MULTISENSORY AUGMENTATION OF UNIVERSITY STUDY ROOMS: THE CROSS-MODAL ROLE OF SCENTS ON SOUNDSCAPE PERCEPTION

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Abstract

Indoor soundscape and smellscape research is transforming the conception of built environments, moving beyond sensory neutrality toward the intentional design of spaces that are pleasant and supportive of occupants' activities, while explicitly recognizing the multisensory nature of environmental experience. This laboratory study investigated the effects of auditory and olfactory augmentation on soundscape perception in university study rooms. Thirty-six students participated in a full-factorial within-subject experiment, experiencing nine combinations of three binaural auditory conditions (baseline study-room background, background plus forest sounds, and background plus music) delivered via closed headphones, and three olfactory conditions (odourless, Talcum, and Swiss pine) administered through an eight-channel olfactometer. Participants evaluated soundscape and smellscape perception. Preliminary results indicate significant effects of sound type on soundscape pleasantness and eventfulness: music enhanced perceived pleasantness, whereas forest sounds increased eventfulness relative to baseline. Importantly, cross-modal effects of olfaction were also observed. Valence-related dimensions were aligned, with higher smellscape pleasantness associated with greater soundscape pleasantness, while activation-related dimensions were linked, as stronger smell presence corresponded to higher soundscape eventfulness. These findings highlight the potential of combined audio–olfactory strategies to enhance indoor study environments, warranting further validation in real-world settings.

Keywords: *indoor soundscape, indoor smellscape, multi-domain*

1. Introduction

University study rooms are environments where students can spend a significant portion of their time engaged in focused learning. Consequently, indoor environmental conditions play a key role in shaping both well-being and cognitive performance, particularly in such spaces that are meant to foster concentration. Moving beyond conventional priorities focused exclusively on noise reduction and the control of indoor air contaminants, recent research highlights the potential of acoustic and olfactory design to enrich user experience, support positive emotions and cognitive performance, and reduce stress [1], [2].

In open-plan offices, added sounds—such as ventilation noise, pseudo-random noise, or water features—have been used to mask speech and enhance comfort and task performance [3], [4]. In contrast, libraries and study areas are generally quiet

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environments characterized by low-level sounds, including whispers and movement-related noises (e.g., chairs scraping or keyboard typing). In these settings, the main objective is to create an atmosphere conducive to studying rather than to strictly address issues of speech privacy or intelligibility.

Similarly, evidence suggests that pleasant ambient scents can positively influence cognitive processes and emotional states [5], [6]. In study spaces where the air may feel stale, scents cannot replace adequate ventilation, but they can enhance perceived air quality.

Drawing on recent frameworks for assessing soundscape and smellscape perception indoors through occupant-based surveys [6], [7], [8], this study presents findings from a laboratory experiment investigating the effects of sound and scent enhancements in university study rooms on students' affective, physiological, and cognitive responses. Given the exploratory nature of the study, the focus is limited to perceptual outcomes, excluding physiological and cognitive responses. Unlike much of the existing literature, which considers auditory and olfactory influences separately, this research adopts a multisensory perspective and explores potential cross-modal interactions [9]. Specifically, it examines whether olfactory stimuli—and their perceptual evaluation as smellscape—can influence soundscape perception in study environments, a topic that remains largely underexplored and for which current evidence has so far reported no significant effects [10], [11].

2. Materials and methods

The experiment was carried out between October and December 2025 in a sound-attenuated booth at the Multisensory Lab of the Center for Brain/ Mind Studies, University of Trento. The facility includes an eight-channel olfactometer and closed electrodynamic headphones for binaural audio playback.

Thirty-six adults participated (30 aged 18–30, five aged 31–40, one aged 41–50; balanced gender distribution). Each was exposed to nine audio–olfactory conditions derived from three auditory scenarios—study room background (B), background plus forest sounds (B+F), and background plus instrumental music (B+M)—combined with three olfactory conditions: odourless (O), Talcum (T), and Swiss pine (P). The study followed a within-subject full-factorial design over two sessions on separate days, with randomized presentation order.

Stimuli were selected based on available anecdotal or scientific evidence suggesting potential positive user appraisal [6, 7], with the aim of informing future soundscape and smellscape interventions in real study spaces. The baseline auditory condition (B) was recorded in a real university study room using a head-and-torso simulator (HATS, Head Acoustics HMS II.3 LN HEC) and a calibrated sound level meter (1/2'' prepolarized free-field condenser microphone connected via a data acquisition system Apollo Box by Sinus to a laptop). A 10-minute excerpt captured HVAC noise and typical low-level study sounds (e.g., footsteps, chair movement, typing), without intelligible speech. For the augmented conditions, either natural sounds (rain, wind in trees, birdsong) or instrumental music were added, drawing on commercial audio tracks used in indoor soundscape augmentation; specific details cannot be disclosed due to intellectual property constraints. Signals were convolved with binaural room impulse responses measured in the same room to reproduce a realistic stereo setup and reproduced binaurally via headphones (HD CL I.1) using a USB adapter with equalization for aurally accurate playback (BPU Bundle by HEAD Acoustics). Playback levels matched the measured background (61.6 dB $L_{Aeq,1min}$ for B) and were slightly higher for augmented conditions (62.8 and 62.5 dB for the B+F and B+M conditions, respectively), ensuring that added sounds remained subtle and non-intrusive.

For olfactory stimulation, Talcum essence (≥99% purity) and Swiss pine oil (100% purity) were placed in sanitized glass jars and delivered through the olfactometer. Odours were presented at 1.5 SLPM for 3 seconds, alternating with clean air at 1 SLPM for 2 seconds, with airflow calibrated before each session. Clean air flowed continuously throughout. Stimulus timing, valve control, and randomization were managed via a custom Python script interfaced through USB.

Participants sat individually at a computer, wearing headphones and nasal cannulae, with physiological sensors attached (not detailed here). At the start of each condition, they viewed a photograph of the study room and were asked to imagine being there. Each condition lasted 12 minutes and included cognitive tasks (not detailed here). After one minute of exposure, participants completed a questionnaire assessing soundscape and smellscape perception. Soundscape was evaluated using the eight attributes of ISO/TS 12913-2 (Method A) on 5-point Likert scales. Responses were transformed following ISO/TS 12913-3 to obtain Pleasantness and Eventfulness coordinates. Smellscape perception was assessed using eight attributes from Torriani et al.'s model [6], yielding coordinates on the Pleasantness and Presence dimensions.

Before the experiment, demographic and profiling data were collected, including noise sensitivity [12], smell sensitivity [13], introversion [14], and psychological well-being (WHO-5) [15]. The study was approved by the University of Trento Research Ethics Committee (protocol no. 2025-030).

Data were analyzed using linear mixed-effects models in R (v4.3.2, *lme4* package). Models tested the effects of auditory and olfactory conditions and their interaction on soundscape dimensions, with individual traits as fixed effects and participant as a random intercept (Section 3.1). Additional models examined the influence of smellscape perceptual dimensions (Pleasantness and Presence) on soundscape outcomes (Section 3.2). Assumptions were verified, fixed effects were tested using the *car* package, and Benjamini-Hochberg-corrected post hoc comparisons were performed with *emmeans*. Effect sizes were estimated using semi-partial R^2 (sr^2) for fixed effects in the linear mixed-effects models, and Cohen's d was calculated for post hoc pairwise comparisons.

3. Results

3.1 Effects of sound and smell type on soundscape perception

A significant main effect of the sound condition was observed on soundscape pleasantness, $F(2, 280.05) = 4.26$, $p = 0.015$, $sr^2 = .030$. While all sound scenarios were on average perceived as pleasant, post hoc comparisons revealed that the background condition (B) was rated as significantly less pleasant than the background condition with music (M+B) ($p = 0.012$, Cohen's $d = 0.40$, small effect).

Among individual factors, gender significantly influenced soundscape pleasantness, $F(1, 26.47) = 4.81$, $p = 0.037$, $sr^2 = 0.154$, with females reporting lower pleasantness scores than males (medium effect, $d = 0.51$). Age, noise sensitivity, smell sensitivity, well-being (WHO-5), and introversion were not significant predictors. No significant main effects of smell type or smell × sound interaction effects were observed for soundscape pleasantness.

As regards soundscape eventfulness, this was significantly affected by the sound condition, $F(2, 279.47) = 4.98$, $p = 0.008$, $sr^2 = 0.034$. Post hoc analysis indicated that the background condition (B) was perceived as less eventful than in the presence of forest sounds (F+B) ($p = 0.024$, $d = 0.36$, small effect).

Noise sensitivity significantly predicted soundscape eventfulness, $F(1, 27.10) = 6.38$, $p = 0.018$, $sr^2 = 0.191$, indicating that individuals with higher noise sensitivity perceived the soundscape as more eventful.

Gender, age, smell sensitivity, well-being, and introversion were not significant predictors. No significant main effects of smell or smell × sound interaction effects were detected for soundscape eventfulness.

3.2 Effects of sound type and smellscape perception on soundscape perception

The analyses that follow concern a different set of variables, in which, in addition to the acoustic conditions, not smell type but the smellscape pleasantness and presence scores are considered. A significant main effect of the sound condition on soundscape pleasantness was observed, $F(2, 285.52) = 3.05$, $p = 0.049$, $sr^2 = 0.021$, indicating small but significant differences in pleasantness across sound conditions, as previously observed. Smell pleasantness emerged as a strong predictor of soundscape pleasantness, $F(1, 309.61) = 27.41$, $p < 0.001$, $sr^2 = 0.081$. Higher olfactory pleasantness was associated with higher perceived soundscape pleasantness, as showed in Fig. 1.

In contrast, smell presence had no significant effect. Among individual factors, gender showed a marginal effect, $F(1, 26.79) = 3.39$, $p = 0.077$, $sr^2 = 0.112$, and age also showed a trend toward significance, $F(2, 26.48) = 2.57$, $p = 0.096$, $sr^2 = 0.163$. However, noise sensitivity, smell sensitivity, psychological well-being (WHO-5), and introversion were not significantly associated with pleasantness ratings (all $p > 0.10$).

As regards soundscape eventfulness, a significant main effect of the sound condition was also found, $F(2, 284.27) = 3.38$, $p = 0.036$, $sr^2 = 0.023$, indicating that perceived eventfulness varied across sound scenarios. Moreover, smell presence significantly influenced soundscape eventfulness, $F(1, 294.26) = 15.79$, $p < 0.001$, $sr^2 = 0.051$, suggesting that the presence of smell increased perceived eventfulness (see Fig. 1). The contribution of smell pleasantness, however, was not significant.

Among individual characteristics, as previously observed, noise sensitivity significantly predicted eventfulness ratings, $F(1, 27.16) = 6.95$, $p = 0.014$,

sr^2 = 0.204, indicating that more noise-sensitive participants perceived the soundscape as more eventful. No significant effects were found for gender, age, smell sensitivity, WHO-5 well-being, or introversion (all $p > .20$).

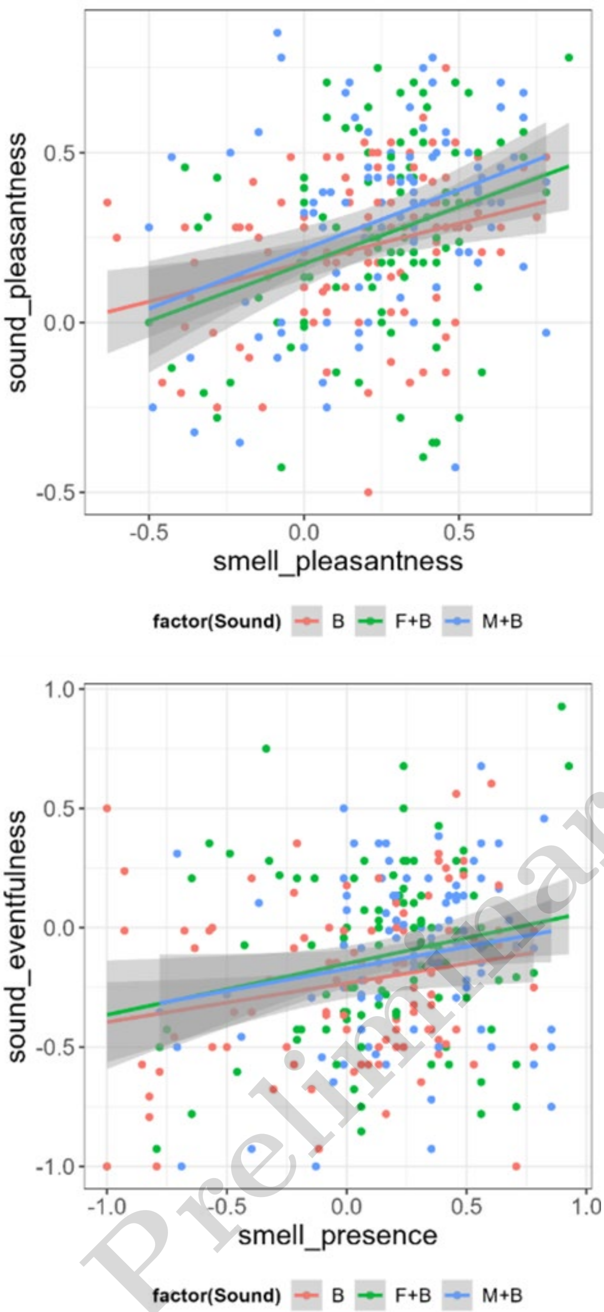

Figure 1. Scatterplot of sound pleasantness and smell pleasantness (top) and of sound eventfulness and smell presence (bottom) ratings across sound conditions. Lines show linear regression fits with 95% confidence intervals.

4. Discussion and final remarks

The present study investigated the main and cross-modal effects of different auditory and olfactory stimuli on soundscape perception in study-room environments using a laboratory-based design. As expected, sound type significantly influenced both soundscape pleasantness and eventfulness. Specifically, augmenting the baseline acoustic environment with music enhanced perceived pleasantness, whereas the addition of forest sounds increased perceived eventfulness compared to the background-only condition.

Notably, to the best of the authors' knowledge, this study is among the few to demonstrate a cross-modal influence of the olfactory domain on soundscape perception [10]. Previous research has explored potential links between odor, olfactory comfort, and noise perception. For instance, Pan et al. reported that odor exerted neither synergistic nor antagonistic effects on sound pressure level perception, suggesting a limited impact on acoustic comfort [16]. Similarly, variations in CO_2 or bioeffluent concentrations did not produce meaningful changes in acoustic comfort or soundscape evaluations [11], [17], [18]. The present findings indicate that it was not the specific type of odor that influenced soundscape perception, but rather its perceived qualities. We observed a systematic coupling between affective dimensions across sensory domains: valence-related dimensions were aligned (i.e., smellscape pleasantness was positively associated with soundscape pleasantness), while orthogonal activation-related dimensions were also linked (i.e., smellscape presence was associated with higher soundscape eventfulness). Thus, more pleasant olfactory environments were associated with more pleasant soundscapes, whereas stronger perceived olfactory presence corresponded to increased soundscape eventfulness.

Overall, the results indicate that soundscape evaluations are not determined solely by auditory inputs, but can also be shaped by olfactory cues. Should these findings be replicated in real-world contexts, they would point to the potential of using pleasant olfactory environments to improve perceived soundscape pleasantness. Moreover, when acoustic conditions are already positively evaluated, the addition of olfactory stimuli may contribute to creating soundscapes that are not only pleasant but also more vibrant (i.e., both pleasant and eventful).

Future studies should further investigate the bidirectional cross-modal relationships between olfactory and auditory domains, with particular attention to the underlying physiological and cognitive mechanisms. Exploring these interactions in both controlled laboratory settings and ecologically valid environments will be essential to better understand their implications for multisensory environmental design.

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