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Causal cross-modal effects between odor and temperature on occupants' perception in a single-person office environment

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ABSTRACT

Both odor and temperature have been suggested to shape occupants' perception of indoor environment, yet quantitative evidence regarding their interdependence remains limited. This study investigated their cross-modal effects on human responses in office environments, theoretically based on negativity bias, revenge effect, and One-Vote Veto effect. A single-blind 2 × 2 within-subject experiment was conducted in the Aachen Workplace Simulation Lab. 23 healthy, mostly young participants experienced room atmospheres with pleasant (0.7 ppm pentyl acetate) and unpleasant (5 ppm 1-butanol) odors at neutral (24 °C) and slightly warm (28.5 °C) temperatures. Standardized questionnaires assessed subjective satisfaction and sensation across sensory domains before and after olfactory adaptation. Modern statistical advancements—including causal inference, adjustment criterion, and Bayesian region of practical equivalence—were leveraged to address existing methodological limitations in multi-domain research. Results revealed cross-modal main effects, with increased warmth reducing olfactory satisfaction. Marginal temperature x odor interactions were found for thermal and overall satisfaction, while other cross-modal effects remained inconclusive. Substantial inter-individual variability was observed in odor valence ratings. These findings highlight the interdependence of thermal and olfactory perception and partially support the notion that negative experiences from one domain can influence another; however, One-Vote Veto effects were not confirmed. The study underscores the need for holistic indoor environmental quality assessments and follow-up multi-domain research. Methodologically, it showcases application of modern statistical tools to improve transparency and rigor in causal human-centric building science. Challenges related to odor selection and concentration manipulation are highlighted as key areas for improvement in related future research.

1. Background

1.1. Context

Cross-modal research has gained increasing attention in building science as occupants generally encounter stimuli across multiple domains simultaneously [1,2]. Cross-modal research focuses on how different sensory inputs—such as temperature, light, sound, and odors—interact to shape occupants' perceptions and behaviors. According to Chinazzo et al. [1], a cross-modal effect occurs when one stimulus influences a response typically triggered by another unrelated stimulus. Specifically, cross-modal main effects involve one stimulus altering responses to another, independently of their magnitudes, while cross-modal interactions occur when varying levels of one stimulus differently affect responses to another. The insights gained from such research are crucial not only for refining indoor-environmental design

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and operation strategies, but also for informing guidelines that create healthier and more productive workspaces.

1.2. Prior research and gaps

Prior studies [3,4] have acknowledged that research regarding cross-modal effects between thermal and olfactory stimuli is limited. For office environments, we are only aware of one study by Jia et al. [3] that investigated the cross-modal interactions between odor and temperature. However, their approach involved participants smelling powdered odor materials contained in glass bottles rather than manipulating the atmosphere of the entire room. Through their method, the odor might be dependent on how strongly participants sniffed. Also, the artificial setup may have skewed participants' perception of the overall room environment, potentially biasing the study's results. Moreover, Jia et al.'s study did not sufficiently adopt causal inference methods—a critical aspect highlighted in recent methodological publications (e.g., [5,6]). These limitations call into question the validity of their (causal) findings and underscore the need for more rigorous approaches in future research.

1.3. Aim

This study seeks to address existing methodological gaps by implementing the causal inference framework proposed by Pan, Mahdavi, et al. [5]. In addition, we plan to manipulate the room atmosphere to create more realistic conditions for studying cross-modal main effects and interactions between odor and temperature.

The primary focus is on perceptual responses, with satisfaction in individual sensory domains as the main outcome variables. According to Chinazzo et al. [1], environmental perception comprises two aspects—sensation and evaluation—with satisfaction representing a key aspect of the latter. Given the well-documented influence of olfactory adaptation on perception (e.g., [7,8]), this study emphasizes responses before adaptation onset. Olfactory adaptation refers to a temporary reduction in olfactory sensitivity following odor exposure, with its effects typically stabilizing after about four minutes [9]. By focusing on satisfaction prior to adaptation, we aim to capture participants' initial, unattenuated perceptual evaluations, where the cross-modal effects are expected to be more prominent.

1.4. Null results

It is crucial to consider that literature has repeatedly reported null results regarding cross-modal effects. For example, Tagliabue [10] studied different colored rooms and odors using virtual reality but did not observe any significant effect of odors on thermal comfort. Similarly, Gentner et al. [11] found no significant effect of perfumes on thermal perception in cars. Although these experiments differ fundamentally from our study—such as not focusing on odor valence or office environments—they underscore the importance of considering potential null effects.

As traditional null hypothesis significance testing (NHST) has numerous well-documented limitations, especially when dealing with null results (e.g., [12–14]), we adopt the Bayesian region of practical equivalence (ROPE) framework advocated by Pan, Christoforou, et al. [15]. This approach, among many other advantages over traditional NHST, promotes cumulative science by allowing for the acceptance or rejection of an effect based on practical relevance rather than solely on statistical significance.

1.5. Theoretical background

As theoretical basis, this study draws on the revenge effect [4,16], the One-Vote Veto effect [17], and the negativity bias [18,19]. A recurring finding in literature is that an unpleasant element in one environmental domain can negatively impact the perception of other domains (e.g., [20–22]). This phenomenon is sometimes referred to as the revenge effect [4,23], in which an unpleasant stimulus in one sensory modality exacerbates dissatisfaction in others. Similarly, the One-Vote Veto effect describes how dissatisfaction with a single domain—such as thermal or acoustic conditions—can override positive evaluations of other domains and reduce overall satisfaction [17, 24–26].

These perceptual distortions may be theoretically grounded in the negativity bias, an extensively studied psychological tendency to assign greater cognitive and emotional weight to negative stimuli than to equally intense positive ones [18,19]. Rozin and Royzman [19] vividly illustrated this asymmetry with an example: a brief contact with a cockroach can render a delicious meal inedible, while the reverse—making cockroaches appetizing by contact with a favorite food—is rarely true. This bias operates across affective, cognitive, and behavioral domains—including interpersonal judgments, attention, and learning [27–29].

Evidence of negativity bias has also emerged in environmental perception research. For example, Kim et al. [30] found that the brain’s late positive potential—a neural marker of evaluative processing—was lower for pleasant stimuli when participants were thermally uncomfortable, suggesting that discomfort in one domain blunts the affective benefits of others. The evidence supports the notion that a negative environmental condition (e.g., slightly warm temperature) may disproportionately shape evaluations of the general indoor environment.

Taken together, the reviewed theoretical background suggests that perceptual responses to indoor environments may not be domain-isolated but integrative and bias-sensitive. Thereby, we expect both cross-modal main effects (e.g., odor influencing satisfaction with air quality or overall comfort) and cross-modal interaction effects (e.g., varying levels of odor and temperature amplifying each other’s influence). Based on negativity bias, we hypothesize asymmetric cross-modal interactions: unpleasant odors will have a stronger detrimental effect on perceived satisfaction under thermally uncomfortable conditions, and vice versa.

Empirical support for such interaction effects has been found in related domains. Seyedrezaei et al. [31], for instance, demonstrated that temperature-induced discomfort more strongly degraded acoustic comfort under high noise conditions. Similarly, Guan et al. [32] reported a significant interaction between temperature and sound pressure level affecting overall comfort. Although these studies focus on thermal-acoustic interactions, they provide conceptual precedence for odor-temperature interplay.

In summary, the revenge effect and One-Vote Veto effect are empirically well-supported and consistent with broader psychological principles like negativity bias. This theoretical framing informs our expectation that cross-modal effects between odor and temperature will manifest both independently and interactively, with disproportionate influence exerted by unpleasant stimuli. These insights underpin our study’s research objectives, detailed in the next section.

2. Objectives

The primary objective of this study is to confirmatively investigate the cross-modal main and interaction effects between odor (prior to olfactory adaptation) and temperature on subjective satisfaction across sensory domains of the office environment. Concretely, we examine how changes from neutral to slightly warm temperatures and from pleasant to unpleasant odors impair satisfaction regarding odor, temperature, sound, lighting, and the overall environment (i.e., main effects). Furthermore, we assess if the changes in temperature or odor amplify each other's negative effects on environmental satisfaction (i.e., interactions).

As secondary objectives, we explore satisfaction after olfactory adaptation, as well as potential cross-modal effects on subjective sensations before and after olfactory adaptation in thermal, olfactory, visual, and acoustic domains.

3. Methods

3.1. Participants

Participants were recruited between July and October 2024 in Aachen and vicinity. The following inclusion criteria were checked during an enrollment visit conducted by medical doctors: no smoking for at least one year; normosmia[1]; feeling fit to tolerate a room temperature of nearly 30 °C for 100 min; a body mass index between 17 and 35 kg/m^2; absence of claustrophobia, a hyperreactive bronchial system, or any known symptomatic cardiovascular, metabolic, respiratory, sinonasal, or neurological diseases; an age between 18 and 59; native-level proficiency in German; and not being pregnant. For females over 40, they must have been postmenopausal, with the last menstruation occurring more than 24 months ago.

Participants received 55 Euro[2] as compensation for completing the experiment. In addition, participants received a five-euro compliance bonus for following all instructions and a three-euro contribution bonus for each further recruited participant that completed the experiment.

Altogether 173 people contacted us via email to express their interest in participation and 56 completed a remote pre-experiment briefing. Of these, 43 attended an enrollment visit and were screened for inclusion criteria, resulting in 31 eligible people. Among these, 24 individuals participated in the experiment. Data from one participant were excluded due to a technical issue that unexpectedly increased the room temperature during the experiment. Altogether 23 participants completed the experiment. Their mean age was 27.4 years (sd = 10.5, range = 18 - 59 years). There were 11 biological females (47.8%) and 12 biological males (52.2%). All of them were native German speakers. 19 participants (82.6%) were university students, three (13.0%) were employees, and one (4.4%) was a trainee.

3.2. Setup

The experiment was conducted in the Aachen Workplace Simulation Lab in Aachen, Germany. Fig. 1 illustrates the spatial layout (photos of the setup available in supplementary materials). The test room, measuring approximately 14 m^2 with 2.42 m in height, was configured to simulate a single-person office. Adjacent to the test room, a sluice served as a transitional space between the test room and the control room. It could be isolated from the test room with a sealed door to prevent odor transfer.

3.3. Treatment

Two odor conditions were employed: 1-butanol (CAS 71–36–3) with a rancid smell and pentyl acetate (CAS 628–63–7) with a fruity and banana-like smell. Based on a priori labelling and the preregistered study design, 1-butanol was designated as the unpleasant odor and administered at a target concentration of 5 ppm, whereas pentyl acetate was designated as the pleasant odor and administered at 0.7 ppm. The terms pleasant and unpleasant thus refer to experimental condition labels rather than participants' valence ratings. These odors were selected primarily based on the following rationales: (1) both were single-component substances suitable for measurement via Fourier-transform infrared spectroscopy (FTIR) and via Tenax sampling and further analysis after thermal desorption via gas chromatography coupled with a time-of-flight mass spectrometer (GC-ToF-MS) using external calibration; (2) target concentrations remained well below the German occupational exposure limits, as recommended by the German MAK-Commission [33]; and (3) moderate concentrations were set to facilitate efficient experimental manipulation and allow reasonable ventilation time.

Odor delivery was implemented using a controlled evaporation system following the setup and methods outlined in [34]. Concretely, liquid odorants were dispensed from a perfusion syringe into a heated vessel (evaporator). The resulting vapor was mixed with an adjustable stream of carrier air and introduced into the laboratory's main air supply. Distribution occurred via a ventilation system through four ceiling-mounted diffusers with vortex flow, ensuring homogeneous distribution throughout the room. The odor concentration in the room was regulated by adjusting the flow rate of a syringe pump and the carrier airflow. Target concentrations were established during pretests by calibrating the pump and airflow parameters with a portable FTIR gas analyzer (Gasmet DX4040). Given our available resources, the FTIR was rented only during the pretest phase. The determined operation and parameters during pretests were exactly repeated during the experimental sessions to ensure consistent odor delivery across conditions. Supplementary material presents pictures of the equipment and setup.

Two thermal conditions were used: a neutral condition at ~24 °C and a slightly warm condition at ~28.5 °C. To ensure consistent clothing insulation across sessions, we instructed participants to wear a predefined outfit comprising a long-sleeved white cotton shirt, long trousers, underwear, socks, and sports shoes. To maintain a comparable metabolic rate and activity level across conditions, participants conducted light physical activity (i.e., marching in place at one step per second) at fixed time points during the experiment.

Lighting was provided by a Spectrasol standing lamp with a correlated color temperature (CCT) of ~4000 K and an illuminance of ~500 lx at desk level. The lighting condition was verified with an Apacer Ai101 spectral irradiance meter. The window remained closed and was covered by blinds to fully block views and daylight from outside. No background sound was intentionally introduced during the sessions. However, operational noise from the ventilation system and odor delivery equipment occurred intermittently. These sources were minimized during the environmental rating periods (e.g., by turning off carrier airflow and turning down ventilation) to avoid influencing participants' immediate perceptual judgments.

Participants were seated at an adjustable desk and chair. They were instructed to adjust the chair, desk and computer monitor position freely to ensure comfort and a natural working posture.

Participants conducted the Attention Network Test (ANT; [35]) to maintain a similar level of cognitive engagement across conditions. This computerized task, implemented in PsychoPy [36], requires participants to respond to the direction of a central arrow displayed on screen by pressing a corresponding keyboard key. While the task performance was not a variable of interest, in order to ensure sufficient task engagement, we informed participants that they would forfeit a compliance bonus if their overall accuracy fell below 60%.[3]

3.4. Measures

Subjective satisfaction and sensation regarding odor, temperature, sound, lighting, and the overall environment were assessed with standardized questionnaires. All satisfaction items had six levels: very dissatisfied, dissatisfied, rather dissatisfied, rather satisfied, satisfied, and very satisfied. Sensation items were assessed with seven levels. All items were developed during an expert workshop to ensure content validity [37]. Questionnaires also assessed demographic information

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[1] Checked via a simplified smell test with Burghart Sniffin' Sticks (minimum four correct identifications out of five).

[2] Originally, the basic compensation was 44 Euro and the compliance bonus was 6 Euro. Because of slow recruitment, they were increased in early August.

[3] Research shows that adults typically achieve accuracy rates above 95% on this task [35,84–86].

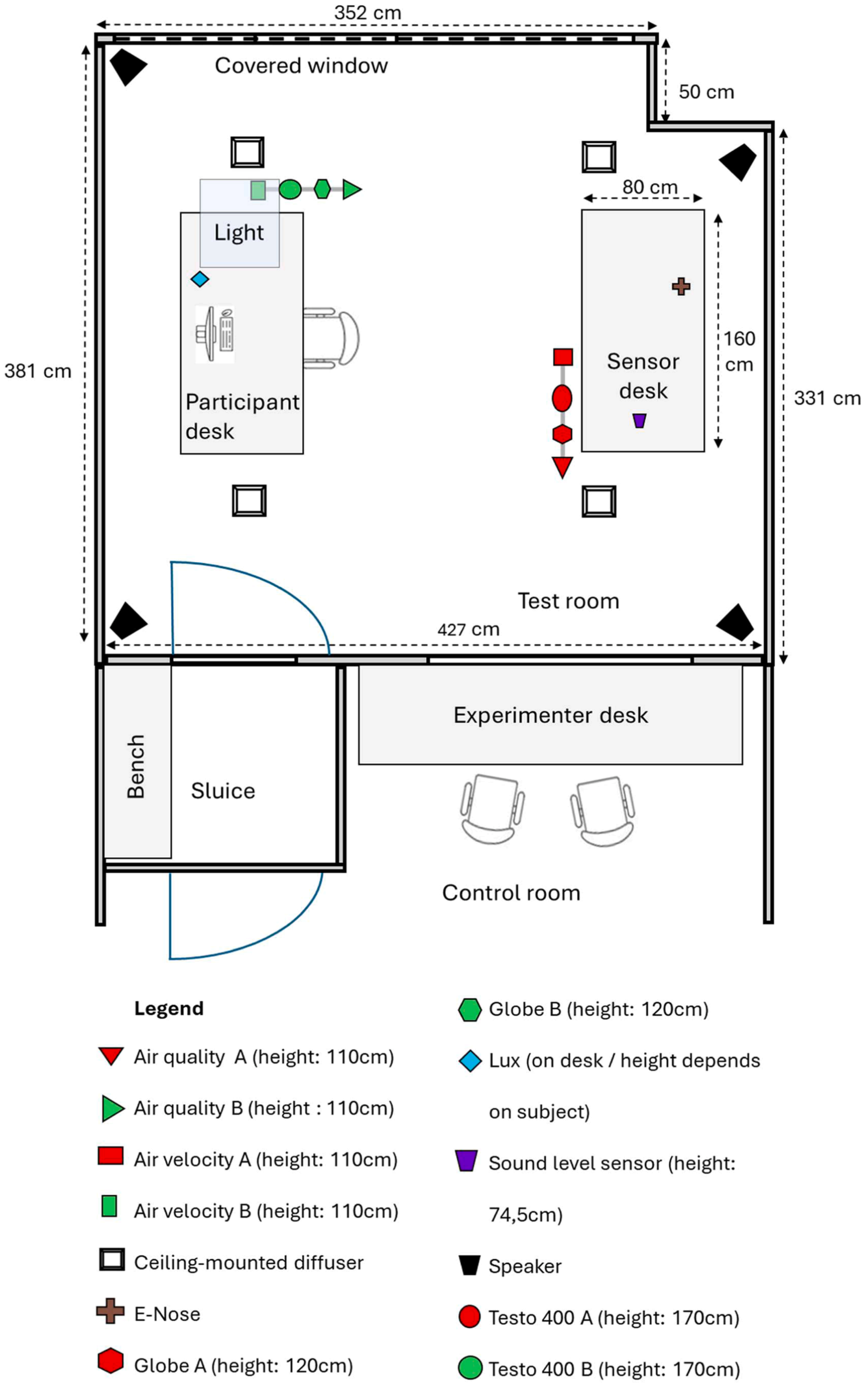

Fig. 1. Schematic overview of lab setup.

and subjective ratings of the valence for both odors. All questionnaires (available in supplementary material) were presented via PsychoPy [36]. Clothing insulation levels were documented at each session start based on experimenter's observation.

Environmental conditions were monitored using calibrated instruments. Testo devices (including two Testo 400, two turbulence probes, two CO_2 probes, two globe thermometers, and one Lux probe) recorded air velocity, relative humidity, air pressure, CO_2 concentration, air temperature, globe temperature, and illuminance. Ambient noise levels were measured using a PCE-SLD 10 sound level meter.

To quantify odor concentration, we used FTIR in the pretest phase for real-time, on-site measurement. Throughout the main experimental phase, we conducted additional air sampling sessions without any participants present to periodically verify the implemented odor conditions. Tenax tubes were placed at subject's desk level with a sampling time of one minute and an air flow of about 40 ml/min. The Tenax samples were analyzed via GC-ToF-MS following the methods outlined in [34].

Several additional environmental and physiological parameters were recorded for completeness, although they were not relevant to the research objectives and will not be analyzed in this study. A sensor array (see [38] for technical specifications) monitored ambient air quality. Heart rate data were continuously recorded using a Polar H10 chest strap (Polar Electro GmbH, DE). Skin temperature was measured at one-minute intervals using iButton® thermometers (Maxim Integrated, USA), attached to four standardized body sites—hand, neck, scapula, and shin—in accordance with ISO 9886 [39].

3.5. Procedure

The study was pre-registered before data collection under https://osf.io/uagws. Ethical consultation (EK 24–154) was received by the ethics committee of the medical department at RWTH Aachen University. All experimental materials and measures were administered in German. To avoid potential response bias, we introduced the study using a cover story that described its purpose as examining the effects of office environments and breaks on cognitive performance. Participants were debriefed orally about the real purpose at the end of the second session and reminded of their right to withdraw.

Each participant completed two sessions on separate days, with at least 24 h in between to minimize carry-over effects. To minimize circadian influences, the two experimental sessions for each participant were scheduled at a similar clock time, with start times within ±120 min.[4] Each session lasted about 90 min and included one fixed thermal condition and both olfactory conditions (see Fig. 2). Only one participant was tested per session.

To facilitate standardization and participant readiness, we instructed participants to comply with several pre-session conditions, including: being free of acute illness; having normal or corrected-to-normal vision and hearing; having remained in Aachen or the same climate zone for at least three months; and refraining from chewing gum or consuming strong-smelling food within one hour, caffeine within two hours, warm or iced foods or drinks within 30 min, and alcohol or vigorous physical activity within 24 h prior to each session. Participants were also asked to maintain consistent sleep and wake times across both sessions. Adherence to these instructions was assessed via self-report prior to each session.[5]

Upon participants' arrival at each session, the experimenter confirmed normal olfactory function using a simplified smell test with Burghart Sniffin' Sticks (minimum three correct identifications out of four), ensured that electronic devices were silenced, that the participant wore the same clothing as in the previous session, and that no strong personal odors (e.g., perfume) were present.

Each experimental session consisted of six phases. The first preparation phase involved the above-mentioned pre-session checks, instructions, and attaching physiological devices.

In the second training phase, participants practiced the cognitive task for ~5 min. A short break was provided midway, during which participants familiarized themselves with the questionnaires assessing their environmental perceptions.

The third phase was the first interlude. The first odor condition was introduced in the test room, while participants stayed in the odor-isolated sluice for ~15 min. The sluice was under the same thermal condition as the test room. At the interlude start, participants first engaged in light physical activity (i.e., marching in place for two minutes). They then viewed neutral travel videos on a tablet computer to maintain a comparable level of cognitive engagement. From the session start until the end of this phase, participants had spent at least 30 min undergoing thermal adaptation.

In the fourth phase, participants re-entered the test room and completed the first set of questionnaires assessing their immediate (i.e., at the moment of assessment) environmental perceptions. They then resumed the cognitive task. A second set of questionnaires was administered ten minutes after entry, allowing for olfactory adaptation in line with ISO 16000–30 [40], which recommends a five- to ten-minute adaptation period. Finally, participants continued the cognitive task for five additional minutes, while the first odor was ventilated out of the test room.

The fifth phase and sixth phase repeated the procedure of phase 3 and 4 under the second odor condition, with the sixth phase ending directly after the second set of questionnaires since no further odor ventilation was needed. At the session's conclusion, participants completed a session-specific survey. For participants completing their second session, an additional end-of-study survey was administered. As part of the end-of-study survey, participants rated the valence of the two odors they had perceived during the experiment, using odor samples in glass bottles as memory cues.[6] The order of valence ratings was randomized across participants.

3.6. Design

This study had a single-blind, 2 × 2 within-subjects design with the odor (pleasant vs. unpleasant) and temperature (neutral vs. slightly warm) as independent variables. The main dependent variables were subjective satisfaction and sensation regarding odor, sound, temperature, lighting, and the overall environment, measured both before and after olfactory adaptation. The order of odor and temperature conditions was randomized for each participant. Environmental perception items were randomized for each participant under each condition. For each domain, every sensation item was directly followed by its corresponding satisfaction item. Questions related to the thermal and olfactory domains were presented before those for the visual, acoustic, and overall domains. The order of the thermal and olfactory questions was randomized, as was the order of the remaining three domains.

3.7. Data analysis

Analysis was performed using *R* [41] with *RStudio* [42] and the following packages: *ggplot2* [43], *gt* [44], *tidyverse* [45], *magrittr* [46], *psych* [47], *openxlsx* [48], *readxl* [49], *tidybayes* [50], *brms* [51], *bayesplot* [52], and *patchwork* [53]. In supplementary materials, we provided

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[4] Due to scheduling constraints, one participant's second session started 170 minutes later than the first. This deviation was not considered to compromise data validity and the session was retained.

[5] One participant reported engaging in yoga before the second session. This deviation was not considered to compromise data validity and the session was retained.

[6] These samples were not calibrated for concentration. Thus, they were not evaluated for their intrinsic scent but solely served to aid recall.

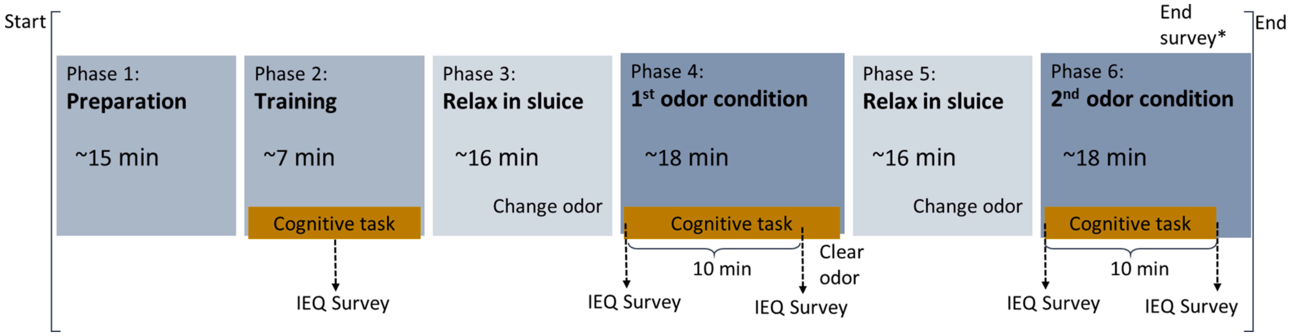

Fig. 2. Experiment procedure for one session.

scripts to reproduce all analyses and specified the estimands and causal assumptions in accordance with the causal inference framework proposed by Pan, Mahdavi, et al. [5].

Given the ordinal nature of the perception ratings and the repeated-measures design, we conducted multilevel Bayesian cumulative probit ordinal regressions following suggestions by Favero, Carlucci, et al. [6] and Favero, Luparelli, et al. [54] to evaluate the cross-modal effects in the primary objective. Separate models were fitted for each dependent variable using the formula: rating ~ 1 + temperature * odor + (1 + temperature + odor | participant) + covariates. This specification included the maximal varying effect components justified by the experimental design following the recommendation by [55]. We adopted the visual framework based on the adjustment criterion advocated by Pan, Favero, et al. [56] to select necessary covariates for causal inference based on our estimands and causal assumptions. Concretely, we adjusted for relative humidity in the analyses related to thermal satisfaction and sensation, and we adjusted for relative humidity and CO_2 for overall satisfaction. No further covariates were adjusted for.

To inform prior distributions, we conducted prior predictive simulations following McElreath [14] and Barreda et al. [57] to determine weakly informative priors. In line with [58,59], we adopted a parameter estimation approach that allows even moderate sample sizes to overwhelm such priors. Specifically, we did not hold specific expectations regarding the direction or magnitude of the effects. Instead, the priors were designed to allocate a reasonable spread of credibility across the full rating scale, with slightly lower probabilities at the extremes. This reflects the fact that the environmental conditions were not designed to be extreme. These priors help prevent undue credibility being assigned to implausible parameter values, improve computational stability, and remain sufficiently broad for the observed data to dominate inference, ensuring that posterior estimates are shaped primarily by participants' responses rather than by restrictive prior assumptions.

Each Bayesian model was sampled using four chains, each with 10,000 iterations (1500 warm-up samples with a thinning rate of two), yielding 17,000 posterior samples per model. Convergence diagnostics with $\hat{R}$, effective sample sizes, trace plots, and posterior predictive checks consistently indicated robust convergence across all models.

As regression results, we reported means and 95% Highest Density Interval (HDI; i.e., the 95% most credible values) of posterior distributions. The estimates from our ordinal regressions can be interpreted as standardized effect sizes, similar to Cohen's *d* [60,61], representing the change in latent[7] satisfaction/sensation in standard deviation units per unit change in the predictor. As mentioned in the background, we applied Bayesian ROPE framework [15] on posterior effect estimates to assess the practical existence of cross-modal effects. The ROPE was defined as −0.1 to 0.1, representing parameter values considered practically equivalent to zero. If the 95% HDI excluded the ROPE, we rejected the null (i.e., concluded that the effect was credibly different from zero). If the 95% HDI was entirely within the ROPE, we accepted the null (i.e., considered the effect practically equivalent to zero). If the 95% HDI overlapped with the ROPE, we remained undecided, and more data are needed.

4. Results

Below, we report descriptive results, confirmatory results addressing the primary objective, and exploratory results addressing the secondary objectives.

4.1. Descriptive results

This section presents the descriptive results that are most relevant to our primary research objectives, given space limitations. For a comprehensive view, additional tables and plots are provided in supplementary materials.

Table 1 summarizes the descriptive statistics for physical environmental conditions under neutral and warm thermal conditions measured during the perception ratings prior to olfactory adaptation. As intended by the thermal manipulation, air and globe temperatures were about 4.5 °C higher in warm sessions compared to neutral sessions (air: 29.7 °C vs. 25.5 °C; globe: 29.0 °C vs. 24.6 °C). The small standard deviations (about 0.3 °C) relative to the means indicate stability within each temperature condition. Regarding other environmental variables, CO_2 concentrations, air velocity, ambient noise, illuminance, and air/barometric pressure showed minimal mean differences between conditions (<10 ppm for CO_2, <0.01 m/s for air velocity, <1 dBA for noise, <5 lx for illuminance, and <80 Pa for air pressure), with standard deviations of generally small absolute size. Absolute humidity remained almost identical between warm and neutral conditions (~11.5 g/m^3), indicating a stable moisture load in room air regardless of temperature manipulation. Consequently, relative humidity adjusted due to temperature changes (≈ 41% in warm vs. ≈ 51% in neutral), reflecting the effect of increased temperature on relative humidity levels. Overall, these results support that differences in thermal conditions were achieved as planned, while other environmental factors, except for relative humidity, remained comparable and consistent across thermal conditions.

Fig. 3 presents boxplots of odor concentrations across all conditions, measured via Tenax sampling before olfactory adaptation, while Table 2 summarizes the corresponding descriptive statistics. Measured concentrations broadly aligned with their respective target values across all conditions. For 1-butanol (target: 5 ppm), mean concentrations were 4.78 ppm (sd = 0.57, CV [Coefficient of Variation] = 12.0%) under neutral and 5.41 ppm (sd = 0.69, CV = 12.8%) under warm conditions, while pentyl acetate (target: 0.7 ppm) yielded means of 0.61 ppm (sd = 0.17, CV = 27.6%) and 0.71 ppm (sd = 0.17, CV = 24.6%) for neutral and warm conditions, respectively. Mean concentrations differed only

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[7] A latent variable (e.g., satisfaction) represents an underlying continuous construct that is not directly observed but inferred from participants' responses through a statistical model.

Table 1
Descriptive statistics for the physical environment at the moment of perception ratings prior to olfactory adaptation across thermal conditions.

thermal condition	variable	mean	sd	min	max
warm	Absolute humidity [g/m^3]	11.67	2.16	7.64	16.14
neutral	Absolute humidity [g/m^3]	11.33	1.37	8.63	13.88
warm	CO$_2$ [ppm]	547.05	29.90	504.50	658.50
neutral	CO$_2$ [ppm]	538.78	25.60	487.67	589.83
warm	Relative humidity [% RH]	41.26	7.50	27.05	56.55
neutral	Relative humidity [% RH]	50.60	5.97	38.81	62.52
warm	Illuminance [lux]	500.30	19.78	447.45	523.30
neutral	Illuminance [lux]	504.50	19.61	462.43	528.45
warm	Air pressure [Pa]	99,290.51	558.61	97,554.44	100,611.67
neutral	Air pressure [Pa]	99,218.46	894.16	97,225.00	100,668.57
warm	Air temperature [°C]	29.71	0.26	29.37	30.28
neutral	Air temperature [°C]	25.45	0.32	24.60	26.04
warm	Globe Temperature [°C]	28.99	0.26	28.30	29.55
neutral	Globe Temperature [°C]	24.58	0.32	23.90	25.13
warm	Air velocity [m/s]	0.05	0.01	0.03	0.07
neutral	Air velocity [m/s]	0.05	0.01	0.01	0.09
warm	Noise [dBA]	39.45	2.45	35.70	45.16
neutral	Noise [dBA]	39.98	2.39	35.95	46.10

slightly between thermal conditions for each odor, indicating moderate comparability. Standard deviations and coefficients of variation were similar within each odorant, indicating generally comparable variability between thermal conditions for each odor.

Fig. 4 presents a quadrifid graph of valence ratings for both odors. Based on our a priori categorization, pentyl acetate was designated as pleasant, while 1-butanol as unpleasant. Thus, we expected that most ratings would fall within the bottom right quadrant. Contrary to these expectations, the plot reveals substantial inter-individual variability, with data points dispersed across three quadrants, excluding the top right. This distribution indicates no clear valence pattern corresponding to either odor.

Finally, Fig. 5 presents bar plots illustrating distributions of thermal and olfactory satisfaction ratings prior to olfactory adaptation across all conditions.

4.2. *Confirmatory results*

Results from confirmatory analysis on satisfaction across domains prior to olfactory adaptation are summarized in Table 3. The regression on thermal satisfaction revealed a main effect of temperature of 1.74, 95% HDI [0.80, 2.76] which excluded the ROPE [−0.1, 0.1], indicating that neutral temperature increased latent thermal satisfaction by 1.74 standard deviation units compared to warm temperature. The regression on olfactory satisfaction revealed a cross-modal main effect of temperature of 1.05, 95% HDI [0.31, 1.80] excluding the ROPE, indicating that neutral temperature increased latent olfactory satisfaction by 1.05 standard deviation units relative to warm temperature (Fig. 6 illustrates its posterior distribution and conditional effects). However, the main effect of odor was 0.21, 95% HDI [−1.25, 1.59] overlapping with the ROPE. Thus, the evidence was inconclusive regarding how pentyl acetate (coded as pleasant) affected latent olfactory satisfaction compared to 1-butanol (coded as unpleasant). The 95% HDIs of all other cross-modal main effects and interactions overlapped with the ROPE, so we remained agnostic.

4.3. *Exploratory results*

Complete exploratory results are available in the supplementary materials. As outlined in the secondary objectives, we explored satisfaction after olfactory adaptation, as well as sensation before and after adaptation, across domains.

Consistent main effects of temperature emerged across thermal perception measures both before and after adaptation. The regression on thermal satisfaction showed a clear main effect of temperature: neutral temperature increased latent thermal satisfaction by 3.38 standard deviation units compared to warm condition (95% HDI [1.94, 4.95] excluding the ROPE). Similarly, thermal sensation ratings revealed main effects of temperature both prior to and after adaptation. Before adaptation, neutral temperature decreased the latent sensation of warmth by 1.99 standard deviation units (95% HDI [−2.99, −1.06]); after adaptation, the effect strengthened to −3.38 standard deviation units (95% HDI [−4.63, −2.18]).

In contrast, main effects of odor on olfactory perception were less conclusive. Only the regression on olfactory sensation after adaptation showed a main effect: exposure to pentyl acetate (coded as pleasant) increased latent odor intensity sensation by 1.12 standard deviation units compared to 1-butanol (coded as unpleasant; 95% HDI [0.47, 1.76] excluding the ROPE). The effect of odor on olfactory sensation before adaptation was inconclusive (0.13, 95% HDI [−0.59, 0.84]), as was the effect on olfactory satisfaction after adaptation (−0.20, 95% HDI [−0.75, 0.38]), both overlapping with the ROPE.

Aligned with the confirmatory findings, we observed a positive cross-modal main effect of temperature on olfactory satisfaction after adaptation. Neutral temperature increased latent olfactory satisfaction by 1.01 standard deviation units compared to warm temperature (95% HDI [0.11, 1.98] excluding the ROPE). In contrast, evidence for all other cross-modal main effects and interactions was inconclusive, as their 95% HDIs overlapped with the ROPE.

Notably, two cross-modal interaction effects were entirely negative, despite their 95% HDIs marginally overlapping with the ROPE—suggesting potential interaction patterns that warrant further investigation. Specifically, the increase in thermal satisfaction from warm to neutral temperature after adaptation was 1.11 standard deviation units smaller under pentyl acetate compared to 1-butanol (95% HDI [−2.18, −0.09]). Similarly, the increase in overall satisfaction under the same temperature shift was 1.07 units smaller under pentyl acetate (95% HDI [−2.20, −0.06]). Interaction plots are provided in Fig. 7.

Finally, we explored potential predictors of valence ratings collected during the end-of-study survey. We conducted a multilevel Bayesian cumulative probit ordinal regression with the formula: valence ∼ odorant + item order + odorant presentation order + (1 | participant). Unexpectedly, the main effects—odorant identity (0.23, 95% HDI [−0.36, 0.83]), rating item order (−0.58, 95% HDI [−1.28, 0.14]), or odorant presentation order during the second session (0.19, 95% HDI [−0.53, 0.89])—were all inconclusive, as their 95% HDIs overlapped

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[8] Marginal means are the model-based averages of an outcome (e.g., overall satisfaction) across predictor values, adjusted for the effects of other variables in the model.

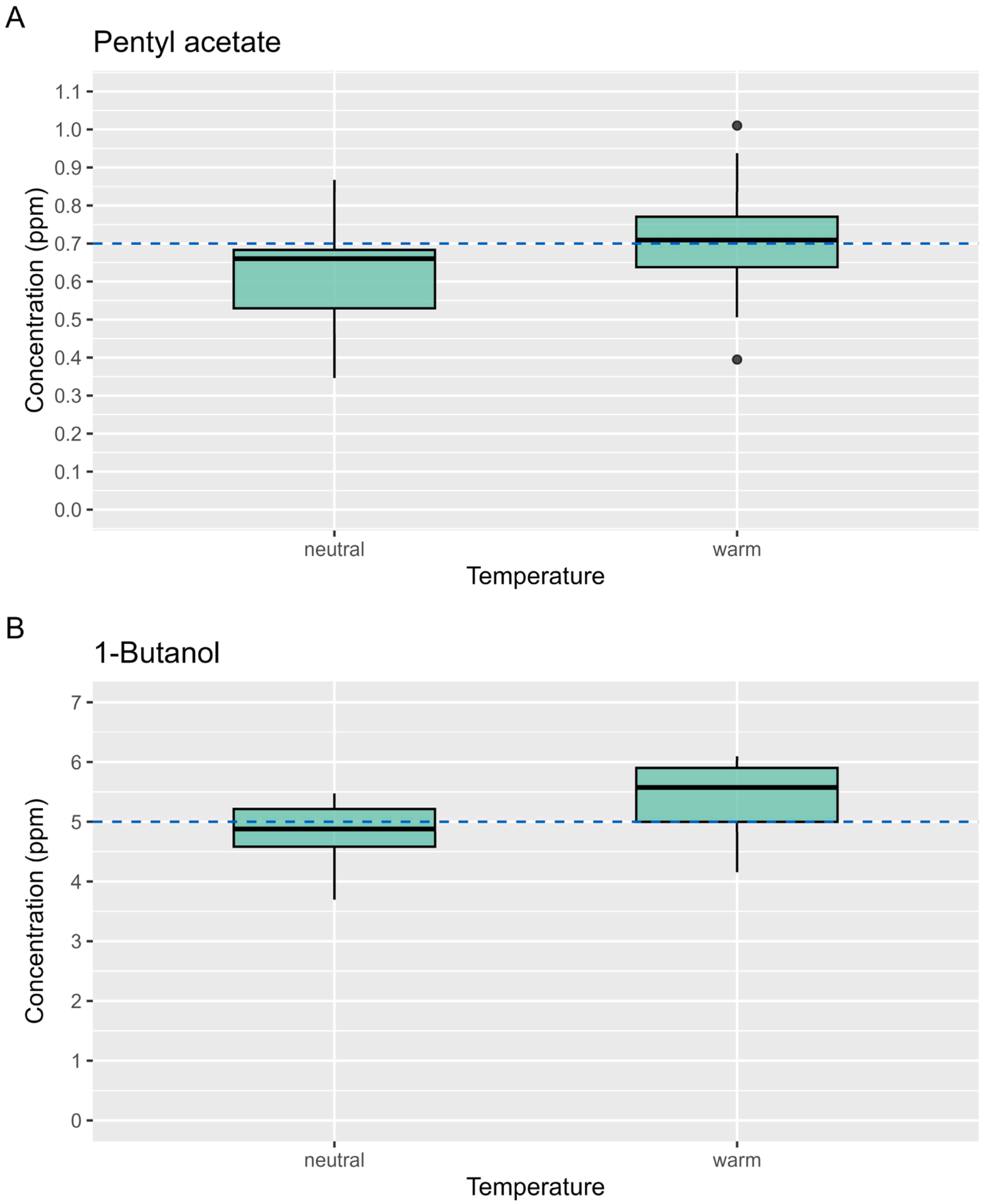

Fig. 3. Boxplots of odor concentrations measured via Tenax sampling at the moment of perception ratings prior to olfactory adaptation across thermal and olfactory conditions. Blue lines indicate the respective target concentrations.

Table 2
Descriptive statistics for odor concentrations (ppm) measured via Tenax sampling prior to olfactory adaptation across thermal and olfactory conditions.

odor	thermal condition	N	mean	sd	Mean Absolute Deviation	Mean Absolute Percentage Deviation	Coefficient of Variation
1-butanol	neutral	11	4.78	0.57	0.45	9.05%	12.02%
1-butanol	warm	11	5.41	0.69	0.74	14.87%	12.82%
pentyl acetate	neutral	9	0.61	0.17	0.13	18.52%	27.64%
pentyl acetate	warm	11	0.71	0.17	0.12	17.65%	24.56%

with the ROPE.

5. Discussion

This study primarily investigated the cross-modal effects of odor and

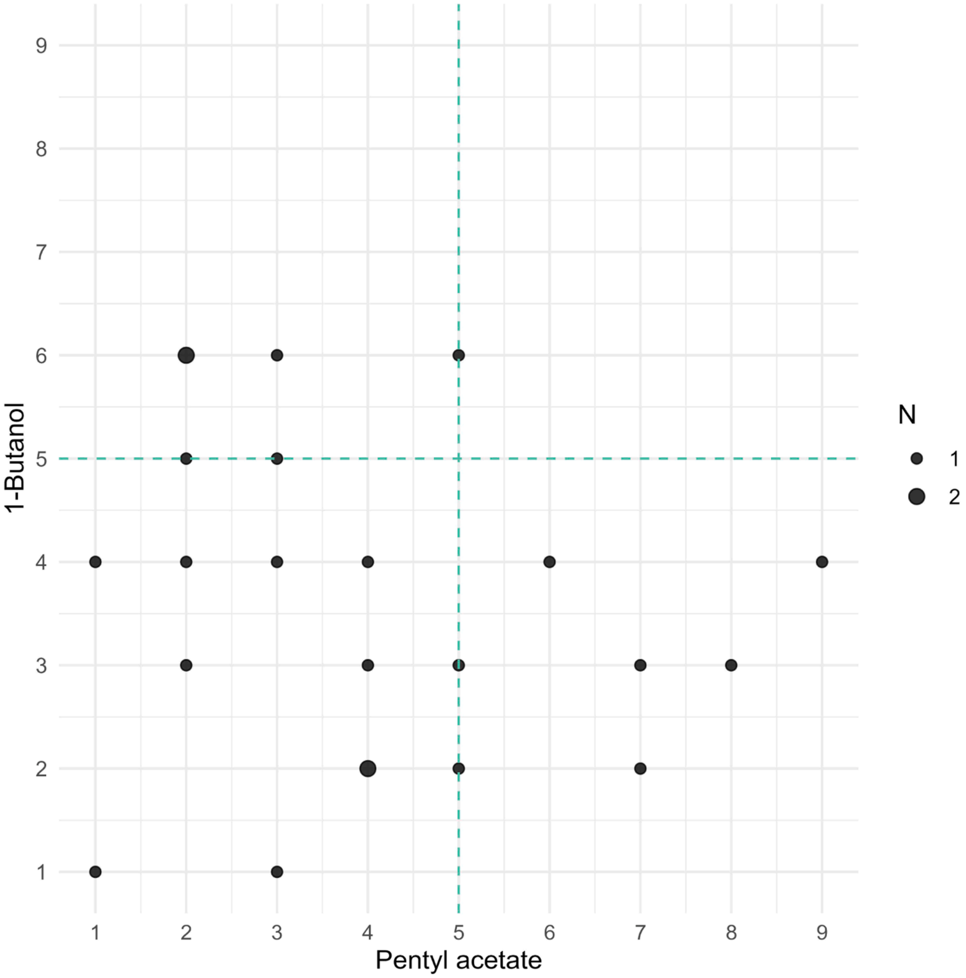

Fig. 4. Quadrifid plot of valence ratings for two odors. Each point represents a participant's rating. On both axes: 1 = very unpleasant; 9 = very pleasant.

temperature on human perception in office environments through a controlled lab experiment. This section will first discuss thematic and methodological considerations, then address limitations and outlooks.

5.1. Thematic considerations

Regarding the primary objective, the results provided direct evidence for a cross-modal main effect of temperature on olfactory satisfaction prior to olfactory adaptation. Specifically, in line with our expectations, a slightly warm temperature reduced olfactory satisfaction relative to a neutral temperature in office environments. Notably, this cross-modal effect was still present after olfactory adaptation, underscoring its robustness.

These findings extend a growing body of research demonstrating cross-modal influences in other sensory domains, such as temperature's impact on visual perceptions [62] and acoustic comfort [31]. Within the thermal-olfactory domain, our results align with Zhao & Li's review [17], which highlighted studies [63,64] reporting occupants' tendency to evaluate indoor air quality (IAQ) more stringently under uncomfortable thermal conditions. The evidence is further supported by field studies [65,66] in office buildings and classrooms where higher temperatures significantly reduced occupants' IAQ comfort and acceptability.

Furthermore, our findings corroborate Chang et al. [4], who observed enhanced fragrance comfort and pleasure with improved thermal comfort in outdoor campus settings. Meanwhile, Jia et al. [3] reported non-significant temperature effects on odor comfort. However, their null findings do not necessarily contradict our results, but may be partly attributable to limitations in traditional NHST (e.g., insufficient statistical power) or their methodology, such as analyzing ordinal variables as continuous, potentially attenuating effects. By utilizing a controlled laboratory design and incorporating recent methodological advancements, the present study addresses these issues and offers stronger evidence for temperature–olfactory interplays. Overall, our work contributes to this literature by confirming temperature's influence on olfactory satisfaction—an underexplored relationship in controlled office contexts.

The observed negative thermal-to-olfactory effect supports the idea that an unpleasant stimulus in one modality can worsen perceptions in another, consistent with negativity bias [18,19] and revenge effect [4,16]. In practical terms, thermal and olfactory perceptions can be interdependent, suggesting that dissatisfaction in one domain may partly arise from the other. Diagnostic approaches to occupant complaints should thus holistically account for potential cross-modal sources of dissatisfaction and avoid isolated assessments of sensory domains.

Theoretically, negativity bias and revenge effect are not confined to specific sensory domains; rather, they should manifest across various sensory domains. Thus, it is reasonable to anticipate similar effects in other combinations of domains (e.g., thermal–visual or

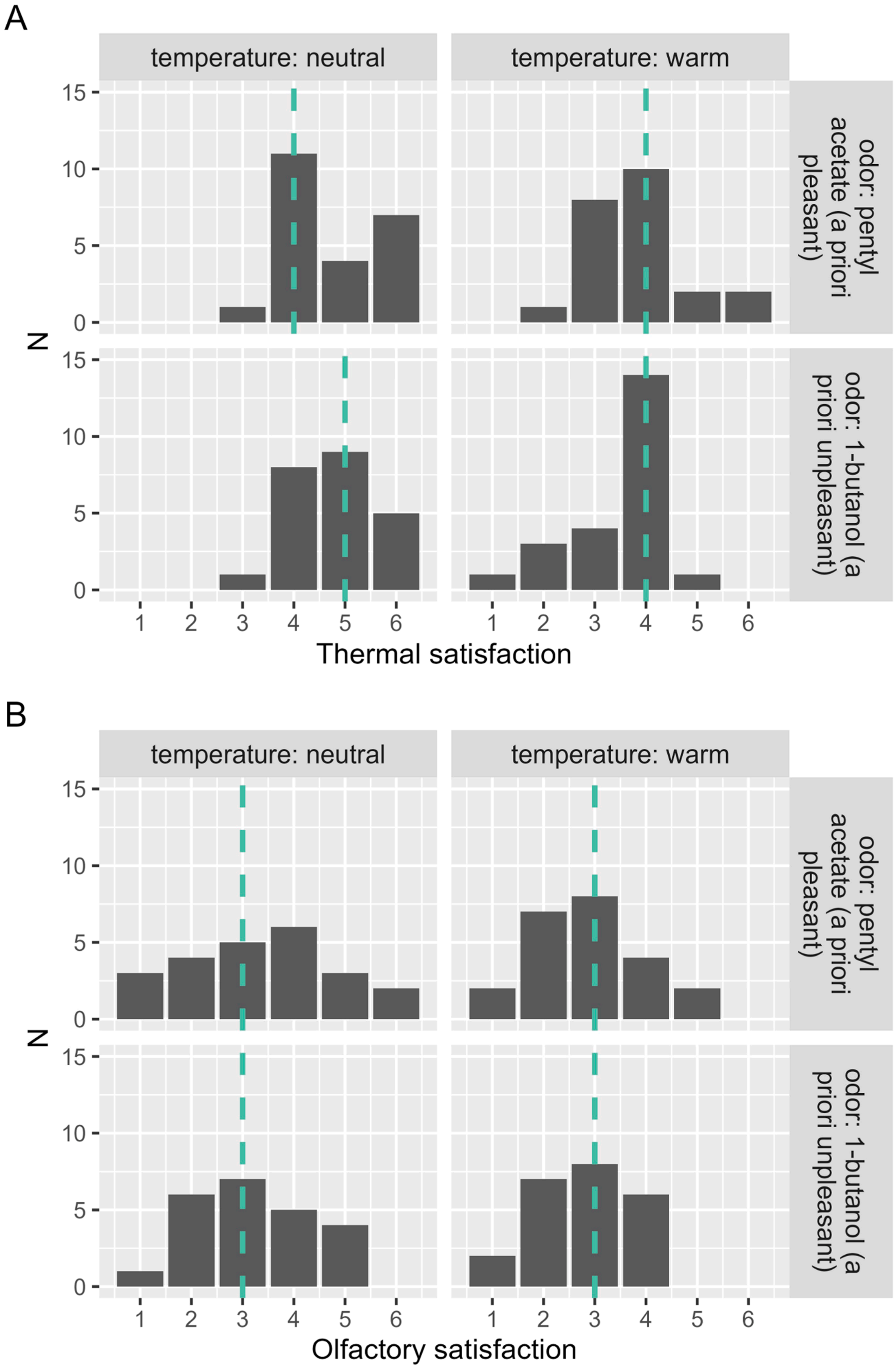

Fig. 5. Bar plots of thermal and olfactory satisfaction ratings prior to olfactory adaptation across thermal and olfactory conditions, with rating 1 = very dissatisfied and 6 = very satisfied. Green lines indicate the respective medians. “Pleasant” and “unpleasant” refer to a priori experimental labels.

Table 3
Population-level main and interaction effect estimates from ordinal regressions on satisfaction across domains prior to adaptation. (*) indicates an effect with a 95% highest density interval (HDI) excluding the region of practical equivalence of [−0.1, 0.1].

domain	effect	estimate	95% HDI
thermal	Temperature (*)	1.74	0.80, 2.76
thermal	odor	0.25	−0.32, 0.78
thermal	temperature x odor	−0.60	−1.56, 0.36
olfactory	Temperature (*)	1.05	0.31, 1.80
olfactory	odor	0.21	−1.25, 1.59
olfactory	temperature x odor	0.07	−0.95, 1.08
visual	temperature	0.48	−0.18, 1.15
visual	odor	−0.45	−1.11, 0.17
visual	temperature x odor	−0.08	−1.17, 0.96
acoustic	temperature	0.34	−0.20, 0.89
acoustic	odor	−0.02	−0.51, 0.50
acoustic	temperature x odor	−0.58	−1.56, 0.35
overall	temperature	0.35	−0.62, 1.37
overall	odor	−0.22	−1.04, 0.59
overall	temperature x odor	0.17	−0.83, 1.19

olfactory–overall). However, our results were inconclusive regarding additional cross-modal effects. Accordingly,[9] we were unable to draw conclusions about the One-Vote Veto effect [17] as reviewed in the background, wherein dissatisfaction in a single sensory domain overrides overall satisfaction. It remains unclear whether our results reflect insufficient sample size or genuine domain-specific differences in cross-modal effects. Psychological literature (e.g., [67,68]) has suggested that sensory domains can differ in their propensity to influence others, with certain domains being more salient or dominant in multisensory integration. Additionally, cross-modal effects may also depend on the specific physical conditions and manipulations employed. The present experiment maintained a constant visual environment. This absence of visual manipulations may have constrained opportunities for visual cross-modal effects. By contrast, acoustic conditions were subject to clear fluctuations: operational noise from odor delivery occurred intermittently, while it was minimized during perception ratings. Such variability could have affected acoustic evaluations, potentially masking subtle cross-modal effects. Future studies with larger samples, alongside broader and more dynamic manipulations across multiple sensory domains, are required to elucidate these speculative mechanisms.

Among the inconclusive results, we want to highlight two marginal cross-modal interactions that warrant particular attention. These interactions, characterized by 95% HDIs being entirely negative despite marginally overlapping with the ROPE, suggest a nuanced influence of odor on thermal and overall satisfaction. Specifically, the shift in temperature from warm to neutral resulted in marginally less improvement in thermal and overall satisfaction measured after olfactory adaptation under pentyl acetate compared to 1-butanol. In other words, participants experienced diminished benefit from the thermal adjustments when exposed to pentyl acetate (coded as pleasant) compared to 1-butanol (coded as unpleasant).

These patterns tentatively hint at a moderating role of odor in shaping responses to thermal conditions regarding thermal and overall satisfaction. While prior literature has provided support for significant cross-modal interactions for other sensory domain combinations (e.g., [31,32]), there were also numerous null findings (e.g., [69,70]). Our marginal results neither confirm nor refute the existence of cross-modal interaction effects, but contribute to a broader body of mixed evidence. More importantly, they underscore the value of alternative methodological approaches such as the Bayesian ROPE framework employed in this study, which can facilitate the integration of existing findings as priors to inform future research and supports the establishment of practical null effects when sufficient evidence is available in the sense of cumulative science [15,71].

Interpreting the observed marginal interactions requires caution, as it hinges on the valence of the two odors. Based on our a priori classification of pentyl acetate as pleasant and 1-butanol as unpleasant, these interactions would suggest that an unpleasant odor intensifies the detrimental effect of a suboptimal thermal condition on thermal and overall satisfaction in comparison to a pleasant odor. This would be in line with our expectations based on negativity bias. However, we note that our data did not empirically support this valence classification, as shown by the substantial inter-individual scatter over three quadrants in the quadrifid plot (Fig. 4) and by the inconclusive result regarding whether shifting from pentyl acetate to 1-butanol systematically affected perceived valence (more discussions in section Methodological considerations). Given this uncertainty, we refrain from post-hoc recoding of odor valence or attributing the observed interactions solely to negativity bias without further empirical evidence. Instead, we acknowledge the limitations and encourage future work to examine these potential moderating effects more directly, ideally with designs that allow for robust classification of odor valence at the individual level.

5.2. *Methodological considerations*

To our knowledge, this study is the first cross-modal research to adopt the causal inference framework proposed by Pan, Mahdavi, et al. [5], which allowed us to investigate causal effects in a principled way. In addition, our covariate selection was guided by the adjustment criterion within a visual causal diagram framework [56], ensuring that potential confounding factors were addressed systematically and that our causal claims rested on transparent causal assumptions.

Moreover, our application of the Bayesian ROPE framework [15] for statistical inference represents an intentional departure from traditional NHST, thereby overcoming numerous well-documented limitations associated with the latter conventional approach (e.g., [12–14]). Through the alternative framework, we were able to provide more nuanced interpretations of our results, explicitly identifying areas where evidence was insufficient or indeterminate rather than defaulting to (often unjustified) acceptance of the null hypothesis. Such transparency and rigor facilitate informed decision-making and can guide future research priorities.

Our methodological integration demonstrates how recent advances in causal inference and statistics can be leveraged to address existing methodological gaps in multi-domain research. This combination enhances robustness and transparency while improving both interpretability and reproducibility of findings—critical factors for advancing cumulative scientific understanding. We contend that this study could serve as a precedent for statistical rigor, and the methodological approach presented here can function as a replicable template for future causal cross-modal studies and beyond, such as human-centric building science research.

Next, we discuss the experimental manipulations employed in this study. The thermal manipulations were effective, as confirmed by the descriptive results from physical measurements and by the consistent main effects of temperature across perception variables from all ordinal regressions. These results validate the success of our thermal manipulations.

In contrast, the olfactory manipulations posed greater methodological challenges. Unlike previous research that relied on localized artificial odor delivery methods such as diffusers or sniffing bottles, our study sought to create more realistic exposure conditions by manipulating the entire room's atmosphere. This approach was implemented within

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[9] As shown by the bar plots in the supplementary materials, satisfactions with visual, acoustic, and overall conditions were generally above low ranges. This aligns with our design assumption that non-manipulated domains remained at least neutral, and thus the analysis focused, as planned, specifically on the thermal and olfactory manipulations, while visual and acoustic environment were not included when examining the One-Vote Veto effect.

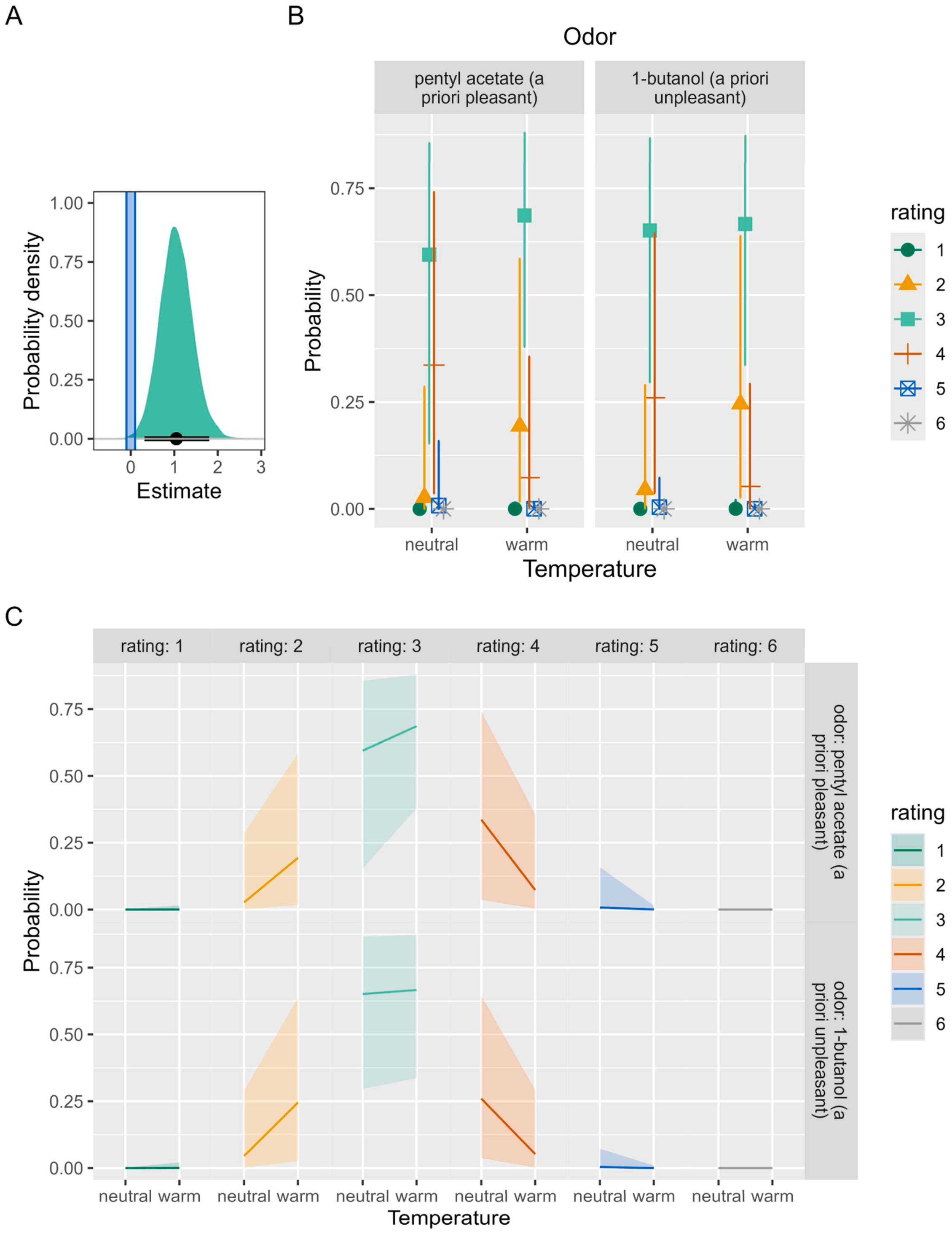

Fig. 6. Population-level estimated cross-modal effect of temperature on olfactory satisfaction. Rating 1 = very dissatisfied and 6 = very satisfied. (A) Half-eye plot showing the posterior distribution (green shades), with the point and line indicating the posterior mean and 95% highest density interval (HDI). The region of practical equivalence is shown in blue. (B) Conditional effects plot depicting estimated probabilities for each rating category across thermal and olfactory conditions. Points indicate posterior means; error bars represent 95% HDIs. (C) Conditional effects plot showing estimated probabilities by rating category across thermal and olfactory conditions. Lines represent posterior medians; shaded ribbons indicate 95% credible intervals.

available resources through pretest calibration using FTIR-based real-time monitoring, followed by Tenax sampling for post-hoc verification during the experimental phase. A significant challenge was the absence of real-time, in-situ odor concentration monitoring during the experimental phase, which restricted our ability to make fine adjustments to release rates and increased susceptibility of the achieved concentrations to environmental variation and system drift.

Despite the difficulties, Tenax results indicated that concentration levels broadly aligned with target values. Descriptive results presented above showed moderate comparability between thermal conditions for each odor. The precision of concentration implementation was similar across conditions, evidenced by generally matching standard deviations and coefficients of variation. Mean concentrations differed slightly—by approximately 13% (≈ 0.63 ppm) for 1-butanol and 16% (≈ 0.10 ppm)

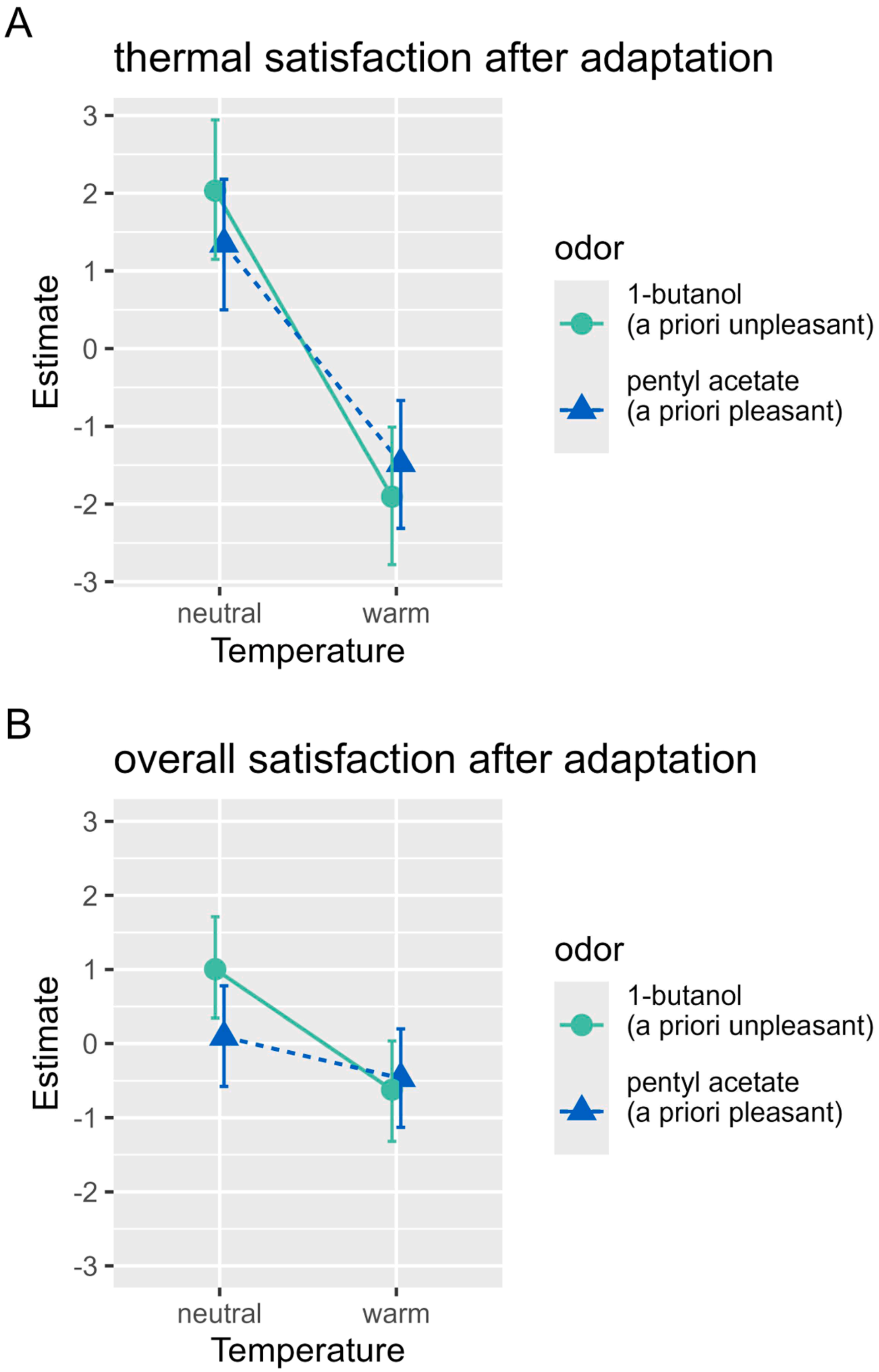

Fig. 7. The estimated marginal means[8] of latent thermal and overall satisfaction as functions of temperature and odor. Points represent posterior means; error bars indicate 95% highest density intervals.

for pentyl acetate.

Notably, these results must be interpreted with consideration on procedural constraints that may have reduced measurement reliability. To fit within short rating periods, we reduced Tenax sampling duration from ~30 min to 60 s and lowered airflow to 40 mL/min to avoid overloading due to high odor levels. These adjustments decreased analyte mass and increased susceptibility to short-term fluctuations. Additionally, GC-ToF-MS run time was shortened from ~90 min to ~30 min per sample due to the multi-week experimental schedule, potentially reducing compound separation accuracy and increasing minor interference from other airborne volatile organic compounds.

Overall, we consider the concentration manipulation to have been relatively effective as intended, with results indicating alignment with target values and moderate comparability across thermal conditions. Nonetheless, there remain areas for improvement, particularly in achieving greater accuracy. It would be beneficial if future investigations addressing similar research questions are carried out with real-time on-site measurement and closed-loop control of odor generation, enabling target concentrations to be achieved and maintained more precisely across varying thermal conditions.

A central challenge in our olfactory manipulations was the selection of suitable odorants with reliably distinct pleasant and unpleasant valences. We chose pentyl acetate (deemed pleasant) and 1-butanol (deemed unpleasant) for their safety profiles and compatibility with measurement techniques. Contrary to expectations, however, our results did not support a clear differentiation in perceived valence between these odorants.

Concretely, exploratory ordinal regression analysis revealed inconclusive effects of odorant identity on valence ratings. The anticipated effect between pentyl acetate and 1-butanol in terms of pleasantness was not observed. Instead, individual responses varied widely, as illustrated by the scattered distribution across three quadrants in the quadrifid plot (Fig. 4). Regression analyses further indicated that, although pentyl acetate was associated with higher perceived odor intensity after adaptation, the effect of odorant identity on olfactory satisfaction remained inconclusive. Specifically, it was unclear whether pentyl acetate led to greater or lower olfactory satisfaction compared to 1-butanol, contrary to our expectation that a shift from a presumed pleasant to an unpleasant odor would reduce satisfaction. Together, these results point to notable hedonic ambiguity in our selected odorants.

Our results echo findings in literature highlighting substantial inter-individual differences in odor valence perceptions. For instance, Butter et al. [72] found pleasantness ratings varied strongly within participants in response to wood odors. Arshamian et al. [73] further reported that individual tastes accounted for 54% of variance in odor pleasantness ratings, far exceeding other factors, such as cultural effects. In line with this variability, four participants in our study reported, either in open responses or orally after the sessions, strong dislike toward pentyl acetate, describing its smell as reminiscent of banana and as dizzying or terrible. These anecdotal feedbacks illustrate how individual associations with specific odor qualities may overwhelm hedonic categorizations.

Several methodological aspects may have contributed to this variability. Literature has indicated strong sensitivity of valence assessments to presentation mode and rating methodology [74]. Thus, our retrospective valence rating approach, which relied on uncalibrated odor samples as memory cues, may have to some extent introduced more variations to the ratings, potentially due to memory decay, experiential averaging, alongside personality traits and baseline preferences. Additionally, presenting odors within room atmospheres rather than through direct exposure could have amplified perceptual ambiguity.

Without further targeted data collection, these ambiguities cannot be fully resolved within the current study framework. As this issue represents a significant challenge for subsequent studies, future research should prioritize refined odorant selection, more rigorous pretesting of odorant valence within the target population and consider real-time or continuous valence rating protocols to mitigate memory-related biases.

Finally, we note that after olfactory adaptation, pentyl acetate was perceived as more intense than 1-butanol. This main effect suggests that adaptation may have been incomplete for pentyl acetate after the 10-minute exposure, and potentially hints at odor-specific differences in adaptation dynamics, as some odors elicit more persistent sensory responses than others [8,75,76]. Hedonic tone could be a contributing factor; however, given the hedonic ambiguity of the two odors, we refrain from speculating on whether participants selectively down-regulated sensitivity along hedonic dimensions. As this is an exploratory side finding, future studies are needed to determine whether such odor-specific persistence is systematic or context-dependent. Moreover, for future studies aiming to examine effects after full adaptation, longer exposure periods than 10 min may be necessary when using pentyl acetate.

5.3. Limitations and outlooks

A primary limitation of this study concerns its external validity. Data were collected exclusively in the Aachen Workplace Simulation Lab between July and October, and the participant pool was relatively limited in size and demographic diversity (e.g., age, occupation). These factors potentially restrict the generalizability to broader office populations and heterogeneous workplace environments.

Furthermore, our investigation was confined to only two odor conditions and two temperature levels. Similarly, lighting and acoustics were held constant during perception ratings but were not systematically varied. While this controlled design facilitated a focused examination of cross-modal effects, it does not encompass a representative environmental variability present in real-world offices. Therefore, our results should be viewed as initial evidence rather than a comprehensive assessment. Also, we acknowledge that the lack of an odorless control condition may limit direct extrapolation of our findings to odor-free settings.

An additional constraint involves contextual realism and procedural aspects. The experimental setup covered the windows completely, creating an artificial visual environment that may have influenced participants' visual and overall perceptions differently from typical offices featuring outdoor views and natural lighting. Moreover, environmental conditions were delivered in episodic 15-minute intervals with intervening breaks, rather than as sustained or gradually shifting exposures. Despite randomization, this intermittent presentation could induce contrast effects, wherein ratings reflect comparisons to preceding conditions [77], potentially introducing more random noise. Additionally, perception under such episodic presentation might diverge from the continuous, slowly drifting dynamics typical of everyday workspaces.

Finally, beyond the psychological theoretical frameworks adopted in this study, the observed cross-modal effects may also reflect physiological and neurocognitive processes that were not directly assessed. For example, ambient temperature may influence olfactory perception by altering intranasal thermodynamics, which affects mucosal cooling and the activation of trigeminal thermal receptors, ultimately changing the peripheral sensitivity of the olfactory system [9,78,79]. Meanwhile, we note that existing sensory research offers no clear expectation as to how such temperature-related changes in olfactory sensitivity translate into subjective satisfaction with the specific odors applied in this study. In addition, thermal discomfort may bias perceptual judgments via attentional mechanisms, whereby cognitive resources are preferentially allocated to the dominant source of discomfort at the expense of processing other sensory inputs [80,81]. Neurocognitive studies support this interpretation, showing that attentional engagement with pleasant stimuli—indexed by neural markers such as the late positive potential—tends to decrease under conditions of increased discomfort or competing demands [82,83]. Because the present study was designed to examine perceptual evaluations rather than to delineate biological or neural pathways, these potential mechanisms remain speculative and warrant targeted investigation in future interdisciplinary research.

Overall, future work should aim to broaden participant demographics, incorporate a wider palette of environmental manipulations, employ longer, steady-state or longitudinal studies in more authentic and diverse office layouts, and investigate potential underlying physiological and neurocognitive mechanisms. It would also be beneficial to consider individual differences, such as thermal sensitivity and cultural associations with odors, as these factors may amplify or dampen cross-modal effects.

6. Conclusion

This study investigated the cross-modal effects of odor and temperature on human perception within office environments through a single-blind, 2 × 2 within-subjects experiment. Room atmospheres were manipulated with pentyl acetate (pleasant) and 1-butanol (unpleasant) at neutral (24 °C) and warm (28.5 °C) temperatures. Standardized questionnaires assessed subjective satisfaction and sensation across sensory domains before and after olfactory adaptation. By integrating recent advancements in statistical methods including the causal inference framework, the adjustment criterion framework, and the Bayesian ROPE framework, we attempted addressing key methodological gaps in prior multi-domain studies.

Results provided direct evidence that room temperature influences olfactory satisfaction, while only marginal evidence was found for cross-modal interactions affecting thermal and overall satisfaction. Other potential effects were inconclusive, necessitating further data. Substantial inter-individual variability in odor valence ratings was observed, underscoring the importance of considering individual differences in odor perception.

These findings indicate an interdependence between thermal and olfactory perceptions, highlighting the importance of holistic assessments of indoor environmental quality (IEQ) and the necessity of follow-up multi-domain research. They partially align with the notion of negativity bias and the revenge effect, demonstrating how negative experiences in one sensory domain can elicit dissatisfaction in another, although the One-Vote Veto effect was not confirmed as anticipated.

Methodologically, we highlight challenges related to odor selection and concentration control as key areas for improvement in future research. Meanwhile, our statistical approach showcases how modern tools can improve rigor and transparency in causal human-centric building science research, offering a replicable template for future studies.

From a practical perspective, recognizing that thermal conditions can impact olfactory satisfaction has implications for building design and facility management. Complaints regarding odors may stem from suboptimal temperatures rather than air quality alone; thus, a multi-domain approach should be considered when diagnosing occupant discomfort and optimizing IEQ interventions.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used *ChatGPT* in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Jian Pan: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jens Bertram:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Jens Rengelshausen:** Writing – review & editing, Investigation, Conceptualization. **Thomas Kraus:** Writing – review & editing, Resources, Conceptualization. **Ardeshir Mahdavi:** Writing – review & editing, Funding acquisition, Conceptualization. **Irene Martínez-Muñoz:** Writing – review & editing, Conceptualization. **Isabel Mino-Rodriguez:** Writing – review & editing, Visualization, Conceptualization. **Andreas Wagner:** Writing – review & editing, Conceptualization. **Christiane Berger:** Writing – review & editing, Conceptualization. **Rania Christoforou:** Writing – review & editing, Conceptualization. **Irene Elisabeth Müller:** Writing – review & editing, Investigation, Conceptualization. **Marcel Schweiker:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

PAN, Jian reports financial support was provided by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation). Schweiker, Marcel reports financial support was provided by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation). Mino-Rodriguez, Isabel reports financial support was provided by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation). Wagner, Andreas reports financial support was provided by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation). Schweiker, Marcel reports financial support was provided by VILLUM FONDEN. Christoforou, Rania reports financial support was provided by VILLUM FONDEN. Mahdavi, Ardeshir reports financial support was provided by Austrian Science Fund. Martínez-Muñoz, Irene reports financial support was provided by Austrian Science Fund. If there are other authors, they 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.2026.114504.

Data availability

Data will be made available on request.

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