fixed effects. The order in which the listening conditions were administered was included as a covariate, and participants were entered as a random factor; the model was specified with a binomial distribution. For the soundscape evaluation, data were collected using Method A of ISO/TS 12913-2 [4]. Participants were asked to provide their evaluations as if they were undertaking an examination. This is significant, as soundscape theory posits that context plays a crucial role in the assessment of acoustic stimuli.

The parameters of pleasantness and eventfulness, as specified in ISO/TS 12913-3 [5], were then computed and analysed using linear mixed models. Specifically, both pleasantness and eventfulness were examined as functions of the auditory stimuli, the CO_2 concentration, and their interaction. Noise sensitivity, together with its interaction with the acoustic condition, was included as a covariate, with participants entered as a random variable.

3. RESULTS

The air quality models revealed only an effect of CO_2 concentration (all ps<0.009) and no cross-modal effect. All evaluations deteriorated when transitioning from a good to a poor IAQ; consequently, the air was perceived as more stuffy, odorous, and polluted. Moreover, the acceptability of both the IAQ and the ventilation was reduced.

Regarding the soundscape evaluations, participants indicated that the noise from the mechanical ventilation was monotonous, the babble noise chaotic, birdsongs generally pleasant, and quiet as calm. In the statistical models, only the acoustic condition influenced soundscape perceptiononly the acoustic condition influenced soundscape perception (Pleasantness $\chi^2(3)=125$, $p<0.001$; Eventfulness $X^2(3)=165$, $p<0.001$). As for the main effect of noise condition, mechanical ventilation and babble were the least pleasant conditions, both differing significantly from quiet and birdsong. No other differences emerged. As concerns eventfulness, the conditions ranked in descending order as follows: babble, birdsong, mechanical ventilation, quiet, with all differences being significant.

All soundscape results are reported in Fig. 1.

4. DISCUSSIONS

The results obtained for IAQ are consistent with the few studies on cross-modal effects, which have not identified any influence of the acoustic domain on IAQ [6]. They also concur with literature indicating that an increase in CO_2 concentration leads to a deterioration in perceived IAQ [7]. Regarding the soundscape, however, our findings oppose those from studies on outdoor soundscapes—which report that odours affect perception [8]—but they align with observations for indoor parameters, where no cross-modal effects have been detected [6]. The absence of cross-modal effects on the soundscape might, however, also be attributable to an insufficient exposure to elevated CO_2 concentrations, as the studies available in the literature have employed prolonged exposures rather than the acute exposures used in the present case [8]. The trends observed for pleasantness and eventfulness are also in line with the literature [9-10].

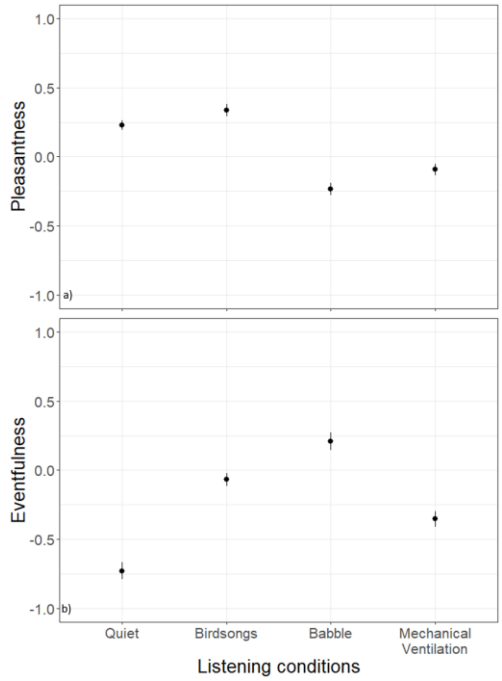

Figure 1. Mean values and standard error for the soundscape assessments of each listening condition. a) Pleasantness, b) Eventfulness.

5. CONCLUSIONS AND LIMITATIONS

This work aimed to provide a broader perspective on the cross-modal effects of acoustics and IAQ in relation to both natural and mechanical ventilation for university students. The results demonstrated that the domains appear to be independent, suggesting that a conventional, unidimensional approach may be sufficient. However, these findings cannot be generalised, as soundscape evaluations depend on the context in which they are assessed; in this case, only an examination setting was considered, and it cannot be excluded that a different scenario might yield divergent results. Furthermore, different sound stimuli and longer exposures could reveal cross-modal effects on both soundscape perception and IAQ assessment; indeed, modulation of variables (e.g. different types or levels of sound) might elicit variations in the evaluation of IAQ, and vice versa. Future studies could extend this research by incorporating additional sound levels, alternative sound stimuli, and varying CO_2 concentrations—as well as by considering longer exposure durations and diverse contexts—in order to either corroborate or refute the present null-effect findings.

6. ACKNOWLEDGMENTS

Matteo Pellegatti wishes to express his gratitude to Stefan Zillekens from Head Acoustics GmBh for the loan of the equipment.

7. REFERENCES

[1] S. Torresin, G. Pernigotto, F. Cappelletti, A. Gasparella: "Combined effects of environmental factors on human perception and objective performance: A review of experimental laboratory works", *Indoor Air*, vol.28, pp. 525–538, 2018.

[2] G. Chinazzo, R. K. Andersen, …, S. Wei: "Quality criteria for multi-domain studies in the indoor environment: Critical review towards research guidelines and recommendations", *Building and Environment,* vol 226, 2022.

[3] V. P. Senese, F. Ruotolo, G. Ruggiero and T. Iachini:"The Italian version of the Weinstein Noise Sensitivity Scale: Measurement invariance across age, sex, and context", *European Journal of Psychological Assessment, 28*(2), pp. 118–124, 2012

[4] ISO - ISO/TS 12913-2:2018 - Acoustics — Soundscape — Part 2: Data collection and reporting requirements

[5] ISO - ISO/TS 12913-3:2019 - Acoustics — Soundscape — Part 3: Data analysis

[6] G. Clausen, L. Carrick, P.O. Fanger, S.W. Kim, T. Poulsen, J.H. Rindel: "A Comparative Study Of Discomfort Caused By Indoor Air Pollution, Thermal Load And Noise", *Indoor Air*, vol.3, pp. 255–262, 1993.

[7] B. Du, M. Tandoc, M.L. Mack, J. Siegel: "Indoor CO2 concentrations and cognitive function: A critical review", *Indoor Air*, vol.30, pp. 1067–1082,2020

[8] M. Ba, J.Kang: "Effect of a fragrant tree on the perception of traffic noise", *Building and Environment*, vol. 156, pp. 147-155, 2019.

[9] S. Shu, H. Ma:. "Restorative Effects of Classroom Soundscapes on Children's Cognitive Performance". *International Journal of Environmental Research and Public Health*, vol. 16, no. 2, 2019

[10] W. Yang, K. Makita, T. Nakao, T. "Affective auditory stimulus database: An expanded version of the International Affective Digitized Sounds (IADS-E)". *Behav Res,* vol. 50, pp. 1415–1429, 2018