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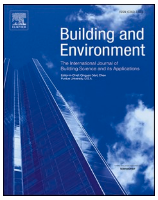

Smells modulate thermal sensation: A multisensory study in office environments during winter

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ABSTRACT

Recent advances in multisensory studies have highlighted the potential influence of sensory interactions on human perception. However, the relationship between environmental smells and thermal sensation remains underexplored. This study investigates how exposure to olfactory stimuli influences perceived thermal sensation over time, using two fragrances with "warm" (vanilla) and "cool" (fig) connotations. A controlled experiment was conducted in a living lab in Bolzano (Italy) during winter, involving 24 participants and three identical test rooms: one odourless (control), and two scented with vanilla and fig scents. Participants experienced each condition for 15 min and rated their thermal sensation using a 7-point Thermal Sensation Vote scale at 5-minute intervals. Data analysis using a Cumulative Link Mixed Model revealed that the vanilla scent consistently increased the likelihood of reporting warmer thermal sensations compared to the odourless condition, with the effect strengthening over time and peaking at 15 min. At that timepoint, the probability of perceiving warmth in the vanilla-scented room was approximately 95% higher than in the control setting ($p < 0.001$). Conversely, the fig scent produced a delayed cooling effect, becoming significant only after 15 min, with an 88% higher probability of reporting cooler sensations compared with the control setting ($p < 0.001$). These effects are attributable to perceptual and cognitive association mechanisms. The findings suggest that incorporating olfactory cues into building design could enhance perceived thermal comfort without changing the set-point temperature, thereby potentially enabling energy savings.

Introduction

Over the past decade, research has increasingly focused on the relationship between humans, smells, and the built environment [1–4]. The term "smellscape" was first introduced by Porteous in 1985, highlighting the significance of the olfactory environment as perceived and understood by individuals in specific places [5].

Historically, managing indoor olfactory environments has focused on controlling odour nuisance, aiming to achieve olfactory neutrality—an environment where occupants do not perceive any odour [3]. However, recent findings challenge this perspective, suggesting that achieving odour neutrality may not always be the optimal approach [6]. The presence of pleasant olfactory stimuli can be perceived as more comfortable than the complete absence of detectable odours, positively affecting people's mood, well-being, health, and satisfaction (also in other domains) [6].

Building occupants are continuously exposed to multiple indoor environmental stimuli beyond odours, including thermal (e.g., air temperature, relative humidity), visual (e.g., light intensity, window view quality), acoustic (e.g., noise levels, reverberation time), and indoor air quality (e.g., particulate matter, carbon dioxide) related factors [6–9]. In recent years, research has increasingly focused on the effects of these factors on human comfort, revealing the presence of cross-modal and combined effects between them [10,11]. According to the definitions proposed in the review by Chinazzo et al. [8] a cross-modal effect occurs when a stimulus in one sensory modality influences a response typically triggered by a different sensory modality. For example, the presence of an odour can make a visual environment appear more or less pleasant, depending on whether the smell is perceived as agreeable or disagreeable [12]. In such interactions, the influence of stimulus B on the

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response to stimulus A can be neutral, positive, or negative, depending on whether it strengthens or weakens the original perception [8]. In contrast, a combined effect refers to the influence of multiple stimuli acting together to affect responses not directly tied to a single indoor stimulus—such as perceptions of overall comfort, physical and psychological states, behaviour, physiology, or performance. These effects can be additive (the combined presence results in the sum of the separate effects), synergistic (the combined presence results in a greater effect than the sum of the separate effects), or antagonistic (the combined presence results in less than the sum of their separate effects) [8]. An example of combined effect is provided by Mattila et al. [13], who showed that consumers were more inclined to make a purchase when background music and ambient scent were aligned in terms of pleasantness and arousal.

Building occupants are continuously exposed to diverse odours, leading to odour habituation—a phenomenon characterized by a reduced sensory response to scents after repeated exposure [14]. The role of exposure duration is particularly critical, as it determines how the intensity and influence of odours evolve over time [15]. Extended exposure may not only diminish the perceived intensity of certain smells but could also potentially alter their interaction with other senses. For instance, odours can sustain visual attention toward matching food products without diminishing over time, but their influence on actual food product choices may decrease with repeated exposure, suggesting a complex role for olfactory cues in decision-making [16].

Moreover, individual factors such as genetics, age, sex, medical history of infection and trauma, neurogenerative diseases and neurodiversity, emotional diseases, and geographical location shape olfactory perception [17]. The variability in olfactory sensitivity makes it essential for studies in this field to employ statistical analyses capable of accounting for both intra- and inter-subject variability [18].

Previous evidence from experimental psychology showed that odours are subjectively categorized as "cold" or "hot" [19]. For example, in the corpus of contemporary American English [20] we can read “the hot smell of plum brandy” or “the cool smell of the pine needles”. Furthermore, in some languages a combination of both olfactory and thermal meaning under a single term is fully lexicalized, e.g., fîk/vîk in Lushai, spoken in India, can refer to pungent smells as well as biting cold [21]. Furthermore, research demonstrate the existence of combined effects of smell-thermal environment [22,23]. However, the cross-modal influence of olfactory environments on thermal sensation in relation to the different adaptation processes in indoor settings remains limited.

Therefore, this study investigated how exposure to different olfactory stimuli influences perceived thermal sensation over time. The study used cumulative link mixed models (CLMM) to analyse data from 24 participants exposed to three olfactory conditions— “hot" vanilla scent, "cold" fig scent, and an odourless control—in an office setting. The study aimed to answer the following research questions: i) how does exposure to environmental scents influence thermal sensation during winter conditions? and ii) how long does it take for olfactory stimuli to significantly affect thermal comfort? Answering these research questions is particularly relevant today, as it may open new avenues for using olfactory stimuli to enhance thermal comfort while reducing reliance on mechanical heating or cooling systems, thereby supporting energy-saving strategies.

Methodology

Testing facility

The experiments were conducted in Eurac Research’s Living Lab, located at NOI Tech Park (Bolzano, Italy). The Living Lab (LL) comprises four identical 28,4 m^2 rooms ($h = 2.7$ m) equipped with four workstations and identical furnishings (Fig. 1, Fig. 2). The glazed surfaces are triple-glazed windows ($U_w = 0.70$ W/m^2K) that face outdoor environment. Each room is equipped with four supply and four return air ducts, resulting in a total of 16 diffusers per room (Fig. 1). The total airflow rate per room is 320 m^3/h, corresponding to an air exchange rate (ACH) of 4.2 h^{-1}. Given the low-velocity mixed-air system and uniformly distributed diffusers, the ventilation effectiveness (ε_v) was assumed to be 1.0, or, conservatively, 0.9, both fully compliant with EN 16,798–3 [24]. Windows were kept closed during the test. The thermal environment and indoor air quality inside the rooms were monitored as detailed in section 2.3.

Scent diffusers were positioned in three rooms (LL_01: fig scent, LL_02: odourless condition, LL_03: vanilla scent), while one room (LL_00) was employed as odour recovery room. A corridor with the same thermo-hygrometric conditions provided a connection between the different rooms.

Scent diffusion system

Following Adams and Doucé’s [25] findings on cross-modal scent perception, vanilla was chosen as a “hot” scent. The fig fragrance instead was chosen as a “cold” scent according to the descriptions and reviews available online and based on an exploratory pilot pre-test in which five individuals associated the fig scent with a cool sensory impression. As this pre-test was informal and no published references support this association, the fig scent was an exploratory choice in this study. . Both scents were diffused in the rooms using a ScentAir Direct™ Diffuser,

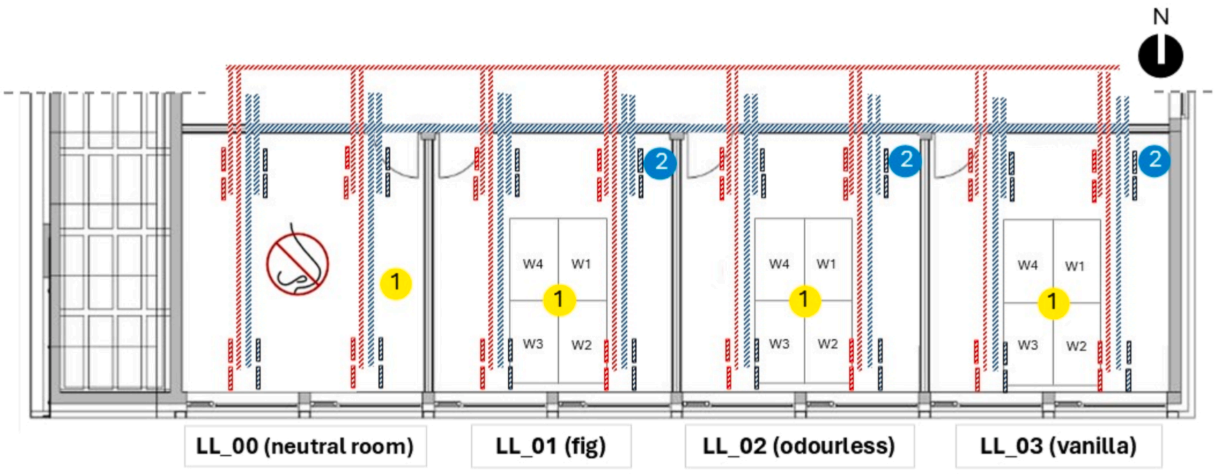

Fig. 1. Floor plan of Eurac Research’s Living Lab (LL). 1 = environmental monitoring (InBiot Mica – 0.60 m from floor), 2 = Scent diffuser. Blue and red ducts represent air supply and air return, respectively.

Fig. 2. Living lab experimental rooms.

provided by AromaDesign® (Fig. 3). The diffusion system has an atomization technology that releases a fine mist for 30 s every 10 min. To prevent participants from recognizing the odour, no label was placed on the air fresheners. An odourless condition was also tested in order to have a baseline.

Environmental measurements

Air temperature (Ta), relative humidity (RH), total volatile organic compounds (TVOCs), carbon dioxide (CO_2), and particulate matters ($PM_{2.5}$ and PM_{10}) were measured using the InBiot Mica devices (Fig. 1). The instruments were placed 0.6 m from the ground to simulate the participant's seated position, 2 m from the external wall, and close to the participant's workstations. The devices were shielded from direct sunlight, cleaned, and calibrated. Annex B shows the key features of the InBiot Mica device.

Fig. 3. ScentAir Direct™ Diffuser (www.aromadesign.it) [26].

Participants

Twenty-four individuals took part in the experiments (14 males, 10 females, mean age: 34.3 years, SD: 8.8 years). Participants were researchers working in the same building where the experimental sessions were conducted and were recruited via email invitation according to the following eligibility criteria: 18 - 65 years old; good general health and no history of known olfactory disorders, neurological conditions, or serious health issues that could affect the olfactory and thermal perception; not pregnant; without known respiratory conditions such as persistent colds, sinusitis, or other issues that might affect olfactory perception; good level of the English language (minimum level: upper-intermediate B2) in order to be able to fill the administered questionnaires; capability of providing informed consent, which all participants gave prior to participate.

Participants were asked to wear typical office winter clothing (i.e., long legs and sleeves, sweater, socks, shoes – approximately 1.00–1.20 clo according to ISO 7730 [27]) and not to change clothing insulation while performing the test. No monetary compensation was provided.

Verification of the olfactory function of participants

The SCENTinel 1.1 Rapid Smell Test [28] was employed before the beginning of the experiment to test the participants' ability to identify and differentiate between odours, as well as their odour threshold, according to ISO 16,000–30 [29] (Fig. 4). Importantly, all four functions were evaluated using the standardised reference odour provided in the SCENTinel kit, which has a floral-like profile and is different from the experimental scents used in this study (fig and vanilla). Additionally, this test included a measure of pleasantness, a key to the test's ability to identify parosmia (i.e., a disorder related to the sense of smell, characterized by a distortion of the perception of odours). The SCENTinel assessment was completed before the 15-minute experimental exposure, allowing sufficient time to minimise any potential olfactory adaptation to the reference odour.

Subjective assessment

Participants were instructed to complete a questionnaire four times

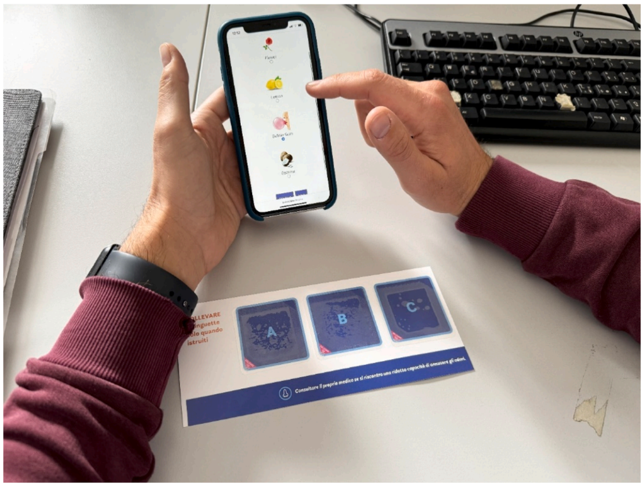

Fig. 4. SCENTinel rapid smell test. By scanning the QR Code, the participants received instructions and targeted questions aimed at understanding olfactory ability from the perspective of: (1) odour identification, (2) odour threshold, (3) discrimination between odours, and (4) identifying pleasantness [4].

during their stay in each room. The survey was implemented on SurveyMonkey.com and was accessible through a QR-code which was present in each workstation.

The questionnaire consisted of two sections. In the first section, the participant's ID, the workstation ID, age, gender were recorded. The second section investigated the indoor environmental comfort, with the following questions:

- "What smells do you detect in your current office room? (Multiple answers allowed)" – Multiple choice ("No smells", "Vanilla", "Fig", "Peppermint", "Coffee", "Body odours", "Plants", "Cleaning products", "Other, please specify")
- (TSV) "Please, rate your current thermal sensation" – 7-point ASHRAE thermal sensation scale (−3 "Cold", −2 "Cool", −1 "Slightly cool", 0 "Neutral", +1 "Slightly warm", +2 "Warm", +3 "Hot") [30].
- "Please, rate the smell intensity of your current office room" – Likert (0 "No odour", 1 "Very weak", 2 "Weak", 3 "Distinct", 4 "Strong", 5 "Very strong", 6 "Extremely strong")
- "Please rate your current satisfaction level for the specific domains: (TSatV) thermal environment, (IAQSatV) indoor air quality (i.e., pollutants), (SSatV) smell environment, (GSatV) overall" – Likert (+3 "Very satisfied", +2 "Satisfied", +1 "Slightly satisfied", 0 "Neither satisfied nor dissatisfied", −1 "Slightly dissatisfied", −2 "Dissatisfied", −3 "Very dissatisfied").

Experimental procedure

The experiment was conducted between December 2024 and January 2025. The experiment was carried out in winter because it represented the first experimental campaign of the project, conducted at the earliest feasible opportunity given laboratory availability and project scheduling. The experimental procedures obtained all relevant legal and ethical approvals and were conducted in compliance with the Declaration of Helsinki. Each participant took part in one experimental session, lasting approximately 85 min (Fig. 5).

During the initial 30 min, participants were briefed on the experiment and provided informed consent while acclimating to the room environment. Participants were briefly informed that the study involved evaluating indoor environmental perceptions, including smells, without disclosing the specific aims related to particular scents in order to avoid biasing their responses. During this phase, participants' ability to recognize, identify, perceive intensity, and assess the pleasantness of odours was also evaluated (please, see Section 2.5). Subsequently, participants entered the first room in randomized order—either LL_01 (fig), LL_02 (odourless) or LL_03 (vanilla)—in groups of four and took their seats at the desk (same position in each of the three room) (Fig. 2). The questionnaire was completed four times over a 15-minute period, at 5-minute intervals. Following this, odour recovery took place in LL_00 (olfactory-neutral room) for 5 min before participants proceeded to the second room, where the procedure was repeated. The 5-minute inter-stimulus interval was selected to align with established olfactory research showing that short-term olfactory adaptation typically dissipates within a few minutes once the odorant is removed, and that intervals of approximately 3–5 min are commonly used to minimise carry-over effects in psychophysical olfactory testing [4,14]. The procedure was then repeated also for the third room. The three experimental rooms, the olfactory-neutral room, and the connecting corridor were all maintained at a constant temperature of 23 ± 1 °C and a relative humidity of 40 % ± 5 %.

Data analysis

Data were analysed using a CLMM in R (ordinal package [31]), which is appropriate for the ordinal nature of the response variable (Thermal Sensation Vote, ranging from –3 to +3). Fixed effects included the olfactory condition, time, participant age and gender, and the interaction between the olfactory condition and time. A random intercept for Participant ID was included to account for repeated

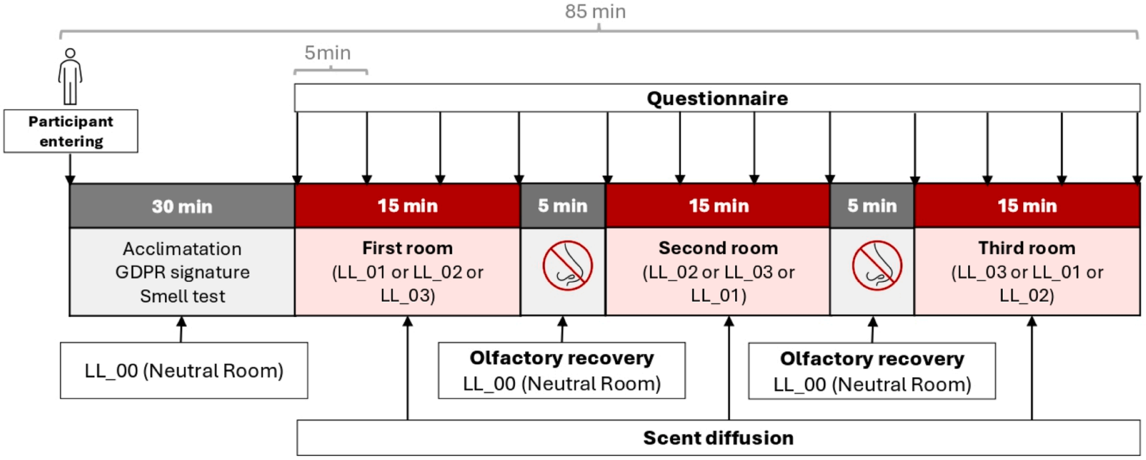

Fig. 5. Experimental procedure.

measurements within individuals. A logit link function was selected, allowing for interpretation of the coefficients in terms of cumulative odds ratios, and a symmetric transition between categories of the response scale was assumed. Estimated marginal means (EMMeans) and post-hoc pairwise comparisons were computed using the emmeans package, with Tukey adjustment for multiple comparisons [32]. All the CLMM assumptions were verified, as detailed in Appendix A.

Results

Measured indoor parameters

Table 1 shows the indoor environmental variables recorded during the experimental sessions. The mean indoor air temperature was 23.0 ± 0.3 °C in LL_01, 23.0 ± 0.2 °C in LL_02, and 22.8 ± 0.1 °C in LL_03. All the recorded values of indoor air temperature, relative humidity and CO_2 were considered satisfactory referring as a general benchmark to the EN 16,798–1 standard [33], which recommends operative temperatures of20–24 °C, RH=30–70 %, and $CO_2 < 1200$ ppm for offices. Since the rooms were operated under closed-window conditions with a low-velocity air distribution system, air velocity was assumed to be below 0.1 m/s.

The mean TVOC concentrations were considered satisfactory in all rooms, according to the World Health Organization (WHO) Guidelines for Indoor Air Quality [34], which recommends TVOC < 220 ppb. The maximum TVOC concentrations in LL_02 (322 ppb) and LL_03 (252 ppb) are still considered acceptable by WHO, which indicates TVOC concentrations above 660 ppb as poor.

The mean $PM_{2.5}$ and PM_{10} concentrations were considered satisfactory in all rooms, according to the WHO Guidelines, which recommends concentrations below 5 $\mu g/m^3$. The maximum PMs concentrations in LL_02 and LL_03 were still considered acceptable by WHO, which indicates PMs concentrations above 15 $\mu g/m^3$ as poor.

In this study, PMV was not computed, as thermal sensation was assessed directly through self-reported votes rather than indirectly through model-based estimations (e.g., Predicted Mean Vote, PMV). In addition, the predominantly thermo-physiological formulation of PMV makes it less suitable for capturing the affective and semantic influences introduced by odours, which represent a key focus of the present investigation.

Subjective responses

Fig. 6 highlights the most frequently reported perceived smells, with word size proportional to their recurrence. In LL_01, participants identified a wide variety of smells besides fig, including, for example, cleaning products, peppermint, and plants, suggesting a complex and not easily recognizable olfactory environment. In contrast, LL_02 was overwhelmingly described as having no smells, indicating a largely neutral sensory impression. LL_03 was dominated by the descriptor vanilla, pointing to a more homogeneous olfactory profile.

Table 1
Values of the indoor environmental variables recorded during the experimental sessions.

Parameter	Olfactory condition	Mean	Max	Min	SD
Ta (°C)	Fig	23.0	23.2	22.6	0.3
	Odourless	23.0	23.2	22.7	0.2
	Vanilla	22.8	23	22.6	0.1
RH (%)	Fig	33.1	34	32	0.8
	Odourless	32.8	34	32	0.8
	Vanilla	33.6	34	33	0.5
CO_2 (ppm)	Fig	677.8	871	547	123.7
	Odourless	605.2	783	478	124.6
	Vanilla	679.3	835	535	122.9
TVOC (ppb)	Fig	84.1	132	56	27.7
	Odourless	135	322	61	91.9
	Vanilla	143.3	252	71	65.4
PM_{10} ($\mu g/m^3$)	Fig	2.0	2	2	0
	Odourless	4.1	5	4	0.4
	Vanilla	4.6	5	4	0.5
$PM_{2.5}$ ($\mu g/m^3$)	Fig	2.0	2	2	0.0
	Odourless	4.1	5	4	0.4
	Vanilla	4.6	5	4	0.5

Fig. 7 illustrates the distribution of thermal sensation votes over time across olfactory conditions, showing how the influence of fig and vanilla becomes more pronounced with exposure duration. The impact of ambient fragrances on thermal sensation is further discussed in section 3.3.

The mean and standard deviation of the other subjective responses are reported in Table 2 and Fig. 8. The average perceived olfactory intensity with the odourless condition was 0.677, corresponding to “very weak”; the vanilla condition was perceived as “distinct” (3.468), and the fig condition as “strong” (4.196), with no notable variation over time.

Overall, the environment (GSatV) was perceived as slightly unsatisfactory with fig smell, neutral with vanilla smell, and slightly satisfactory with no odour. Global satisfaction increased slightly over the 15-minute period in both the vanilla and fig conditions, while it slightly decreased in the odourless condition.

Thermal satisfaction (TSatV) remained stable over time in the odourless condition, consistently rated as slightly satisfactory. For both vanilla and fig scents, thermal satisfaction increased over time: vanilla reached the same level as the odourless condition after 15 min, while fig remained at neutral levels.

Perceived air quality satisfaction (IAQSatV) remained slightly satisfactory throughout for the odourless condition and increased over time for both vanilla and fig scents. In the vanilla condition, satisfaction started as slightly unsatisfactory and reached a neutral level at 15 min; in the fig condition, it remained slightly unsatisfactory despite some improvement.

Olfactory satisfaction (SSatV) was initially highest in the odourless condition but decreased over time. Conversely, satisfaction increased similarly in the vanilla and fig conditions. At 15 min, vanilla reached the level of odourless, while fig—despite its increase compared to minute 0—remained slightly unsatisfactory.

Impact of ambient fragrances on thermal sensation

TSV in response to olfactory conditions across exposure time were analysed using a CLMM (Eq. 1) (Appendix A):

$$TSV \sim \text{Olfactory\_condition} + \text{time} + \text{Olfactory\_condition} * \text{time} + \text{Age} + \text{Gender} + (1|\text{Participant.ID}) \quad (3)$$

The dependent variable of the model is the TSV, on a Likert scale from −3 to +3. The fixed effects of the model are the olfactory condition (Odourless, Vanilla, Fig), exposure time (0,5,10,15 min) and their interaction. Also, gender (Male, Female) and age (18–30, 31–40, 41–50) were included as covariates. Participant ID was included as a random intercept considering individual variabilities in thermal sensation.

The model converged successfully (max gradient < 0.001) and was estimated using a logit link with flexible threshold, allowing cumulative probabilities to vary across ordinal categories. Model fit was adequate (logLik = −384.58, AIC = 803.16) and no issues of numerical instability were detected (condition number of the Hessian matrix = 220).

The variance in participants’ thermal sensation votes was 0.112, indicating individual variability in thermal comfort perception. The standard deviation of the responses was 0.334, representing a low level of individual variation relative to the full-scale range (<10 % of the 7-point range).

Table 3 shows a summary of fixed effects from the CLMM predicting thermal sensation votes. All coefficients are expressed in log-odds: higher values indicate a greater probability of perceiving warmth.

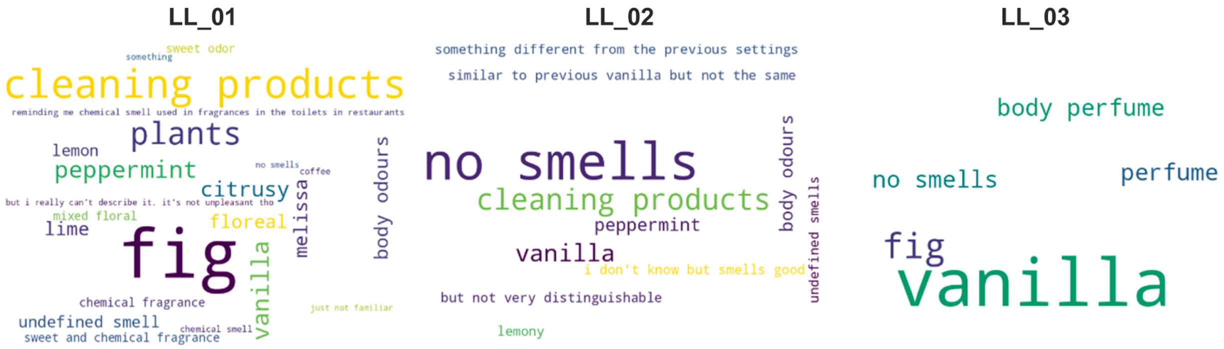

Fig. 6. Word clouds showing the perceived smells reported by participants for each room (LL_01, LL_02, LL_03). The size of each word is proportional to the number of times it was mentioned.

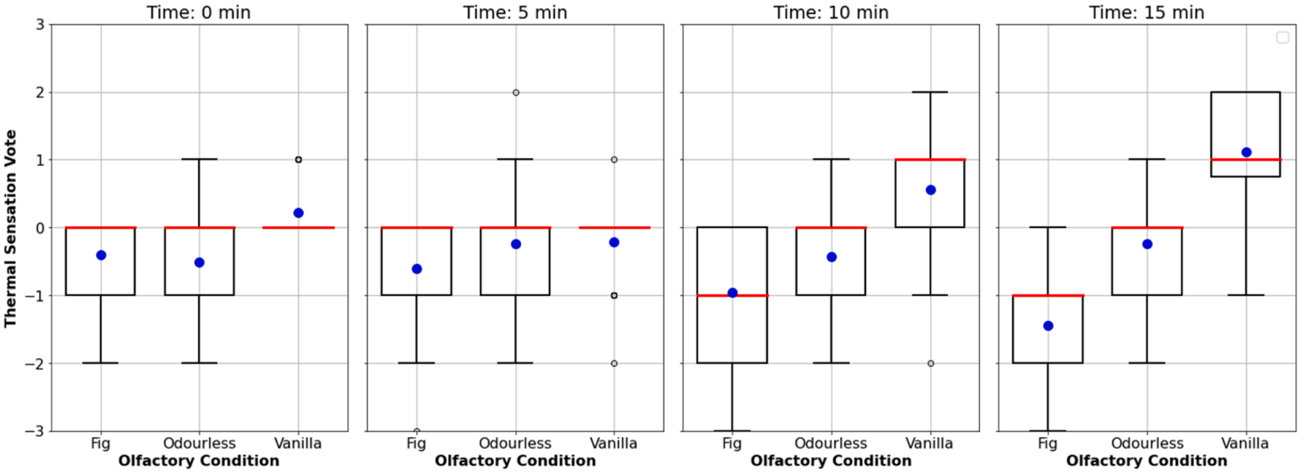

Fig. 7. Distribution of thermal sensation votes over time across olfactory conditions. Blue dots represent mean values, while red horizontal bars indicate median values.

The vanilla scent was associated with a significantly increased probability of perceiving a higher thermal sensation compared to the odourless condition (Estimate = 1.886, $p < 0.001$). This corresponds to an odds ratio of 6.59, calculated as exp(1.886), indicating that participants exposed to the vanilla scent were approximately 6.6 times more likely to perceive the environment as warmer than those exposed to no scent. All time points (5, 10, or 15 min) showed no statistically significant main effect, suggesting that time alone does not influence TSV, but may play a role through interaction with olfactory conditions. Likewise, no significant effects were observed for gender or age. The fig scent, on the other hand, showed a strong cooling effect but only after 15 min of exposure (*Estimate* = –2.790, $p < 0.001$). This translates to an odds ratio of 0.062 (i.e., exp(–2.790)), meaning that the odds of reporting a higher TSV were approximately 16.3 times lower than in the baseline condition (odourless at time 0).

Post-hoc pairwise comparisons between olfactory conditions over time (Table 4) revealed that the vanilla scent consistently increased the probability of having a warmer TSV compared to both the odourless and fig conditions. This effect was already statistically significant at baseline ($t = 0$ min; $p = 0.001$), and became progressively stronger over time, reaching its peak at 15 min ($p < 0.001$). In contrast, the fig scent showed a delayed cooling effect, with no significant differences at time 0 or 5 min, but a noticeable reduction in TSV after 10 min ($p = 0.050$), and a highly significant decrease after 15 min ($p < 0.001$). No significant differences were found between conditions at 5 min, suggesting a possible transient adaptation phase.

Table 5 reports the predicted probabilities of each TSV level for every combination of olfactory condition and time. Fig. 9 presents this information in the form of a stacked bar plot. This data reveals distinct temporal trends across olfactory conditions. Under the Odourless condition, responses are consistently centred around TSV = 0 (neutral), with a moderate probability of having slightly cool (−1) and slightly warm (+1) votes and little to no movement toward the extreme categories. This pattern remains relatively stable across time, with the probability of neutral responses ranging from approximately 47 % to 58 %. In the *Fig* condition, the distribution at Time=0 and Time=5 resembles that of the *Odourless* condition but shifts markedly toward cooler sensations at Time=10 and Time=15. By Time=15, approximately 55 % of responses fall into the colder categories (TSV = −3 and −2), and the probability of a neutral vote drops to just 12 %. Conversely, the *Vanilla* condition clearly pushes perceptions toward warmth over time. At Time=0, TSV = 0 dominates (63 %), but slightly warm and warm responses (TSV = +1 and +2) begin to emerge (19 % and 5 %, respectively). By Time=10, these warm responses increase substantially, and at Time=15, TSV = +2 becomes the most likely outcome (35 %), with over 73 % of responses falling into the warm range (TSV = +1 or +2).

Discussion

Although there has been a growing interest in multisensory perception, the link between olfactory stimuli and thermal perception remains largely unexplored, with only a few empirical studies directly addressing how odours influence thermal sensation [10]. The present study provides evidence that, in an office-like environment maintained at 23 °C, participants reported on average a 1.35-point increase in thermal

Table 2

Statistical summary of subjective responses depending on olfactory condition and time (min). TSV = Thermal Sensation Votes. TSatV = thermal satisfaction vote; IAQSatV = indoor air quality satisfaction vote; SSatV = smell satisfaction vote; GSatV = global satisfaction vote.

Parameter	Olfactory condition	Time (min)	Mean	SD
TSV	Fig	0	−0.400	0.577
		5	−0.600	0.957
		10	−0.960	0.889
		15	−1.440	0.961
	Odourless	0	−0.517	0.949
		5	−0.241	0.786
		10	−0.429	0.790
		15	−0.241	0.689
	Vanilla	0	0.214	0.418
		5	−0.214	0.568
		10	0.552	1.183
		15	1.107	0.956
TSatV	Fig	0	−0.083	1.782
		5	0.000	1.519
		10	0.429	1.223
		15	0.500	1.345
	Odourless	0	1.071	0.997
		5	1.143	0.949
		10	1.143	0.864
		15	1.077	0.954
	Vanilla	0	0.357	1.598
		5	0.857	1.610
		10	0.786	1.424
		15	1.143	1.292
IAQSatV	Fig	0	−0.333	1.231
		5	−0.071	1.328
		10	0.357	1.447
		15	0.571	1.505
	Odourless	0	1.143	1.027
		5	1.071	0.997
		10	1.143	0.864
		15	1.000	0.913
	Vanilla	0	0.643	1.692
		5	1.071	1.385
		10	1.286	1.204
		15	1.429	1.016
SSatV	Fig	0	−1.500	1.382
		5	−1.143	1.292
		10	−0.714	1.590
		15	−0.571	1.555
	Odourless	0	1.000	1.109
		5	1.143	0.949
		10	0.857	1.167
		15	0.462	1.330
	Vanilla	0	−0.857	1.562
		5	0.000	1.797
		10	0.357	1.781
		15	0.571	1.785
GSatV	Fig	0	−0.917	1.165
		5	−0.929	1.328
		10	−0.643	1.393
		15	−0.571	1.555
	Odourless	0	1.214	0.893
		5	1.143	0.864
		10	1.143	0.949
		15	1.077	1.038
	Vanilla	0	0.357	1.598
		5	0.214	1.672
		10	0.429	1.697
		15	0.714	1.684
Odour intensity	Fig	0	4.000	1.128
		5	4.000	1.301
		10	4.214	1.251
		15	4.571	1.223
	Odourless	0	0.714	0.995
		5	0.429	0.646
		10	0.643	1.008
		15	0.923	0.954
	Vanilla	0	3.571	1.785
		5	3.643	1.550
		10	3.231	1.423
		15	3.429	1.399

sensation (on a 7-point scale) following 15 min of exposure to a warm scent (vanilla), and a 1.20-point decrease with a cold scent (fig), relative to an odourless control condition.

Previous research had already demonstrated that many odorant molecules have the propensity to simultaneously stimulate olfactory and trigeminal systems in the nasal cavity [35]. These so-called “trigeminal” odours, such as menthol or cinnamon, can elicit thermal sensations, such as cooling or burning, and other somatic sensations, such as tingling or stinging [36,37]. These somatosensory effects are mediated by ion channels (e.g., TRPM8 for cold and TRPV1 for heat) involved in chemesthetic responses [38] (Fig. 10). Jia et al. [22] employed trigeminal odours such as peppermint (cool-associated), Homalomena occulta (warm-associated), and dried ginger (hot-associated) and they observed that at 24 °C, peppermint elicited a 1.05-point decrease in thermal sensation, Homalomena a 0.12-point increase, and ginger a 0.51-point increase (all $ps < 0.05$).

In contrast, the present study employed vanilla and fig scents. The former contains vanillin, which is known to be non-trigeminal [39,40]. The latter consists of a proprietary chemical composition, for which there is no specific evidence base demonstrating activation of the trigeminal system. Therefore, the observed thermal effects may be attributable to cognitive-affective mechanisms rather than from direct somatosensory input. To contextualise this interpretation, Fig. 11 provides a schematic representation of the cognitive, semantic, and affective pathways through which olfactory stimuli may modulate thermal perception.

One possible explanation for the influence of olfactory stimuli on thermal sensation may lie in the existence of cross-modal correspondences between the two sensory modalities. Cross-modal correspondences refer to the tendency for a sensory attribute in one modality—whether actually perceived or simply imagined—to be consistently associated with a feature in another sensory modality (see [41] for a review and the Introduction section). These correspondences have been widely documented across nearly every combination of sensory modalities, suggesting a robust and pervasive mechanism of multisensory integration. Several theories have been proposed over time to explain the phenomenon of cross-modal correspondences. Many of these correspondences likely arise from the internalization of statistical regularities in the environment, potentially functioning as coupling priors within a Bayesian framework [42]. Another perspective, known as the semantic or linguistic account, posits that the use of similar descriptive language across senses—such as calling both colours and temperatures “warm” or “cool”—could support or reinforce these correspondences (see e.g., [43]). Additionally, the emotional mediation account proposes that sensory pairings may occur because they evoke similar affective responses [44]. Importantly, these explanations are not mutually exclusive; for instance, linguistic patterns may themselves reflect underlying statistical regularities in the environment [45].

Learned, experience-based cross-modal correspondences may exist between olfactory and thermal sensations, whereby specific odours evoke semantic memories and affective states that, in turn, influence perceived temperature [46]. Vanilla, for example, is culturally associated with warm environments and calorically dense comfort foods [47]. These semantic links, stored in long-term memory, may unconsciously bias the interpretation of thermal cues, leading to heightened thermal sensation in the presence of vanilla odour Fig. 11[48] (Fig. 11).

Another novel contribution of the present study is the investigation of the temporal dynamics in the effects of odour on thermal sensation. The results show that vanilla consistently increased the likelihood of a warmer thermal sensation vote (TSV) compared to the odourless condition, with the effect already statistically significant at $t = 0$ min ($p = 0.0011$). In contrast, fig exhibited a delayed cooling effect: no significant difference in TSV was observed at time 0 or 5 min, but a noticeable reduction emerged at 10 min ($p = 0.050$), followed by a highly significant decrease at 15 min ($p < 0.001$).

While the influence of odours on thermal sensation can be

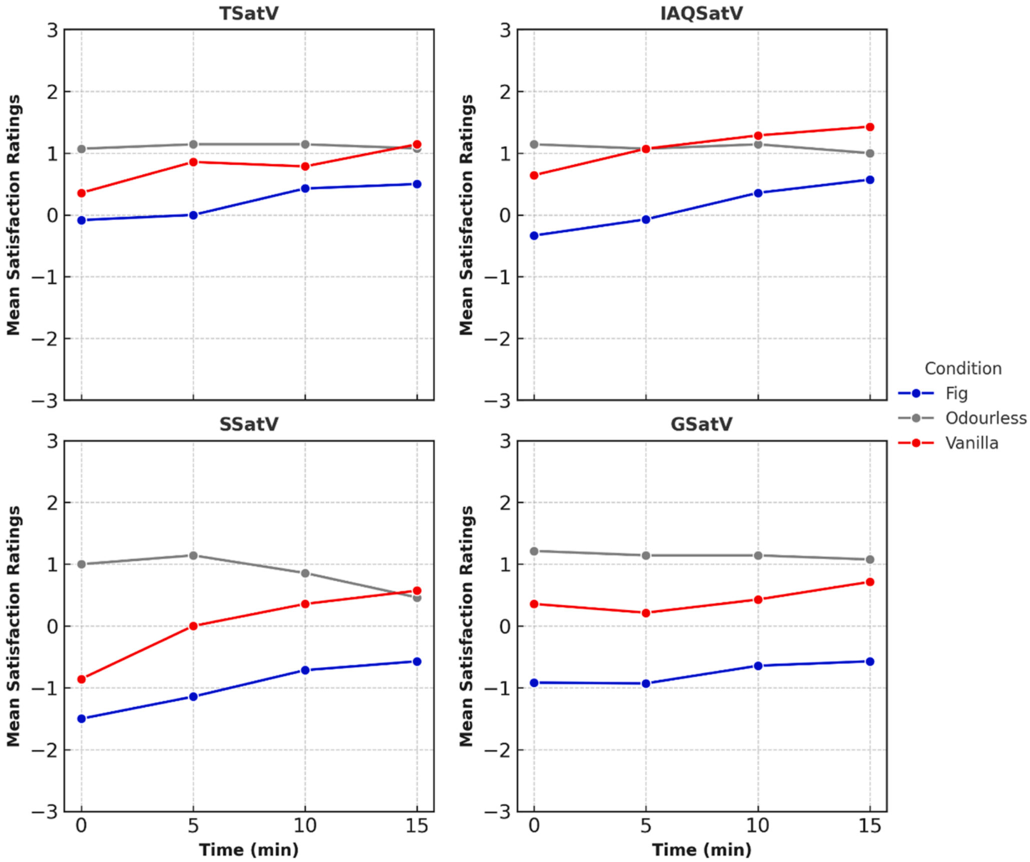

Fig. 8. Mean satisfaction ratings over time (0, 5, 10, and 15 min) for TSatV (Thermal satisfaction), IAQSatV (Indoor Air Quality Satisfaction), SSatV (Smell satisfaction), GSatV (Global satisfaction) across the three olfactory conditions (Odourless, Fig, and vanilla).

Table 3

Summary of fixed effects from the CLMM predicting thermal sensation votes. Estimates represent changes in cumulative log-odds relative to the reference category (Odourless condition, time = 0, age 18–30, female). Standard error is the uncertainty associated with the coefficient estimate. Z-ratio represents the ration between the estimate and its standard error (higher absolute values indicate a stronger and more robust effect). P-value represents the probability that the estimated effect would be observed by chance if the true effect were null.

Predictor	Estimate	Standard error	z-ratio	p-value
Room: Fig	0.149	0.521	0.285	0.776
Room: Vanilla	1.886	0.529	3.567	$p < 0.001$***
time: 5	0.551	0.521	1.057	0.291
time: 10	0.162	0.520	0.312	0.755
time: 15	0.592	0.521	1.136	0.256
Age 31–40	−0.554	0.290	−1.909	0.056
Age 41–50	−0.469	0.511	−0.919	0.358
Gender: Male	−0.186	0.314	−0.593	0.553
Fig × time5	−0.755	0.751	−1.005	0.315
Vanilla × time5	0.731	0.732	0.998	0.118
Fig × time10	−1.377	0.738	−1.867	0.062
Vanilla × time10	0.810	0.743	1.091	0.275
Fig × time15	−2.790	0.759	−3.676	$p < 0.001$***
Vanilla × time15	1.661	0.749	2.216	0.027*

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

interpreted through perceptual and cognitive association mechanisms—engaging memory, emotion, and multisensory integration—it is plausible that different levels of familiarity and recognisability of the stimuli modulate the speed at which these processes occur. Indeed, participants' responses revealed that vanilla was clearly and consistently recognised, whereas in the fig condition, a wide variety of smells were reported besides fig itself (cf. Fig. 6), suggesting a more ambiguous olfactory experience that may have delayed the cooling effect.

In conclusion, from an applied perspective, the results of this study suggest that olfactory design in indoor environments may serve as a non-invasive means of enhancing thermal comfort. However, such interventions must account for exposure duration and cultural variability in scent interpretation to be effective and contextually appropriate. It is also important to consider the substantial interindividual variability in olfactory perception—including differences linked to sensory sensitivity and neurodiversity —which means that scent-based strategies may not be equally beneficial or suitable for all occupants. Such variability underscores the need for flexible or customisable approaches when integrating olfactory cues into indoor environmental design.

Limitations and future work

This study presents some limitations. First, the study assessed whether olfactory cues influence thermal sensation, focusing on how quickly these effects emerge, but it did not investigate how long they persisted over the medium to long term, i.e., over hours or days. During the observation window, the ratings of the indoor environmental quality components under olfactory stimulation did not reach a steady state (Fig. 8). Future research should explore the temporal dynamics of these perceptual changes to better understand their duration and potential applications in real-world settings. Furthermore, future research should repeat the study in summer and investigate how alternative diffusion patterns (e.g., continuous versus intermittent delivery) shape olfactory–thermal interactions in applied settings.

Secondly, the cultural context likely plays a role in how odours are interpreted and in odour-temperature associations. The findings reported here are based on a sample within an Italian/Western cultural

Table 4
Pairwise comparisons of estimated marginal means (EMMeans) of thermal sensation votes by olfactory condition and time. The table reports estimated differences in cumulative log-odds between olfactory conditions at each time point (0, 5, 10, 15 min), based on the CLMM. Values in parentheses indicate the estimated marginal means for each olfactory condition.

Time (min)	Olfactory condition (EMMean)	Estimate	Standard error	z-ratio	p-value
0	Odourless (−0.201) – Fig (−0.091)	−0.149	0.521	−0.285	0.956
0	Odourless (−0.201) – Vanilla (0.757)	−1.886	0.529	−3.567	0.0011**
0	Fig (−0.091) – Vanilla (0.757)	−1.737	0.524	−3.314	0.0026**
5	Odourless (0.363) – Fig (0.073)	+0.606	0.544	1.115	0.505
5	Odourless (0.363) – Vanilla (0.950)	−0.155	0.514	−0.301	0.951
5	Fig (0.073) – Vanilla (0.950)	−0.761	0.538	−1.414	0.334
10	Odourless (−0.020) – Fig (−0.615)	+1.229	0.524	2.345	0.060
10	Odourless (−0.020) – Vanilla (1.340)	−2.696	0.573	−4.702	<0.001***
10	Fig (−0.615) – Vanilla (1.340)	−3.925	0.594	−6.610	<0.001***
15	Odourless (0.441) – Fig (−0.880)	+2.642	0.552	4.788	<0.001***
15	Odourless (0.441) – Vanilla (2.200)	−3.546	0.579	−6.124	<0.001***
15	Fig (−0.880) – Vanilla (2.200)	−6.188	0.636	−9.728	<0.001***

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

framework and may not be generalisable to other cultural groups. Cross-cultural replication studies are recommended. Future study should also consider how neurodiversity plays a role in odour–temperature associations.

Furthermore, the intervals between the seven response options on the ASHRAE 55 thermal sensation scale were assumed as uniformly spaced. While this approach is commonly used, recent research suggests that these intervals may be perceived as uneven and interpreted differently by participants, which could influence the precision of the thermal sensation ratings.

Third, due to commercial confidentiality, the complete chemical composition of the two odour stimuli (vanilla and fig) is not publicly available. As such, we cannot completely exclude the presence of trigeminal components — despite the manufacturer's exclusion — that may have influenced participants' sensations. This potential limitation should be acknowledged, although the primary aim of this study was to test whether odours had an effect on thermal sensation—not to identify the precise mechanism behind it.

Furthermore, it should be noted that local thermal discomfort was not assessed in this study; parameters such as draft, radiant temperature asymmetry, or vertical temperature gradients were not measured, and therefore potential local discomfort effects cannot be fully excluded. The three test rooms were identical in glazed surface orientation, area and thermal transmittance, and all participants were seated in the same position across sessions, making mean radiant temperature asymmetry negligible for the purposes of the comparative analysis. Nonetheless, as this parameter was not directly measured, minor residual effects cannot be entirely ruled out.

Finally, future research should aim to translate these findings into practical applications, also taking into account the peculiarities of different building types and usage. Moreover, the potential for energy efficiency improvements should be further quantified to support future design strategies.

Conclusions

This study investigated how environmental scents influence thermal sensation in an office-like setting during winter. Twenty-four participants were exposed to three olfactory conditions—a "warm-associated" vanilla scent, a "cool-associated" fig scent, and an odourless control. The objective was to assess (i) whether olfactory stimuli modulate subjective thermal sensation and (ii) how quickly these effects emerge.

Regarding the first research question, results showed that olfactory stimuli can significantly modulate thermal perception, even in the absence of trigeminal stimulation.

Regarding the second research question, the vanilla scent consistently increased the likelihood of perceiving the environment as warmer compared to the odourless condition, with this effect evident from the outset and intensifying over time. Conversely, the fig scent produced a delayed but clear cooling effect, becoming significant after 10 min and peaking at 15 min, when responses were strongly skewed toward cooler sensations.

Since the stimuli did not contain known trigeminal active compounds, the observed cross-modal effects of olfactory stimuli on thermal sensation were interpreted as arising from perceptual and cognitive association mechanisms. However, further research is needed to explore the mechanisms underlying such cross-modal effects.

Ultimately, these findings highlight the potential of incorporating olfactory design into indoor environments. Scents that evoke sensations of warmth or coolness can serve as a subtle yet effective tool for enhancing thermal comfort with affecting energy consumption.

CRediT authorship contribution statement

Giulia Torriani: Writing – review & editing, Writing – original draft,

Table 5
Predicted probabilities for each value of the Thermal sensation vote (TSV) as a function of olfactory condition and time (t = 0, 5, 10, 15 min). Probabilities were estimated using a cumulative link mixed model (CLMM). The columns indicate the probability of each TSV level, ranging from cold (−3) to hot (+3).

Olfactory Condition	Time	TSV = −3	TSV = −2	TSV = −1	TSV = 0	TSV = +1	TSV = +2	TSV +3
Odourless	**0**	0.018	0.118	0.339	0.477	0.039	0.009	0.001
Fig	**0**	0.016	0.104	0.320	0.506	0.044	0.010	−0.000
Vanilla	**0**	0.003	0.021	0.100	0.633	0.189	0.055	−0.000
Odourless	**5**	0.011	0.073	0.262	0.575	0.064	0.015	0.000
Fig	**5**	0.019	0.124	0.346	0.465	0.037	0.008	0.001
Vanilla	**5**	0.009	0.064	0.239	0.597	0.073	0.017	0.000
Odourless	**10**	0.016	0.103	0.318	0.508	0.045	0.010	0.000
Fig	**10**	0.051	0.262	0.409	0.261	0.014	0.003	−0.000
Vanilla	**10**	0.001	0.008	0.042	0.493	0.324	0.132	0.000
Odourless	**15**	0.010	0.071	0.256	0.581	0.066	0.016	0.000
Fig	**15**	0.126	0.419	0.328	0.121	0.005	0.001	−0.000
Vanilla	**15**	0.000	0.002	0.012	0.238	0.398	0.349	0.000

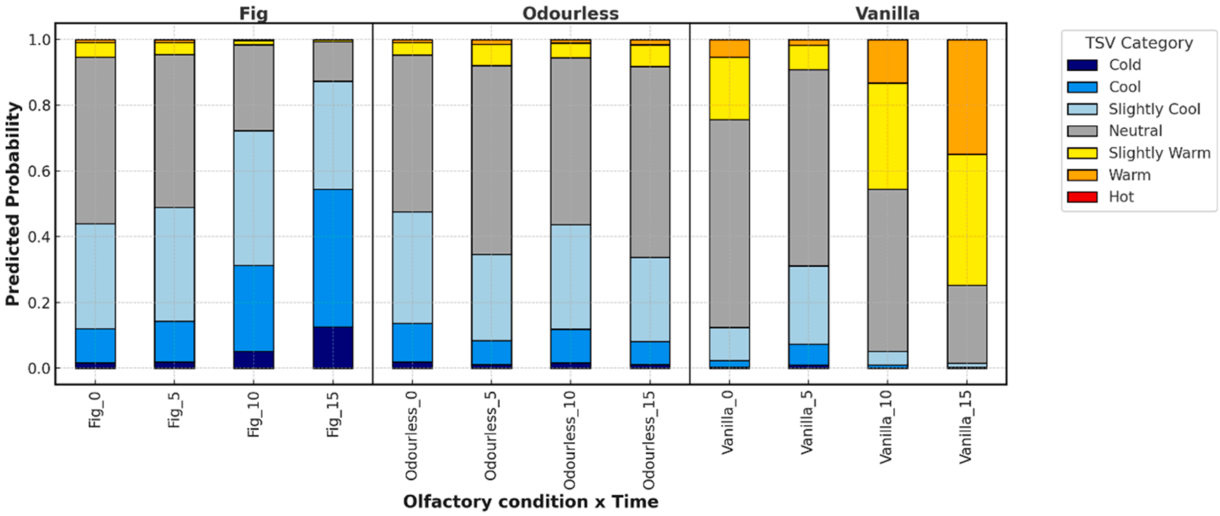

Fig. 9. Predicted distribution of probabilities for each level of Thermal Sensation Vote (TSV) as a function of olfactory condition and time. Each bar represents the predicted probability for a specific TSV level (from +3 Cold to −3 Hot) within each olfactory condition-time combination.

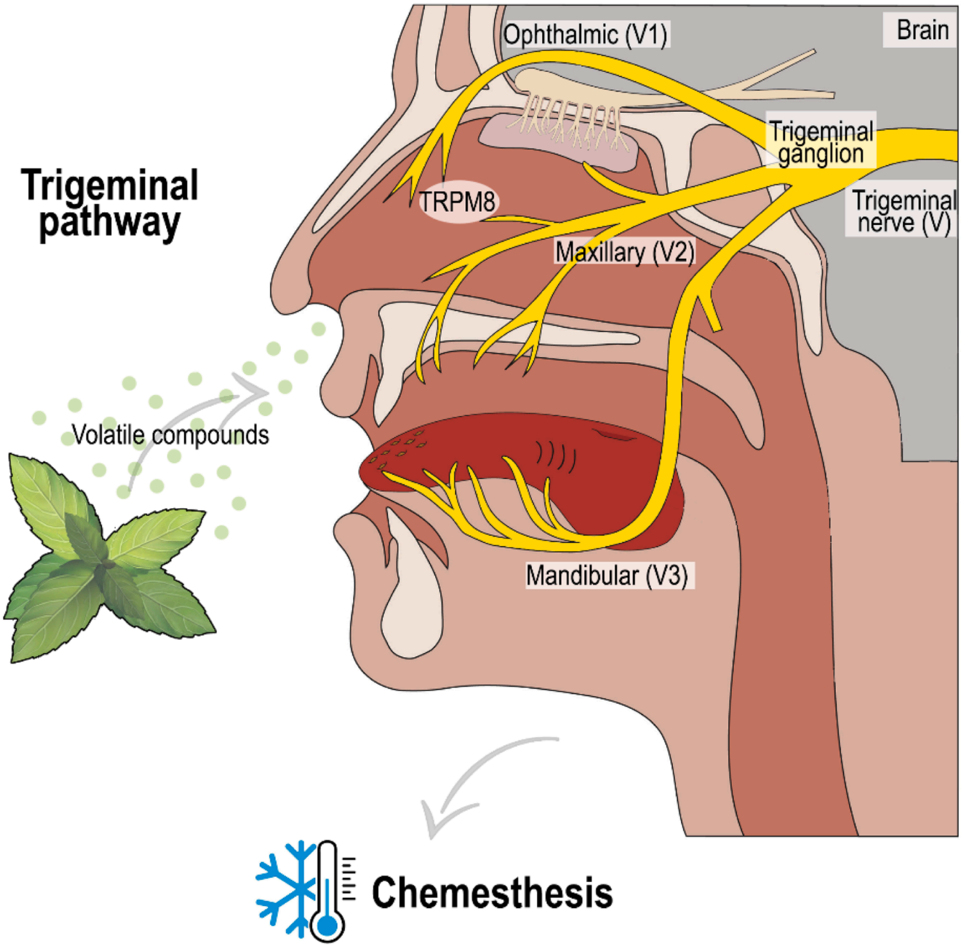

Fig. 10. Trigeminal Stimulation of Odours. The trigeminal nerve (cranial nerve V) has sensory fibres branching into the nasal mucosa via its ophthalmic (V1) and maxillary (V2) branches. Its free nerve endings express ion channels of the TRP (Transient Receptor Potential) family, such as TRPM8, which mediates cold sensations, and TRPV1, which mediates heat sensations. Signals are transmitted to the trigeminal ganglion (located in the middle cranial fossa) and then relayed to the brainstem. Trigeminal input is processed as chemesthetic sensations—chemical-somatic perceptions such as freshness or pungency. Illustration © Authors.

Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simone Torresin:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Francesco Babich:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Massimiliano Zampini:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Rossano Albatici:** Writing – review &

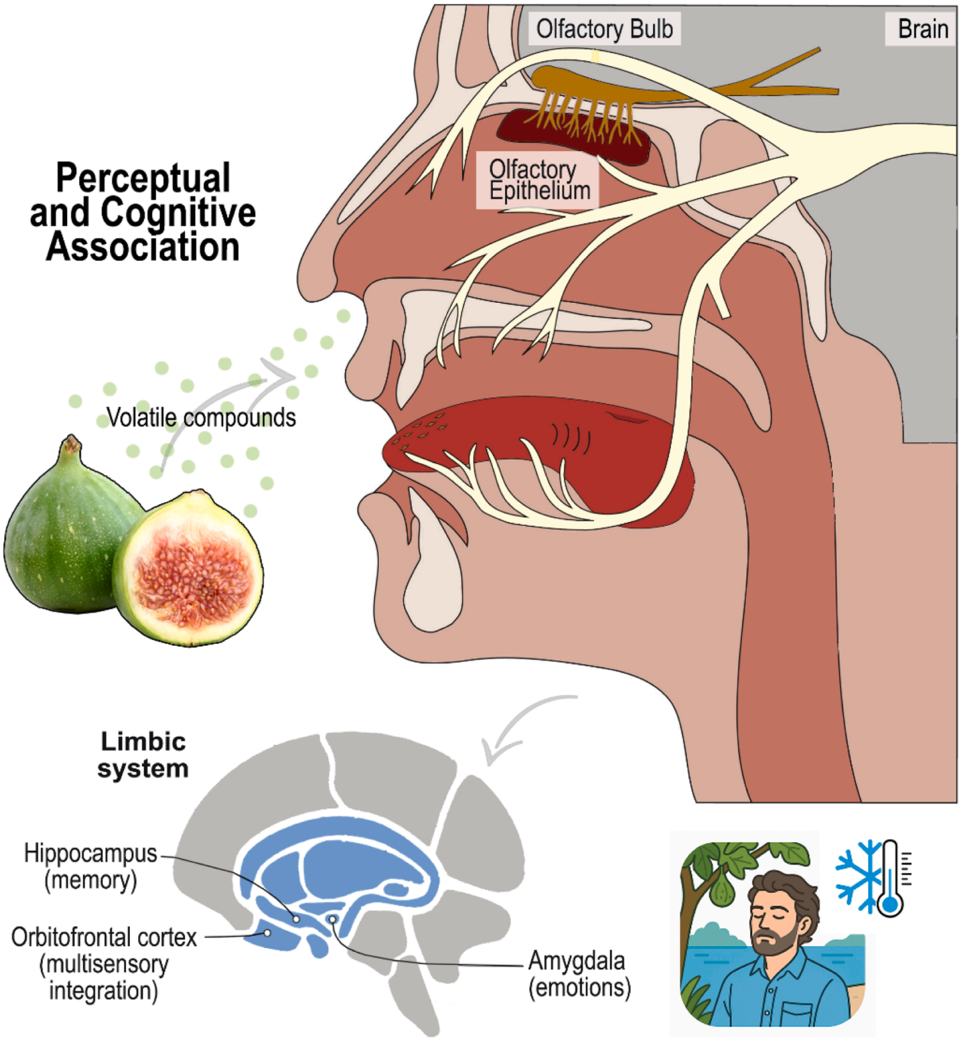

Fig. 11. Olfactory Stimulation of Odours. Volatile molecules enter the nasal cavity and reach a region in the upper part of the nose called the olfactory epithelium. There, each molecule binds to one or more receptors, generating an electrical signal. This signal travels to the olfactory bulb and is then transmitted to the limbic system. Odours can evoke a thermal context through emotional responses (amygdala), associative memory (hippocampus), and multisensory integration (orbitofrontal cortex). Illustration © authors.

editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2026.114369.

Data availability

Data will be made available on request.

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