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FINAL REPORT

1 General Information

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Project title: MuDoCo: Multi-domain comfort models – development of a systematic approach to theory, experimental design and modelling

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2 Summary

Indoor environmental quality (IEQ) is inherently multi-domain: occupants are simultaneously exposed to thermal, visual, aural, and olfactory stimuli. In response, research on multi-domain comfort has expanded across the fields of building science and environmental psychology. Despite increasing numbers of experiments and data availability, findings remain fragmented and difficult to accumulate. These limitations are often attributed to contextual variability, yet growing evidence suggests that deeper structural constraints hinder cumulative progress.

The project MuDoCo aimed to develop theoretical and methodological foundations for multi-domain comfort modelling by combining laboratory experiments, modelling work, and behavioural integration research. The project's core contributions lie in the development of conceptual and methodological frameworks, supported by systematic laboratory experiments designed to test causal assumptions and model evaluation. These activities were extended through surveys: a discrete choice survey examining cross-modal weighting, as well as an expert survey and experimental assessment of impact and mitigation of careless responding.

The findings are relevant for comfort theory, modelling practice, and the future development of IEQ standards. Besides, results provide important methodological insight by identifying informative null findings and structural limits in the empirical and modelling approaches. This aligns with the original project aim to advance cross-domain effects, integrations, and modelling approaches in multidomain comfort.

3 Progress Report

The MuDoCo project aimed to advance the theoretical and methodological foundations for multi-domain comfort research by systematically investigating crossed effects and interactions between thermal, visual, aural and olfactory domains. The overarching objective was to advance on clarifying mechanisms, improve experimental design logic, and evaluate modelling strategies that could enable more coherent multi-domain integration in future work.

In line with these objectives, this progress report is structured in three parts. Section 3.1 presents the conceptual foundations developed during the project, including theoretical advances, methodological considerations, and clarification of constructs and scales used in multi-domain research. Section 3.2 reports on three experimental strands, each implemented under controlled and semi-controlled conditions, addressing different domain pairings; these are presented separately to reflect their distinct designs while contributing collectively to the evaluation of cross-domain integration under varied methodological constraints. Section 3.3 complements the laboratory studies with survey-based studies that examine evaluative weighting and

trade-offs across domains. Together, these components provide an integrated assessment of the possibilities and limits of multi-domain comfort modelling.

3.1 Theoretical and methodological frameworks

3.1.1 Cumulative multi-domain research: Theory as a foundation

Multi-domain comfort research has grown rapidly, yet findings remain fragmented. Domain-specific models of thermal, visual, aural and olfactory comfort inadequately explain combined exposures. Cross-domain effects are therefore often inconsistent, weak or dismissed as methodological noise rather than theoretically meaningful. Ambiguities between sensation, perception, comfort and acceptability further hinder cumulative progress.

The project advances with a conceptual framework for multi-domain comfort grounded in multisensory perception and regulatory physiology. Human experience of the indoor environment is inherently integrative. Cross-domain effects should, therefore, be understood as potentially arising through distinct pathways, including physiological coupling, perceptual integration, or appraisal-level combination. Contextual and/or personal factors – such as expectations, task demands, or perceived control – may further moderate sensitivity and weighting across these levels. Building on these foundations, we suggest a four-level structural framework comprising environmental exposure, physiological state, and perceptual representation, as well as appraisal and decision. This mapping provides a pathway to better understand when cross-domain effects should emerge and when a null finding is theoretically expected, thereby supporting informative null results. It also provides a basis for multi-domain experimental design and modelling while challenging current approaches that rely on domain-specific aggregation without mechanistic integration.

3.1.2 Methodology

A methodological approach integrating three complementary frameworks was introduced. The first provides three guidelines for causal cross-modal research: (i) the explicit formulation of the research objective in terms of a causal estimand, (ii) the design of empirically identifiable quantities that are informative for this estimand under clearly stated causal assumptions, and (iii) the selection and implementation of appropriate estimation strategies aligned with these assumptions.

Second, we proposed the use of backdoor and adjustment criteria as an intuitive and visual framework for covariate selection. This framework responds to widespread problems associated with inappropriate statistical adjustments, which may systematically introduce bias. By contrast, our framework enables researchers to identify valid adjustment sets through explicit causal assumptions and graphical reasoning.

Third, the Bayesian Region of Practical Equivalence (ROPE) was introduced as an alternative to conventional null hypothesis significance testing (NHST). This framework was motivated by limitations of NHST in multi-domain research, where null effects can be both common and theoretically meaningful. The ROPE approach supports more nuanced conclusions—allowing effects to be supported, rejected, or judged as inconclusive—while offering more intuitive interpretations and reduced dependence on large sample sizes or testing intentions. Together, these frameworks form a coherent approach that enhances robustness and transparency while improving both the interpretability and reproducibility of findings.

3.1.3 Constructs and scales

A review of 39 multi-domain occupant-centric IEQ studies assessed the constructs and scales used to measure subjective responses, focusing on systematic validation procedures and potential limitations. The first limitation identified in this review of 246 constructs concerns challenges in communicating the meaning of the constructs. Semantic differences in construct labelling make their meaning unclear and inconsistent across studies. This is also reflected in the questions used to ask participants. Hence, to assess the reliability and validity of findings related to participants' evaluation of indoor-environmental exposure conditions, information on the exact wording of such questions is crucial. Furthermore, the use of scales was found to be rather inconsistent. Without standardisation, the ad hoc use of scales leads to problems in upscaling studies. In addition, a considerable fraction of the constructs (40%) was not accompanied by references. The findings of this review effort point to significant gaps in how constructs and scales are defined, documented, and validated and underscore the need for efforts in the IEQ multi-domain research community to adopt a more systematic approach to applying constructs in experimental studies.

3.2 Experimental implementation and empirical validation

3.2.1 Visual – Thermal

Controlled visual-thermal laboratory experiments were conducted in the LOBSTER climate chamber at KIT to examine cross-effects and interaction effects between temperature and daylight. The two identical office rooms enable parallel sessions and environmental control.

A single-blind 2 × 2 within-subject design was implemented with varying temperature (cool vs warm) and daylight level (dim vs bright). Each participant experienced all four exposure combinations in a counterbalanced order. During the sessions, participants completed cognitive tasks and provided subjective evaluations. Environmental and physiological variables were recorded continuously. Outcome measures included subjective ratings of sensation and satisfaction. After data cleaning and quality control, data from 68 participants were analysed using

Bayesian cumulative ordinal (probit) models for subjective outcomes, including participant-specific random intercepts and random slopes whenever supported by the design.

Results showed clear and robust domain-specific effects. Temperature consistently influenced thermal sensation and thermal satisfaction, while lighting strongly affected visual sensation and more weakly visual satisfaction. Cross-domain effects were small, inconsistent, and typically within uncertainty intervals, and no stable temperature × lighting interaction was detected. Overall satisfaction, reflecting a multi-domain evaluation, showed a more consistent contribution from temperature than lighting, with no evidence of interaction or cross-domain compensation. Satisfaction outcomes were more variable than sensation, indicating greater integration beyond immediate sensory input.

These findings suggest a predominantly domain-specific evaluation of comfort, with cross-modal integration operating as a weak, second-order mechanism. The study provides clearer empirical boundaries on which effects are robust and which are unlikely to be identified under realistic experimental conditions.

3.2.2 Thermal – Olfactory

An experiment was conducted to examine how olfactory and thermal conditions interact in shaping occupants' perception of indoor environments. The conceptual aim was to test whether negative experiences in one sensory domain disproportionately influence evaluations in another domain.

A single-blind 2 × 2 within-subject laboratory experiment was conducted in the Aachen Workplace Simulation Lab at UKA to systematically vary odour and temperature conditions and assess their cross-modal effects on subjective responses. 23 participants experienced a room atmosphere with pleasant (0.7 ppm pentyl acetate) and unpleasant (5 ppm 1-butanol) odours at neutral (24 °C) and warm (28.5 °C) temperatures. Standardised questionnaires assessed subjective satisfaction and sensation across sensory domains before and after olfactory adaptation. Statistical analysis – including causal inference, adjustment criterion, and Bayesian region of practical equivalence – revealed cross-modal main effects, with increased warmth reducing olfactory satisfaction. Marginal temperature × odour interactions were found for thermal and overall satisfaction, while other cross-modal effects remained inconclusive. Substantial inter-individual variability was observed in odour valence ratings.

The 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 also underscores the need for holistic IEQ assessments and follow-up multi-domain research. Challenges related to odour selection and concentration manipulation are highlighted as key areas for improvement in related future research.

3.2.3 Visual – Acoustic

The TUG experiment investigated cross-domain interactions between acoustic stimuli and visual discomfort in an office environment. Specifically, it examined whether greater acoustic strain led to a less favourable evaluation of the same visual setting, characterised by glare-induced dissatisfaction.

Individual sessions were conducted in which 78 participants were exposed to three sound settings and four visual conditions. Participants performed office-related tasks and answered IEQ questions while being exposed to the twelve combinations of visual and acoustic conditions. The set-up consisted of a desk equipped with a computer screen with a square-shaped dimmable luminaire (26.5 by 26.5 cm) positioned directly above the computer screen. The visual settings corresponded to four different UGR levels, while background luminance, the luminance and position of the light sources, and the observer's position were kept constant. The three acoustic settings included background pink noise at an equivalent sound pressure level, as well as office and traffic noise, both at the same sound pressure level. Due to the objective of this study, the office and traffic noise conditions represent a relatively higher degree of acoustic strain, whereas the pink noise condition serves as a steady, neutral background. Participants evaluated the IEQ via questions regarding their sensation and satisfaction responses in the four key domains (thermal, visual, acoustic, and IAQ) as well as provided an overall assessment of the IEQ conditions.

After data cleaning, processing, and analysis, the main results pointed to a certain—albeit small—effect of the acoustic environment on glare-induced dissatisfaction in an office environment, whereby a higher degree of acoustic strain led to a less favourable evaluation of the same visual exposure setting. The results of the study contribute to the growing body of research on the combined effects of indoor-environmental stimuli.

3.2.4 Empirical method experiment

Two studies examined the impact and mitigation of careless responding (CR) in multi-domain research. Two pseudonymised, single-blind, randomised within-subjects experiments were conducted at the Aachen Workplace Simulation Lab and in a field office. We studied and replicated how CR affected subjective ratings of olfactory, acoustic, visual, thermal, and overall environmental perceptions, as well as evaluated countermeasures to reduce CR.

We found initial evidence that prolonged engagement with repetitive items can induce CR behaviour. The results indicate the importance of considering the potential impact of CR when designing multi-domain studies, as well as the application of mitigation measures.

3.3 Surveys

3.3.1 An exploration of experts' views on the relative importance of indoor-environmental quality parameters

An online survey, primarily targeting IEQ experts, included the ranking of five IEQ domains and five sub-items per domain using a forced-ranking format (no ties permitted). Results from 73 respondents revealed a clear overall ranking tendency: thermal and indoor air quality were prioritised highest, whereas infrastructure/amenities ranked lowest. Within domains, maintaining preferred air temperature, ensuring air freshness, and providing daylight availability were consistently prioritised. The derived coefficients were operationalised in an illustrative Total IEQ (TIEQ) index. The core contribution is transparency and traceability in the derivation of IEQ weighting schemes, highlighting the need for more systematic, validated, and context-sensitive approaches in future frameworks.

3.3.2 Choice of Office Spaces and Indoor Environments experiment – CoSi

This study uses a theory-driven discrete choice experiment to examine decision-level integration. Respondents repeatedly selected their preferred office from systematically varied descriptions of thermal, visual, acoustic and air-quality conditions. Rather than measuring physical exposure, these choices enabled estimation of each domain's relative influence and how domain-level information is combined within a random utility framework. After quality-control exclusions, the analysis included 362 respondents. The baseline model revealed clear directional preferences, for quiet rather than noisy, cool rather than warm, and fresh rather than stuffy office conditions, indicating that acoustic, thermal, and air-quality cues played important roles in overall office preferences. Results also indicated that office preferences were activity-dependent, with the relative importance assigned to the indoor environmental domains varying according to the activity respondents expected to perform. Office comfort preferences depend on the individual domain conditions but also their combination together with the activity performed. These findings support a context-sensitive, multi-domain understanding of comfort rather than assessing each domain uniformly and in isolation.

3.4 Deviation from original concept

The principal deviation concerned the empirical implementation. The proposal envisaged a coordinated fractional-factorial design across the three laboratory settings, with data combined in a joint database. Instead, each partner implemented a separate experimental strand and managed its dataset independently. The analytical strategy was also refined during the project, with greater emphasis on causal inference and methods suited to assessing weak, null or uncertain cross-domain effects. As the experimental strands were conducted separately, the integrated multi-domain comfort model could not be developed and the global IEQ construct

could not be specified to the extent originally envisaged. Instead, the project placed greater emphasis on conceptual decomposition and investigated decision-level integration through discrete-choice surveys. Research on careless responding in multi-domain surveys also emerged as a complementary strand.

3.5 Quality assurance

The methodological framework provides a replicable template for future research and strengthens robustness, transparency, and interpretability. Reproducibility was further supported through open-access supplementary materials, including source code, reproducible outputs, photographs of the experimental setups and detailed statistical information. One of the empirical studies was preregistered on the Open Science Framework (OSF). Published project outcomes also underwent rigorous peer review in leading journals and conferences.

3.6 Research data management

All research data were newly generated through experiments at UKA, KIT and TU Graz; no existing datasets were reused (Table 1). Each institution managed and curated its own dataset, and no joint database was created. All three experiments received ethics approval and written informed consent. Personal data were handled in accordance with the EU General Data Protection Regulation. Data will be publicly available, once experimental results are published, in an appropriate repository such as OSF. Only fully anonymised data that can be lawfully shared will be made accessible. In some cases, analysis code is accessible together with the publication. No dataset had been deposited at the time of reporting. Anonymised data are stored on institutional servers, with access restricted to research-group members. The respective principal investigators remain responsible for long-term curation.

Table 1: Overview of data generation, processing, storage and access by project partner.

Part.	Data generated	Processing
UKA	Subjective data (votes), objective data (environmental and physiological), and cognitive performance. Approx. 7.2 GB of project data.	Processing was conducted primarily in R and included plausibility, completeness, synchronisation, duplicate and exclusion checks.
KIT	Subjective data (votes), objective data (environmental and physiological), cognitive performance. Approx: 7 GB raw and 1 MB processed data	Processing was conducted primarily in R and included plausibility, completeness, synchronisation, duplicate and exclusion checks.
TUG	Subjective data (votes), objective data (environmental and physiological). Approx: 1 MB processed data.	Processing was conducted primarily in R and included plausibility, completeness, duplicate and exclusion checks.

3.7 Scientific events and communication

In parallel, project results were disseminated through oral and poster presentations and workshops at major international conferences, including but not limited to Indoor Air, Healthy Buildings, CATE, and DGAUM, ensuring continuous visibility and peer validation. Lastly, engagement in international research networks, including IEA EBC Annex 79 and IEA EBC Annex 95, supported collaboration and alignment with broader research agendas.

4 Published Project Results

4.1 Category A - Journal publications

Mahdavi, A., Miño-Rodríguez, I., Berger, C., et al. (2025). 'An exploration of experts' views on the relative importance of indoor-environmental quality parameters'. Building Research & Information, 53. doi:10.1080/09613218.2024.2350563.

Martínez-Muñoz, I., Mahdavi, A., Berger, C., et al. (2026). 'Deconstructing the constructs in multi-domain investigations of perceived indoor-environmental quality'. Architectural Engineering and Design Management, 22. doi:10.1080/17452007.2025.2527422.

Pan, J., Mahdavi, A., Miño-Rodríguez, I., et al. (2024). 'The untapped potential of causal inference in cross-modal research'. Building and Environment, 248, 111074. doi:10.1016/j.buildenv.2023.111074.

Pan, J., Christoforou, R., Wiedermann, L.N., et al. (2025). 'The untapped potential of Bayesian region of practical equivalence for assessing null effects in multi-domain research'. Building and Environment, 113390. doi:10.1016/j.buildenv.2025.113390.

Pan, J., Bertram, J., Rengelshausen, J., et al. (2026a). 'Causal cross-modal effects between odor and temperature on occupants' perception in a single-person office environment'. Building and Environment, 297, 114504. doi:10.1016/j.buildenv.2026.114504.

Pan, J., Favero, M., Sonta, A., et al. (2026b). 'Stop adjusting for anything: How the backdoor and adjustment criteria empower causal human-centric research'. Building and Environment, 289, 114002. doi:10.1016/j.buildenv.2025.114002.

Conference proceedings – Full conference papers

Berger, C., Heyselberghs, A., et al. (2026). 'Does acoustics influence people's perception of the other dimensions of indoor-environmental quality?'. Indoor Air 2026, Singapore.

Mahdavi, A., Martínez-Muñoz, I. and Berger, C. (2024). 'Assessing people's perception of indoor-environmental quality: Can we improve the signal-to-noise ratio?'. Comfort at the Extremes 2024, Seville. doi:10.5281/zenodo.17643071.

Mahdavi, A., Martínez-Muñoz, I., Hopfe, C., et al. (2025a). 'Exploring the consistency of UGR calculations, measurements, and evaluations'. Building Simulation 2025, Australia. doi:10.26868/25222708.2025.1147.

Mahdavi, A. and Martínez-Muñoz, I. (2025b). 'Integrative evaluation of indoor-environmental quality: A critical investigation of weighting-based approaches'. Journal of Physics: Conference Series, 3140, 072003. doi:10.1088/1742-6596/3140/7/072003.

Mahdavi, A., Martínez-Muñoz, I. and Berger, C. (2025c). 'Toward multi-domain occupant-centric indoor-environmental quality indicators'. Building Simulation 2025, Australia. doi:10.26868/25222708.2025.1146.

Mahdavi, A., Martínez-Muñoz, I. and Berger, C. (2026). 'Occupants' evaluation of the total indoor-environmental quality: Toward a variable-weights theory'. NSB 2026, Finland.

Martínez-Muñoz, I. and Mahdavi, A. (2025). 'Visual and auditory dimensions of the indoor-environmental exposure: An empirical case study of cross-domain effects'. Journal of Physics: Conference Series, 3140, 102013. doi:10.1088/1742-6596/3140/10/102013.

Martínez-Muñoz, I., Berger, C. and Mahdavi, A. (2026). 'Impact of personal factors on people's perception of indoor-environmental quality'. ROOMVENT 2026, Czech Republic.

Miño-Rodríguez, I., Balakrishnan, P., Karmann, C., et al. (2024). 'Colourful daylight: Evaluating the spectral transmittance of daylight through window films'. Comfort at the Extremes 2024, Seville. doi:10.5281/zenodo.17643071.

Miño-Rodríguez, I. and Wagner, A. (2026). 'Early physiological markers under moderate thermal–visual exposures'. Indoor Air 2026, Singapore.

Conference proceedings – Extended abstracts

Miño-Rodríguez, I., Pan, J., et al. (2026). 'Limitations of multi-domain comfort research: Weak theory, fragile constructs, and inadequate methods'. Indoor Air 2026, Singapore.

Pan, J., Wiedermann, L.N., Hofmann, C.M., et al. (2024). 'Causal inference empowers occupant-centric building science'. Indoor Air 2024, USA.

Pan, J., Bertram, J., Rengelshausen, J., et al. (2025a). 'Cross-modal effects of odor and temperature on occupants' perception in a single-person office environment'. Healthy Buildings Europe 2025, Iceland.

Pan, J., Christoforou, R., Wiedermann, L.N., et al. (2025b). 'Facilitating cumulative occupant-centric building science through Bayesian region of practical equivalence'. Healthy Buildings Europe 2025, Iceland.

Pan, J., Favero, M., Sonta, A., et al. (2026a). 'Adjustment criterion empowers causal human-centric building science'. Indoor Air 2026, Singapore.

Pan, J., Bertram, J., Rengelshausen, J., et al. (2026b). 'Cross-modal effects of temperature and odor on human perception in a single-person office environment: A study applying causal inference and Bayesian ROPE'. 66th Scientific Annual Meeting of the German Society for Occupational and Environmental Medicine, Germany.

4.2 Category B – Any other form of published results

Martínez-Muñoz, I., Berger, C., Hopfe, C., et al. (2026). 'Exploring the influence of auditory stimuli on visual discomfort in an office environment'. Manuscript submitted to Building Research & Information, March 2026. Review process

4.3 Patents (applied for and granted)

Not applicable