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Critical review towards research guidelines and recommendations

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Giorgia Chinazzo [a,*], Rune Korsholm Andersen [b], Elie Azar [c,d], Verena M. Barthelmes [e], Cristina Becchio [f], Lorenzo Belussi [g], Christiane Berger [h], Salvatore Carlucci [i], Stefano Paolo Corgnati [f], Sarah Crosby [j], Ludovico Danza [g], Luiza de Castro [k], Matteo Favero [l], Stephanie Gauthier [m], Runa T. Hellwig [h], Quan Jin [n], Joyce Kim [o], Mandana Sarey Khanie [b], Dolaana Khovalyg [e], Carola Lingua [f], Alessandra Luna-Navarro [p], Ardeshir Mahdavi [q], Clayton Miller [r], Isabel Mino-Rodriguez [s], Ilaria Pigliautile [t], Anna Laura Pisello [t,u], Ricardo Forgiarini Rupp [b], Abdul-Manan Sadick [v], Francesco Salamone [g], Marcel Schweiker [w], Marc Syndicus [x], Giorgia Spigliantini [f,y], Natalia Giraldo Vasquez [b], Donna Vakalis [z], Marika Vellei [aa], Shen Wei [ab]

[a] Department of Civil and Environmental Engineering, Northwestern University, Evanston, USA
[b] International Centre for Indoor Environment and Energy, Department of Environmental and Resource Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark
[c] Department of Civil and Environmental Engineering, Carleton University, Ottawa, ON, Canada
[d] Department of Industrial and Systems Engineering, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates
[e] Laboratory of Integrated Comfort Engineering (ICE), School of Architecture, Civil and Environmental Engineering (ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[f] TEBE-IEEM Research Group, Department of Energy (DENERG), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy
[g] Construction Technologies Institute, National Research Council of Italy (ITC-CNR), San Giuliano Milanese, Italy
[h] Department of Architecture, Design and Media Technology, Human Building Interaction, Aalborg University, Aalborg, Denmark
[i] Energy, Environment and Water Research Center, The Cyprus Institute, Nicosia, Cyprus
[j] Department of Mechanical Engineering, University of British Columbia, Vancouver, BC, Canada
[k] Federal University of Santa Catarina, Department of Civil Engineering, Laboratory of Energy Efficiency in Buildings, Florianópolis, Brazil
[l] Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[m] Faculty of Engineering & Physical Sciences, University of Southampton, Southampton, UK
[n] Department of Architecture and Civil Engineering, Chalmers University of Technology, Sven Hultins gata 6, SE-412 96, Göteborg, Sweden
[o] Civil and Environmental Engineering, University of Waterloo, Canada
[p] Department of Architectural Engineering and Technology, Faculty of Architecture and the Built Environment, TU Delft, the Netherlands
[q] Department of Building Physics and Building Ecology, Faculty of Architecture and Planning, TU Wien, Vienna, Austria
[r] Department of the Built Environment, College of Design and Engineering, National University of Singapore (NUS), Singapore
[s] Building Science Group, Faculty of Architecture, Karlsruhe Institute of Technology, Englerstr. 7, 76131, Karlsruhe, Germany
[t] Department of Engineering, University of Perugia, Perugia, Italy
[u] Department of Civil and Environmental Engineering, Princeton University, NJ, USA
[v] School of Architecture and Built Environment, Faculty of Science, Engineering and Built Environment, Deakin University, Geelong, Australia
[w] Healthy Living Spaces lab, Institute for Occupational, Social and Environmental Medicine, Medical Faculty, RWTH Aachen University, Pauwelsstr. 30, 52074, Aachen, Germany
[x] Energy Efficiency and Sustainable Building, RWTH Aachen University, Mathieustrasse 30, 52074, Aachen, Germany
[y] RINA Consulting S.p.a., Via Gran S. Bernardo, Palazzo R, 20089, Rozzano, MI, Italy
[z] Building Decisions Research Group, University of British Columbia, Canada
[aa] Laboratory of Engineering Sciences for the Environment LaSIE (UMR CNRS 7356), La Rochelle University, La Rochelle, France
[ab] The Bartlett School of Sustainable Construction, Faculty of the Built Environment, University College London, London, United Kingdom

A B S T R A C T

The perception, physiology, behavior, and performance of building occupants are influenced by multi-domain exposures: the simultaneous presence of multiple environmental stimuli, i.e., visual, thermal, acoustic, and air quality. Despite being extensive, the literature on multi-domain exposures presents heterogeneous methodological approaches and inconsistent study reporting, which hinder direct comparison between studies and meta-analyses. Therefore, in addition to carrying out more multi-domain studies, such investigations need to be designed, conducted, and documented in a systematic and transparent way. With the goal to facilitate and support future multi-domain studies and their meta-analyses, this work provides (1) a range of criteria for multi-domain study design and reporting (i.e., defined as quality criteria), and (2) a critical review of the multi-domain literature based on the described criteria, which can serve as guidelines and recommendations for future studies on the topic. The identified quality criteria encompass study set-up, study deployment and analysis, and study outcome, stressing the importance of adopting a consistent terminology and result reporting style. The developed critical review highlights several shortcomings in the design, deployment, and documentation of multi-domain studies, emphasizing the need for quality improvements of future multi-domain research. The ultimate goal of this work is to consolidate our knowledge on multi-domain exposures for its integration into regulatory resources and guidelines, which are currently dominated by single-domain knowledge.

1. Introduction

In industrialized areas, people spend about 90 % of their time indoors [1], where they are simultaneously exposed to multiple indoor environmental stimuli, i.e., thermal, visual, acoustic, and air quality variables. It is well known that indoor environmental stimuli affect how people perceive the indoor environment [2], their behaviors [3], health [4,5], and work-related matters such as real and self-estimated performance [6–8], job absenteeism [9], and job satisfaction [10–12]. Consequently, indoor environmental stimuli have indirect implications on energy consumption linked to changes in human behavior (e.g., openings/closing windows when mechanical systems are operating) [13–15] and on companies' financial revenues, due to the aforementioned work-related issues [16] and health effects [17]. Therefore, it is paramount to understand occupants' responses to indoor environmental stimuli to design and operate comfortable, healthy, and productive spaces.

Over the past years, many efforts have been devoted to studying human responses to indoor environmental stimuli. Investigations were predominantly carried out for each stimulus, considering visual, thermal, acoustic, and air quality separately. These studies resulted in comfort models and metrics (e.g., Fanger's predicted mean vote model [18], daylight glare probability model [19]), which are included in technical standards and design guidelines (e.g., Refs. [20,21]), and provide comfort requirements for temperature, light, noise and air quality separately. Consequently, buildings and current technologies devoted to controlling the indoor environment are designed on the supposedly independent effects of indoor environmental stimuli [22, 23].

From a cognitive perspective, this approach implies that human perception is a modular function, composed of independent sensory modalities processing sensory stimuli independently of each other as separate *modules*. For example, the underlying assumption of this mono-sensory approach is that light does not influence thermal perception, and temperature does not affect how the visual environment is perceived. However, it has been shown that human perceptual experience is not modular but is shaped by the combination and integration of a multitude of stimuli experienced simultaneously [24–27]. The integration of different sensory modalities is called multisensory integration and results in more robust estimates of occupants' perception [28–30]. Examples of multisensory integration relevant to the indoor environment can be found in Calvert et al. [29] and Bertelson and Gelder [31], while anthropological and architectural approaches are found in Hall [32] and Rapoport [33].

As sensory perception is inherently multimodal, so is people's perception of the indoor environment. While synesthesia (e.g., music excites the perception of color [34]) seems to be a widely known

example of the underlying topic, it understates and occasionally misrepresents the nature and importance of integration and binding problems in human perception. Not always are human senses equally involved (think of a visual acuity test such as the Snellen Chart), and oftentimes a specific quality of an indoor environment stands out and annoys or satisfies people predominantly. Yet, the overall impression and the effects of an indoor environment remain interwoven and holistic, which is why a multimodal and integrative approach to the investigation of indoor environments appears more valid and representative. Multisensory integration might be one of the factors explaining discrepancies observed between predicted and reported occupant satisfaction [35–37], as people are often not satisfied with their indoor environment although threshold values indicated by standards are met. A recent analysis of an extensive survey database shows that only two-thirds of building occupants are satisfied with their environment and multiple environmental stimuli contribute to dissatisfaction, including sound privacy, temperature, and noise level [38].

Although the explanation of how our brains integrate various sensory information is yet to be solved by neuroscience and related fields, it is a good starting point for researchers in the Indoor Environmental Quality (IEQ) domain to expand research in a multimodal manner. Research in this field is necessary considering that "current knowledge on interactions between and among factors that most affect occupants of indoor environments is limited" [39, p. 2]. Since each IEQ stimulus includes several variables, such as (relative) humidity and (air, mean radiant or operative) temperature for the thermal environment, considering all the potential interactions in a single study is unfeasible, even more, if several human responses are considered. For this reason, existing studies focus on the interaction of a few stimuli with selected human responses. To gain a comprehensive understanding of the effect of all the stimuli that can be found in the built environment on all human responses, it is, therefore, necessary to conduct reviews and meta-analyses to combine the results from several studies. This *collective approach* builds upon the knowledge generated as suggested in Schweiker et al. [40].

In recent years, some studies have analyzed the existing literature to understand human responses to multiple indoor environmental stimuli. Torresin et al. [41] reviewed 45 laboratory studies that examined the effects of two or more environmental stimuli on human perception and performance. Wu et al. [42] expanded their review to include field studies and identified multi-domain effects (thermal, acoustic, and illumination) on human perception. Schweiker et al. [40] recognized the link between human perception and behavior and conducted a comprehensive review of multi-domain influences on occupant perception and behavior based on field and laboratory studies. By identifying motivations, theoretical foundations, key methods, findings, and gaps in the field of multi-domain approaches, the authors conclude

that "results were often inconclusive and in part contradictory" and emphasize the need to establish a common framework to analyze diverse results, design future studies, and develop standards and guidelines. The incomplete knowledge of multi-domain effects and the inconsistencies across results have been also highlighted in other studies [43,44]. According to Rupp et al. [45], this outcome is the result of a lack of interdisciplinary research between different disciplines within building science (i.e., visual, thermal, acoustic, and air quality), and between research fields such as psychology, physiology, engineering, and architecture. In addition, the direct comparison of the results of studies can be misleading as the great majority of them differ in terms of objectives, magnitude of considered stimuli, experimental design and setting, studied population, analysis conducted and reporting of the results. Without a common way of designing, conducting, and reporting multi-domain studies, comparisons are difficult to conduct. This is not the first field to recognize and call for the development of more rigorous study designs, transparent reporting, and quality assurance checklists (e. g., Ref. [46]).

To address this need, the present work identifies criteria covering the key research aspects that should be considered when designing, conducting, and reporting multi-domain studies and critically reviews the published studies on the basis of these criteria. It is necessary to highlight that this work does not review existing multi-domain investigations for conducting a meta-analysis of their results. In other words, this study does not focus on the questions: "is factor x affecting the perception of factor y?" or "are interactions between factors x and y affecting human response z?", but rather on the methodological aspects and characteristics of the reported information for addressing these questions. The described criteria are defined as *quality criteria* as their presence and accurate description in the literature can determine the degree of excellence of a study, which in turn allows its replicability and comparability. The quality criteria can thus be considered as research guidelines and recommendations that aim to establish a solid foundation for future multi-domain studies as a unified approach to facilitate meta-analyses on this topic, helping to untangle the complex effects of multi-domain stimuli on different human responses.

First, the methods applied in this paper are described. Then, the quality criteria are outlined in terms of (1) study set-up (dependent and independent variables, hypothesis, setting features, exposure features, experimental design quality), (2) study deployment and analysis (data collection and processing, participants, data analysis), and (3) study outcome (reporting results, study discussion and conclusion) (see details in Fig. 2). Next, the critical review of the multi-domain literature is performed based on the quality criteria. Finally, the key findings of the critical review are summarized, and future directions are highlighted.

2. Methods

Three steps were followed to define the quality criteria and carry out the critical review of existing multi-domain studies: (i) selection of multi-domain studies, (ii) categorization of the studies based on the type of multi-domain effect (i.e., cross-modal or combined) and study type (i. e., laboratory or field study), and (iii) definition of the quality criteria.

2.1. Multi-domain studies selection

The selection of research studies analyzed in this work is based on three recent literature reviews reporting studies on the effect of multiple indoor environmental stimuli on different human responses: Schweiker et al. [40], Torresin et al. [41], and Wu et al. [42]. Furthermore, the list of papers analyzed in the reviews was expanded to include additional studies based on forward reference searching and authors' knowledge. The list of considered papers is reported in Appendix A.

Not all studies reported in the three reviews were included in the analysis. Three main selection criteria were applied to meet the aim of the research, described as follows: (i) the study had to involve the

response of people (i.e., no simulations, no physical measurements only); (ii) the study had to focus on perception, behavior, and/or performance (i.e., not on physiology only); and (iii) the study had to have as independent variables the physical measurements of two or more of the four IEQ stimuli (i.e., visual, thermal, indoor air quality, and acoustic). Papers in languages other than in English, with an unavailable full text, or not peer-reviewed are also excluded. The excluded papers are reported in Appendix B.

2.2. Multi-domain studies' categorization

The existing literature is reviewed and analyzed by distinguishing the papers according to two study features: type of effect investigated and study type.

Two types of effects are considered in this research (see Fig. 1), described as follows:

- *Cross-modal* effect is when one stimulus influences a non-related response, which is usually triggered by another stimulus (e.g., when light influences thermal responses).
- *Combined effect* is when multiple stimuli, in combination, affect a response not directly related to a specific indoor stimulus (i.e., individual perception such as overall comfort perception and physical status, behavior, physiology, and performance). The stimulus can be environmental or belong to other domains (e.g., personal, and contextual).

A cross-modal effect can be further categorized into (i) Cross-modal *main* effect; and (ii) Cross-modal *interaction* effect. The difference between the two types of cross-modal effects depends on the levels of the considered stimuli (e.g., dim, and bright are two levels for the visual stimulus, and hot and cold are two levels for the thermal stimulus). Cross-modal main effects occur when the response to stimulus A is influenced by the presence of stimulus B, independently of the levels that they have. Cross-modal interaction effects occur when the effect of different levels of stimulus B on the response to stimulus A differs according to stimulus A's level. See Fig. 1 for a graphical representation of the cross-modal effects. The sub-categorization into main and interaction effects is reported to provide a complete description of multi-domain effects, but it is not used to analyze the reviewed literature in Section 4. However, the authors believe that a comprehensive description of the type of effects could benefit the reporting and interpretation of future multi-domain studies.

Fig. 1 schematizes cross-modal and combined effects (multi-domain studies), distinguishing them from the same-modality effects (single-domain studies), which are not considered in this research.

The study types considered in the analysis are: (i) lab study (including test room, climate chamber, and airplane simulator) [48], and (ii) field study [49]. The living lab (i.e., a conventional space equipped with measurement tools in which occupants conduct their normal lives or work [50] is a study type not used in the considered papers and hence it is not used to categorize the papers in the following analysis.

Table 1 summarizes the distribution of the considered studies according to the effect type and study type. Lab studies outnumbered field studies, while cross-modal and combined effects were equally investigated across studies. Most of the cross-modal effects were investigated in lab studies, while an equal number of combined effects were tested in both lab and field studies. Sometimes, cross-modal and combined effect types were investigated in the same study, in the great majority of the cases in lab studies.

2.3. Research quality criteria

The research quality criteria (Fig. 2) were used to critically analyze the published studies and can serve as research guidelines and
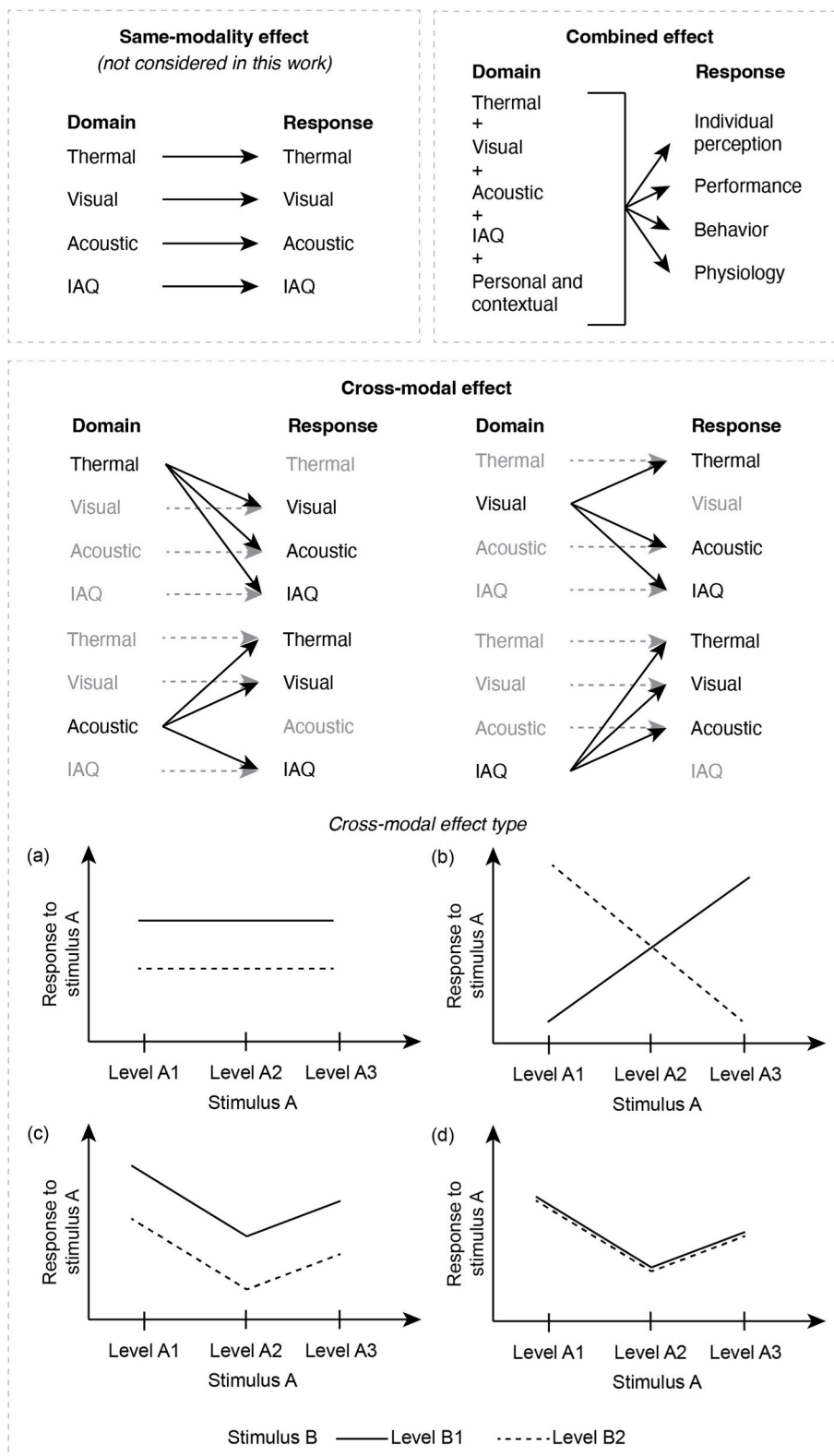
Fig. 1. Top: Schematic description of the type of effect: cross-modal, combined and same-modality effects. The light gray dashed lines in the cross-modality effect refer to the influence of one domain (e.g., temperature) on the same-modality response (e.g., thermal comfort) when another domain is considered in the investigation (e.g., illuminance). In a multi-domain study, such effect does not have to be included (e.g., a study could look solely at visual influences on thermal perception without observing the effects of thermal properties (or their interactions with the visual properties) but only controlling for them). Bottom: Graphic representation of the types of cross-modal effects between two stimuli. a) Cross-modal *main* effect of stimulus B and no effect of stimulus A; b) cross-modal main effect of stimulus B and the main effect of stimulus A; c) cross-modal *interaction* effect of stimuli A and B; d) the main effect of stimulus A, no effect of stimulus B. Adapted and expanded from Coolican [47].

recommendations for future studies. These criteria are categorized into three groups, defined as (1) study set-up, (2) study deployment and analysis, and (3) study outcome (Fig. 2). The collection of quality criteria was determined first on the basis of the authors' experience with multi-domain studies, previous review efforts, and intensive online meetings within and beyond meetings of the Annex 79 promoted by the International Energy Agency's Energy in Buildings and Communities

Programme (IEA-EBC).[1] Such basis was constantly reviewed during the analysis of the studies considered for this work and augmented upon necessity. The selected criteria focused on methodological and reporting

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[1] "Occupant-centric building design and operation" (http://annex79.iea-ebc.org/).

Quality criteria for multi-domain studies

Study set-up

- Dependent variable
  - human response type and details
  - collection approach (subjective, objective)
  - detailed response description
- Independent variables
  - sensory domain and their combination
  - environmental variable description
    - number of levels
    - design values
- Hypothesis
  - hypothesis statement
  - hypothesis description
- Setting feature
  - environmental condition not varied as independent variable
  - building or space type
  - setting description and picture
  - building systems (heating, cooling, ventilation, lighting)
  - facade/ fenestration description
  - human-building interaction features (control opportunities)
  - location
- Exposure feature
  - study design
  - exposure characteristics
    - exposure type (steady-state, dynamic or combined)
    - length of exposure
    - number of participants per experimental condition
    - timing of the exposure during the day and the year
    - no. of conditions in a day if within subjects
    - total length of the experiment per participant
  - adaptation time
- Experimental design quality
  - randomization and counterbalancing
  - blind procedure
  - confounding variable control (experimental, statistical)
  - null condition
  - repeated stimulus

Study conduction and analysis

- Data collection and processing
  - environmental stimuli measured description
  - measurements' features (location, frequency, post-processing)
  - design vs. measurement values comparison
- Participants
  - distribution (total number and sex)
  - personal characteristics (culture/ origin, physical condition pre-experiment, health status, age height, weight)
  - experimental involvement (type of observation, task, payment, ethical approval, information sheet, consent sheet)
- Statistical analysis
  - justification of choice
  - statistics type
  - power analysis
  - effect size

Study outcome

- Reporting results
  - data documentation
  - descriptive statistics
  - inferential statistics
  - classification of observed effect type
  - effect size
  - effect direction
- Study discussion and conclusions
  - mechanism explanation
  - limitations
  - conclusions
  - practical implications
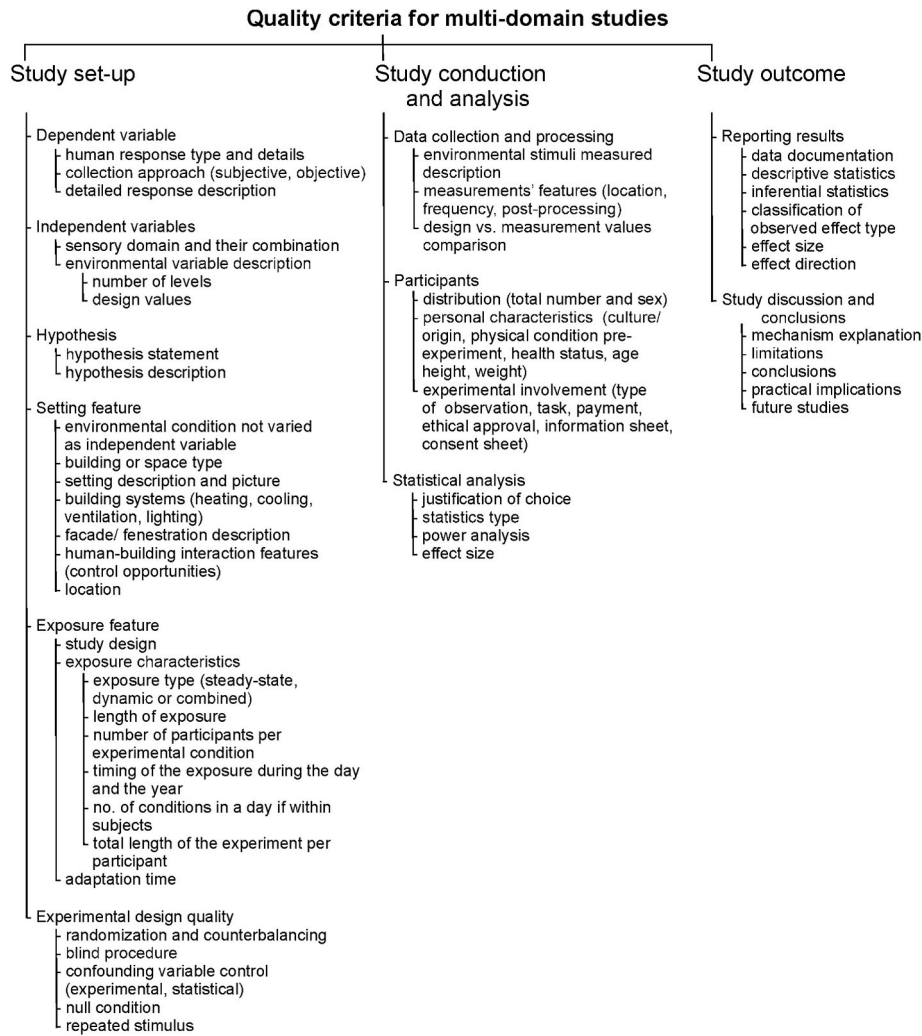 - future studies

Fig. 2. Research quality criteria considered in the critical review of existing multi-domain studies and these can serve as guidelines and recommendations for future multi-domain research.

Table 1
Distribution of the considered studies according to the effect type and study type.

		Effect type			Total
		Cross-modal	Combined	Combined and cross-modal	
Study type	Lab	36 %	17 %	23 %	76 %
	Field	4 %	19 %	1 %	24 %
	Total	40 %	36 %	24 %	100 %

features. The introductory sections with the related analysis of previous literature and reference to validated theoretical models and theoretical assumptions are not considered in the analysis as multi-domain studies have been reported to rarely carryover previous studies' findings and to lack foundational theories to formulate and test research hypothesis [40].

Some of the considered research quality criteria are common to all experimental investigations, while others are specific to multi-domain studies. However, to guide future researchers on what to consider while designing, deploying, and reporting multi-domain investigations, all quality criteria are described in the same depth in the next section followed by their application in a critical review of published literature.

3. Description of research quality criteria for multi-domain studies

The quality criteria shown in Fig. 2 are described in the following.

3.1. Study set-up

3.1.1. Dependent variables

A clear description of the investigated dependent variable(s) is of primary importance since they express the human responses to variations of the independent variables (i.e., the investigated stimuli).

The dependent variables in multi-domain studies refer to the different human responses that can be captured in experimental or observational settings. Fig. 3 illustrates the type of human responses that can be collected and the associated methods of assessment in both field and laboratory investigations, and in relation to the type of effect considered (combined or cross-modal). Responses can be described according to the nature of the data collection approach, i.e., subjective or objective. Subjective data from occupants is collected by interviews or survey methods querying self-reported perceptions or opinions. Objective responses include physiological signals, test grades and other quantitative observations (e.g., number of interactions between occupants and building components).

In addition to a clear description of the human response type under consideration, studies should clearly report how these responses were
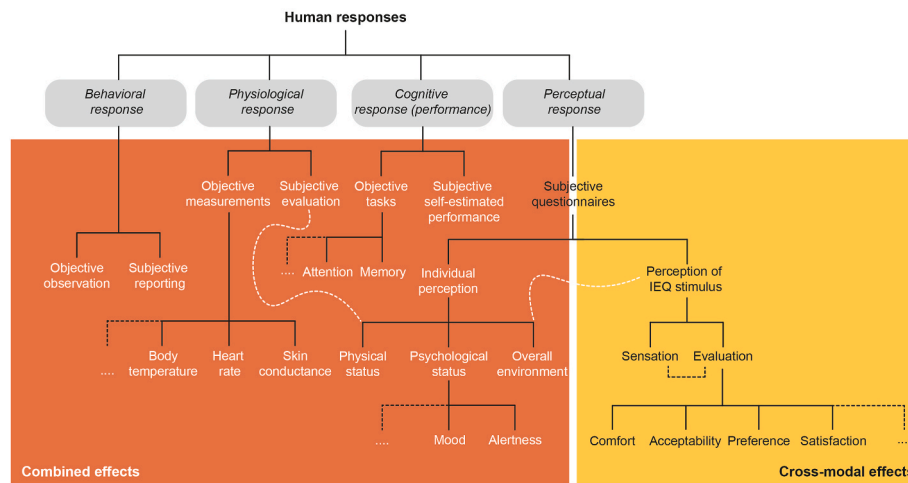
Fig. 3. Schematic representation of the type of human responses that can be collected in studies investigating cross-modal or combined effects.

gathered by specifying the method(s) of assessment and the adopted tools used (e.g., questionnaire for perception responses, test type for performance responses, sensing technology for behavioral and physiological responses). Such tools must be described in detail to allow reproducibility and a comprehensive understanding of the followed methodology. In addition to the details of the assessment method, the time and frequency of assessment must also be reported. Special attention must be given to the description of the questionnaires and the related responses when subjective evaluations are sought. Questionnaire responses, if not in an open-ended format, refer to scales that can be categorical (CS), visual analogue (VAS), categorical scale combined with VAS (graphic CS), semantic differential, or dichotomous. To get comparable data and results, agreement on specific aspects of the subjective assessment scales is of primary importance. These can be summarized in (i) adopted terminology in the questions and responses, (ii) type of scale used, and (iii) (only in case of CS) number of provided response categories. From this point of view, it is essential to report the original text of the adopted questionnaire, preferably in both the original language and English.

3.1.2. Independent variables

Multi-domain studies are characterized by the presence of more than one environmental stimulus, presented in combination. Such environmental stimuli are the independent variables of the study. Reporting the type of combination of the environmental stimuli is taken for granted as it represents the essence of each multi-domain investigation. However, the detailed description of the independent variables needs further attention. Correctly describing independent variables in multi-domain investigations is crucial for conducting replication studies and facilitating meta-analysis and comparison across studies. The way of reporting independent variables depends on the study approach, either experimental or observational. In experimental investigations, usually carried out in a climate chamber or an environmentally controlled space, the experimenter manipulates the independent variables to measure their effect on the dependent variable. In contrast, in observational studies conducted in field setups, the experimenter cannot usually control the independent variables, which are measured to observe correlations between independent and dependent variables.

In multi-domain papers reporting experimental studies, researchers should always clearly indicate the independent environmental variables in terms of type (e.g., air temperature), the number of levels (e.g., 3), and design values (e.g., 22 °C, 25 °C, and 28 °C). In experimental cross-modal studies, both same-modality and cross-modal independent variables must be clearly described. For example, in a study investigating the effect of Correlated Color Temperature (CCT) of light on thermal

perception, the cross-modal independent variable CCT must be reported together with the air temperature, representing the same-modality variable.

In multi-domain papers reporting observational studies, as the independent variables are usually not controlled but measured, researchers must clearly report the measured variables' descriptive statistics, i.e., measures of central tendency and variability. This information is critical for evaluating the external validity of the study's findings, and whether the findings are generalizable to the study's source population of people and buildings. If the researchers cut the independent variables' continuous values into bins for analysis (e.g., Ref. [51]), then each bin must be described in terms of value counts and mean or median. Such description is necessary as the choice of bin number and position is arbitrary and generally do not have practical/scientific meaning and could influence the results. Analyzing solely with the described bin method may lead to some loss of information. Therefore, it must be complementary to other descriptions of the independent variables.

It is recommended to opt for continuous and numerical design values (rather than categorical ones such as *blue* and *red* when colors are assessed) that enable replication studies and facilitate meta-analysis. When several levels of the same independent variable are considered, it is a good practice to assign different labels to the different levels, facilitating the comprehension of both the experimental design and the results. Another good practice is the consideration of possible covariates (e.g., summarized for thermal comfort by Wang et al. [52] or Schweiker et al. [53]) that are not environmental, for example, gender, age, and body mass index. Refer to 3.1.4 and 3.2.2 for further discussion on the topic.

3.1.3. Research hypothesis

Stating and describing the research hypotheses of a study leads to a better comprehension of the work, even if it consists of an exploratory study searching for discoveries, trends, correlations, or relationships between the measurements in which outcomes would generate new ideas or hypotheses (that need to be confirmed in follow-up studies). When conducting a causal research based on a pre-existing theory and aimed to determine what occurs to one measurement on average when another measurement is changed, it is possible to state causal hypotheses. The causal hypothesis should be stated in all cases where the scientific literature reasonably sounds or where the current state of knowledge on the topic makes it possible. This makes it easier to determine the research scope and establish a correlation between the initial assumptions and the results.

Research hypotheses should be described in terms of *directions*. A

hypothesis with direction expresses a direct or inverse relationship between dependent and independent variables, that is if the independent variables increase (or decrease), the dependent variable increases (or decreases). An example is the Hue-Heat Hypothesis, posing that warm-appearing colors, such as red or yellow, make people feel warmer, while the opposite effect is obtained with cold-appearing colors [54,55]. A hypothesis *without direction* expresses a general relationship between dependent and independent variables regarding the influence one may have on the other (e.g., thermal conditions influence acoustic sensation and perception [56]).

3.1.4. Setting feature

Experimental setting features play a fundamental role in the combination and interaction of the variables investigated in multi-domain studies. The following paragraphs summarize the importance of collecting and reporting information regarding (i) the environmental conditions not varied as independent variables, (ii) the building and space type, (iii) the space layout, equipment, ventilation, and lighting, (iv) the control opportunity, and (v) the experimental location.

Along with a detailed description of the environmental stimuli investigated as independent variables, it is necessary to include a comprehensive description of all the environmental features, considering as well those that were not included as independent variables. Such a comprehensive description of the indoor environment might help to understand potential differences across studies and detect confounding factors.

The type of building or space (i.e., office, educational, residential, or others) determines several aspects of the experimental setting, e.g., indoor space layout, furniture, occupants' activity, or interaction with other people. Specifying the building or space type in a field study but also the *emulated* space in an experimental lab setting is crucial.

Besides indicating building and space typology, a description of the space layout, equipment, ventilation, and lighting gives a comprehensive and immediate overview of the space. Layout description should include dimensions and photos for furniture type and disposition, for instance, the distance between the seats and relevant building elements (e.g., windows). Describing relevant equipment (such as the heating, ventilation and air-conditioning systems, HVAC, artificial lighting etc.) and building elements (windows, shadings etc.) is also important, as these influence indoor environmental conditions and occupants' interaction with available interfaces [57]. Lighting type and related details should be described, that is, electric, natural, or a combination of the previous, and possibly specifying if electric lighting was designed to obtain extreme conditions (e.g., a poorly lit environment). Related to lighting, fenestration systems should be detailed with reference to shadings (internal or external) or, if present, advanced technologies (e. g., smart windows, low-emissivity coatings etc.).

Another relevant feature involves the interactions that occupants can have with building interfaces (i.e., occupant control). Occupant control can influence not only human interactions but also the satisfaction and behavior of users in different domains [58,59]. Thus, reporting exhaustive information on control opportunities within the indoor space is highly recommended.

Despite not being directly related to the experimental indoor space, knowing the location brings insights into the climatic conditions and indicates participants' cultural approach, including their habits, perception, and reporting attitudes.

3.1.5. Exposure feature

This section covers the conditions to which subjects are exposed (i.e., exposure features). Such information is essential when analyzing the results and ease the replicability of the experiments. The first aspect to consider when defining and describing the exposure features is whether the experimenter measures human responses to different exposures within-subjects (i.e., all participants are exposed to all conditions), between-subjects (i.e., each participant is exposed to some of the conditions), or a mix of the two (i.e., participants are exposed to all conditions of one experimental variable and to some of the conditions of another experimental variable). An important aspect to provide clearly in this latter case is the number and combination of tested experimental conditions (e.g., mixed design with one between-subjects condition and two within-subjects conditions).

Each study must then define and report the characteristics of exposure, which we can divide into (i) the "exposure type" (i.e., steady-state, dynamic, or combined), (ii) the length of exposure for each experimental condition (e.g., exposure to warm temperature for 30 min and to each light condition for 10 min), (iii) the number (and demographic information) of participants per experimental condition, and (iv) the timing of the exposure (during the day and the year). For example, seasonal variations are important to be recorded given their impact on several human responses [60]. In addition, publications suggest the potential variations of human responses during the day [61–63], highlighting the importance of recording and reporting the exact time of the day during which the experiment is conducted. In the case of within-subjects design, it is also necessary to report the number of experimental conditions experienced in a day by the same participant and their potential distribution over several days. It is also good practice to report the total length of the experiment for each participant, especially in the presence of within-subjects design when each participant is exposed to a series of experimental conditions.

The adaptation time (or acclimation time, i.e., is the time given to the participants to adapt to the experimental conditions) is another exposure feature that should be considered and reported in all studies. The consideration of the adaptation time is more relevant in studies involving the thermal domain since the human body requires longer time to reach a steady-state thermal response in a new thermal condition and/or at a different activity level [64] and strongly depends on the temperature difference between experimental and pre-experimental conditions.

3.1.6. Experimental design quality

Recently, a replication crisis has been in the spotlight of the scientific community [65,66]. This crisis is mainly attributed to selective reporting bias (i.e., reporting only significant results and omitting non-significant results) and poor experimental design quality (e.g., lack of a random assignment of subjects). A quality experimental design should follow several principles commonly reported in statistics books (e.g., Refs. [47,67,68]): (i) randomly assigned or counterbalanced experimental conditions, (ii) blinded (single- or double-blind) experimental procedure, (iii) controlled confounding variables (experimentally or statistically), (iv) reported study null condition, and (v) repeated one or more experimental conditions.

Besides the recommendations above for specific experimental design elements, a pre-design step for countering the replication crisis trend of underreporting results that did not reach significance is pre-registration. In pre-registration, before beginning to run an experiment or study, the authors outline their hypotheses, methods, and analyses in a public registry (e.g., https://aspredicted.org/). If this step had been taken, the reporting of randomization, blinding, controls, and hypotheses in the analyzed multi-domain studies would have also been accomplished. None of the reviewed studies were pre-registered, as far as could be determined. The lack of pre-registration is a common feature of all the experiments conducted in the Building Science field and not only for multi-domain experiments. A noteworthy exception in this field is the study by Schweiker et al. [69], which had been registered on osf.io.

3.2. Study deployment and analysis

3.2.1. Data collection and processing

A comprehensive reporting of the data collected and the way such data is processed before the statistical analysis is essential as it facilitates comparison, meta-analysis, and the reproduction of an experiment.

In multi-domain studies, it is important to measure and report all the environmental stimuli – not only the investigated independent variables but additional factors that are hypothesized to be relevant. For example, in a study on the cross-modal effect of light on thermal perception, the air quality, and acoustic conditions should be reported as well (at the best of the researcher's knowledge). Without measuring the possible confounders, the analysis necessarily excludes them, and therefore the results of the analysis are less valid. Besides the type of environmental stimuli collected, it is important to report how the measurements were performed and the data processed before the statistical analysis. More specifically, the measurements' location, frequency, processing (e.g., "is data averaged over a specific period of time? How is missing data treated?"), and differences from the design conditions should always be reported or discussed. Regarding the measurement location, it is important to highlight that measurements, whenever possible, should be taken in proximity to the occupant, based on the recommendations of the domain-specific guidelines, to correctly evaluate the effect of one environmental stimulus on another domain perception or behavior since those are the actual environmental conditions that affect the occupant.

3.2.2. Participants

Like all studies involving human subjects, multi-domain studies should include a concise but exhaustive description of participants' characteristics to (i) demonstrate the representativeness of the research findings (sample size and confidence interval), (ii) provide insights on the generalizability of the findings as well as possible limitations of the study (external and internal validity), and (iii) test the impact of these confounding factors on the hypothesis testing and provide confidence of the results. Sufficiently detailed information, as far as possible by obeying privacy issues (e.g. following the European General Data Protection Regulation [70]) on the distribution of participants (e.g., total number, number of males/females/not disclosed gender), the personal characteristics of the subjects (e.g., culture/origin, age/height/weight, health status, and verification of physical conditions before the experiment), as well as information related to their experimental involvement (e.g., direct observation, described task, participation payment, detail on the ethical approval and consent), is required for reviewing research findings and aid future replication studies.

3.2.3. Statistical analysis

Statistical methods are fundamental instruments in experimental studies to support the interpretation of the results and develop accurate, reliable, and representative experimental designs. To this end, statistical tools are used for characterizing the recorded observations, testing for differences among data series, quantifying the effect size, developing, and validating models, and identifying the sample size required to detect an effect in an experiment given the desired significance level, effect size, and statistical power. The adoption of a specific statistical method should always be justified. Also, the studies should communicate clearly the hypotheses tested and the assumptions set together with the adopted statistical tests and significance levels.

Although publication space is scarce, and journals often urge authors to draft their manuscripts as concise as possible, detailed reporting of statistical analyses is mandatory if authors wish to present their results in a replicable fashion and to make their findings amenable to meta-analytical efforts [71]. To rely on the results of statistical methods, to promote transparency and reproducibility of experiments, and to ensure robustness to systematic errors, it is essential that studies clearly state the sample size, identified through an *a priori* power analysis or justified by any other method (e.g., resource constraints, accuracy, heuristics) to provide evidence of representativity. Effect sizes are important as a measure of how meaningful the difference between different variables or groups is to demonstrate the actual real-life significance of the experimental outcomes. It not only indicates the strength of the statistical results, but also puts a study into perspective by facilitating the comparison across different studies and helping to determine sample

sizes for future studies.

Beyond the basic descriptive findings such as measures of central tendency, error, and dispersion as well as data distribution characteristics, a detailed summary of the statistical results also includes the reporting of non-significant results, degrees of freedom (related to sample size), missing data, and potential exclusions of data points as well as imputation methods, if applied. Lastly, any changes and adaptations applied to the statistical models and tests need to be stated [72].

In case the full report of these figures is not possible in a paper's results section or may appear redundant to the reviewers (indeed, some statistics can be reverse-engineered and checked for plausibility from reported results with tools such as G*Power or statcheck, see Refs. [73, 74]), authors are encouraged to seek online supplemental publication possibilities which are provided by a growing number of journals. Lastly, although the full extent of how strong various research fields are plagued by publication bias remains unknown, selective publication of only significant findings bears the threat of misrepresenting findings and puts the burden of detailed checks and evaluations on the researchers conducting the research synthesis [75,76]. Finally, it is recommended that the statistical method is decided before the experimental design, guided by the aim of the study. In this way, the experiment is designed to get the data needed to support the data analysis and aim of the study.

3.3. Study outcome

3.3.1. Reporting results

This section does not focus on the specific results obtained in the considered papers (e.g., "is temperature affecting visual sensation?") but on the content that should be reported in the result section of each study and the way such content should be presented. In general, for reasons of transparency, comparability, and general advancements in a particular research area, the results must contain sufficient information regarding each individual outcome to facilitate replication or metanalysis efforts. This is especially true for the case of multi-domain studies due to a large number of potentially dependent and independent variables, which cannot be addressed through a single study. Given the need to report on each permutation of possible interactions between variables, the number of reported outcomes increases exponentially when compared to single variable studies. As space is usually limited, documenting data alongside the paper – including a detailed description of the number of data points excluded and argument (statistical, thematic) for exclusion can be done in a separate document, such as data descriptors, e.g. Refs. [77,78].

While the section about results in general reports problem-specific findings intended to answer a specific research hypothesis, the following basic information needs to be provided[2]: (1) descriptive statistics for each individual variable collected (depending on data type, e. g. measures of central tendency and variability alongside with sample size); and (2) results from inferential statistics, disregarding whether they are statistically significant or not (see reporting bias in science and the potential of misrepresentation of scientific results [79]). From this perspective, it is of utmost importance to report all main and interaction effects, the exact level of significance (i.e., $p = .04$ and not $p < .05$) [80], and the effect size, whenever it is possible to determine it. The results should be in line with the type of the statistical test and its purpose described in the paper (most likely in the Methods section). The observed effects, but not stated as primary or secondary research hypotheses, need to be flagged as *explorative*.

Specifically for multi-domain studies, a classification of the expected and observed effect is recommended, that is, whether it is a cross-modal

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[2] For some readers, some of these points may appear as common knowledge. However, our review showed that there are still a substantial number of papers published without including even basic information such as measures of dispersion like standard deviations.

effect, or a combined effect. In addition, further classification of the results should be reported according to the effect type. For cross-modal effects, it is necessary to indicate the *direction* (i.e., positive, negative or no effect) of the effect instead of merely reporting the presence of an interaction. The direction should be described according to the level(s) of the same-modality independent variable. For example, if temperature influences visual perception, the study should clarify if the effect of a specific visual level (e.g., dim illuminance) is positive or negative according to a specific thermal level (e.g., cold temperature).

Fig. 4 schematizes the possible cross-modal effects between two stimuli and the resulting directions. As illustrated, the presence of a stimulus B can result in a negative effect (i.e., strengthen a negative or weaken a positive response of stimulus A alone as in Fig. 4a and b), positive effect (i.e., weaken a negative or strengthen a positive response of stimulus A alone as in Fig. 4d and e) or no effect (i.e., response to stimulus A is not affected by the presence of stimulus B as in Fig. 4c) on the response to stimulus A.

Table 2 illustrates a possible scheme for summarizing the results of a cross-modal effect between two stimuli, with three levels each. The number of columns and rows can be adapted to the number of levels tested for each stimulus. The following descriptions of the results are suggested as examples:

- Significant *negative* effect: the presence of stimulus B at level x (e.g., illuminance, dimmer condition*) strengthen the negative* or *weaken the positive or neutral* response of stimulus A (e.g., thermal comfort) at y level (or all levels) of stimulus A (e.g., colder and warmer). In Table 2, this effect is shown in the first column of stimulus B.

- Significant *positive* effect: the presence of stimulus B at level x (e.g., illuminance, brighter condition) *weaken the negative* or *strengthen the positive* response of stimulus A (e.g., thermal comfort) at y level (or all levels) of stimulus A (e.g., colder and warmer). Table 2, this effect is shown in the last column of stimulus B.

Contrary to the example described, note that the effects can be different according to the level of stimulus A (e.g., be positive at low level and negative at high level). Results could also be represented graphically as in Fig. 1.

Concerning combined effects, when not described as a combined index, they can be further specified into additive, synergistic, or antagonistic, with reference to the *medical analogies* described in the ASHRAE Guideline 10–2016 [39, p. 7]. Fig. 5 describes the possible combined effect types, according to the following definitions reported in the standard:

- Additive: when each of the stimuli affects the human response and their combined presence results in the sum of their separate effects (no effect of interactions);
- Synergistic: when the combined presence of two or more stimuli results in a greater effect than the sum of their separate effects (enhancement effect of interactions);
- Antagonistic: when the effect of the combined presence of two or more stimuli is less than the sum of their separate effects (diminishing effect of interactions).

Also, in the case of combined effects, results could be described as illustrated in Table 3 according to the levels of the considered stimuli.
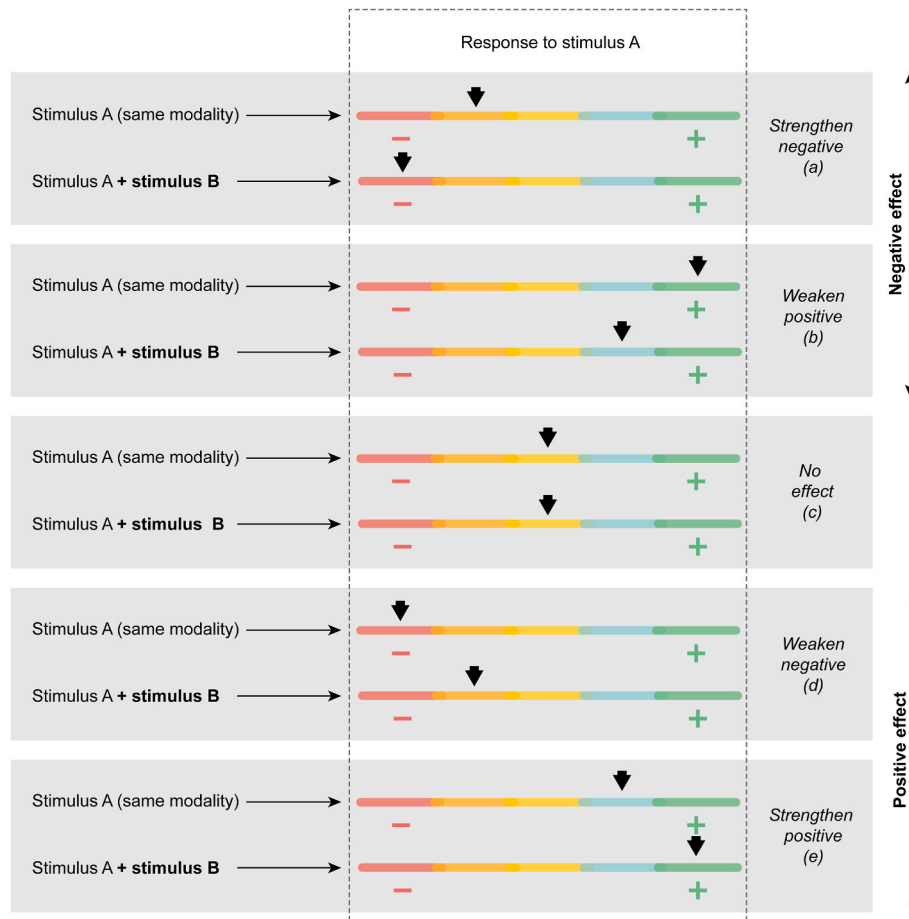

Fig. 4. Schematic example of cross-modal effects of stimulus B on the response to stimulus A and the resulting effect directions.

Table 2

Template for results reporting for cross-modal effects of stimulus A + stimulus B on the response to stimulus A.

		Original effect of stimulus A on the response to stimulus A (same-modality)	Effect of Stimulus A + Stimulus B on the response to stimulus A		
			Stimulus B levels (e.g., visual – illuminance)		
			Lower level (e.g., dimmer)	Comfort level	Higher level (e.g., brighter)
Stimulus A levels (e.g., thermal – air temperature)	Lower level (e.g., colder)	discomfort	*e.g., negative*		*e.g., positive*
	Comfort level	comfort	*e.g., negative*		*e.g., positive*
	Higher level (e.g., warmer)	discomfort	*e.g., negative*		*e.g., positive*
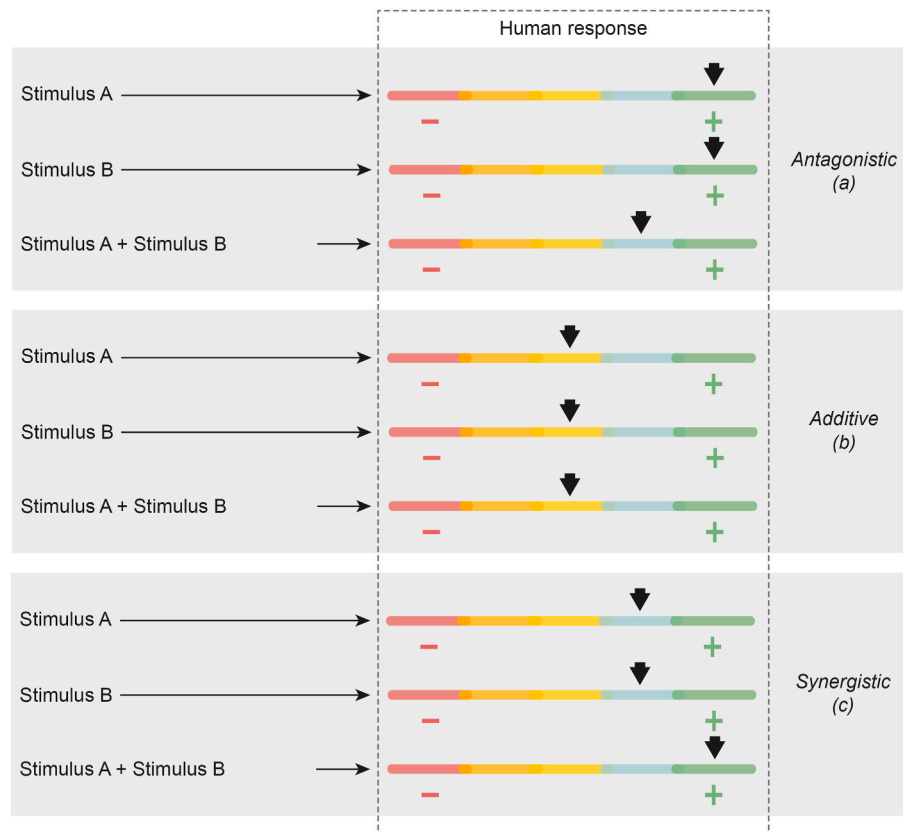
Fig. 5. Schematic example of combined effects of stimuli A and B on human response and the resulting effect description.

Table 3

Template for results reporting for combined effects of stimulus A and B on human responses.

		Effect of Stimulus A + Stimulus B on human response "x"		
		Stimulus B level		
		Lower level	Comfort level	Higher level
Stimulus A level	Lower level Comfort level Higher level	e.g., additive		

3.3.2. Study discussion and conclusion

As for all research papers, it is obvious that multi-domain studies should present the discussion and conclusion sections. They should naturally follow and comment on the results of the study (hence being data-informed and not speculative), with reference to the results of previous studies on the topic. These sections should also include future studies, study limitations, mechanism explanations, and practical implications. With the declaration of future studies and the identification of the limitations, authors provide food for thought for the scientific communities pointing out the direction of the research highlighting the way to create a shared opinion. The tentative explanation of the mechanisms related to the results can be used as the basis for future research. Finally, the identification of practical implications of the research creates a direct link between the experiment and the impact on human life and society.

4. Critical review of existing multi-domain research

The following sections review existing multi-domain research based on the quality criteria defined in Section 3, presenting a transversal analysis of the percentage of studies reporting the aspects whenever a specific quality criterion is not present in all studies.

4.1. Review of study set-up

4.1.1. Dependent variables: human responses

Fig. 6 summarizes the distribution of human response types investigated in the considered multi-domain studies and shows that most of the studies investigated perceptual responses. In most of the studies, perceptual responses were the only human responses considered, and only in a few studies were human responses considered in combination with performance (e.g., Refs. [81–85]), physiology (e.g., Refs. [86–88]), or behavior [89–91]. Behavior and performance alone were investigated in fewer studies compared to perception. The limited number of studies reporting physiological responses may be due to the papers considered in this research, although it included studies with physiological responses in combination with other human responses only. Physiological responses were collected in lab studies only. This outcome may suggest that sensing techniques for collecting physiological signals are still too invasive or too expensive to be used in field studies. Similarly, performance studies were only conducted in lab environments. Behavioral responses were primarily collected in field studies, unless they were investigated with other human responses in lab studies [90–94]. Additionally, behavioral investigations in field studies were based on the collection of data on windows and blinds operations [95–102], thermostat setpoints [81] and ventilation speed settings [94]. Perception responses were equally collected in both lab and field studies.

When observing the distribution of data collection approaches (objective and subjective) adopted for gathering human responses, performance, behavior, and physiological responses were primarily collected via objective approaches. Performance was objectively assessed through dedicated performance tests while exploring different cognitive dimensions (e.g., proofreading, arithmetic, problem solving, creative thinking, etc.), which were generally quantified through the number of correct answers provided [103–106], the associated response times [84,107], or both [108]. The subjective assessment of the performance was conducted through questionnaires [81–83,109]. Methods for the objective evaluation of human behavior were based on the experimenter's observations of subjects' clothing adaptation throughout the test (e.g., number of clothing items put on/off) [92], sensors to assess windows and blinds state [102], or equipment settings (e.g., selected fan speed level) [94]. Information on windows state was also commonly collected through physical measurements by means of sensors, especially in long-term field studies [95,97,101,102]. The objective approach for physiological aspects relied upon the use of wearable sensing technologies. The most investigated signals were heart rate, skin temperature, and blood pressure, while other signals such as core temperature, electroencephalography (EEG), electrooculography (EOG), blink measurement, eye movement, respiration rate and skin conductance (also through the use of an algorithm for the detection of artifacts [110]) were rarely included in multi-domain studies [55,108]. The

subjective approach to collecting physiological observations focused on direct questions about subjects' perception of health symptoms (e.g., eye irritation, throat irritation, and skin dryness) via questionnaires [87,88, 111].

When studying human perception through subjective assessment, the top five assessment categories were perception, comfort, satisfaction, acceptability, and preference. They were primarily assessed through categorical scales. Perception, satisfaction, and preference were most often expressed through a 7-points scale, while comfort was mainly investigated on a 5-points scale, and acceptance on a 3-points, 4-points, or dichotomous scale (acceptable, not acceptable). Some trends can be identified, most likely as a result of questionnaires referencing standards pertaining to human perception research [21,112,113]. It must be noted that sometimes, despite evaluating the same assessment category (e.g., thermal sensation) and indicating the same number of response categories, the labels used can vary [114]. Similarly, visual analogue scales can have varying ranges (e.g., 0 to 100 or 0 to 60) [111,115]. These differences may increase the difficulty of comparing results across studies.

4.1.2. Independent variables: combined environmental stimuli

Fig. 7 reports the distribution of independent variable combinations in the considered papers. In general, thermal and visual stimuli were the most investigated combination of independent variables, mainly studied in cross-modal investigations. Thermal and IAQ, and thermal and acoustic, were the second and third most common combinations in cross-modal studies, highlighting the dominant interest in thermal studies. In contrast, combined effect papers tended to focus more on all four environmental stimuli and their effect on overall perception and performance. Behavior and physiological responses were primarily studied in response to thermal and visual, and thermal and IAQ combinations. The least studied combinations were visual and IAQ, and acoustic and IAQ, both in cross-modal and combined investigations.

All the reviewed studies reporting experimental investigations about cross-modal effects indicated the type of cross-modal independent variables. Only a few studies did not report the number of levels (3 %) or the design values (6 %). In contrast, the same-modality independent variable was sometimes not described in terms of type (12 %) and design value (18 %). Fig. 8 summarizes the design values of the independent variables (facet headings) used in experimental cross-modal investigations. The sensory domains on which their effect was tested are indicated on the x-axis. For example, the first box on the top-left of the graph illustrates the values of indoor air temperature tested to assess their influence on acoustic, IAQ and visual responses. The "thermal" response is not indicated as it is a same-modality response. Each dot represents a tested condition, while the box-plots illustrate the overall ranges of values for each independent variable (i.e., mean and inter-quartile range). It can be observed that the thermal independent
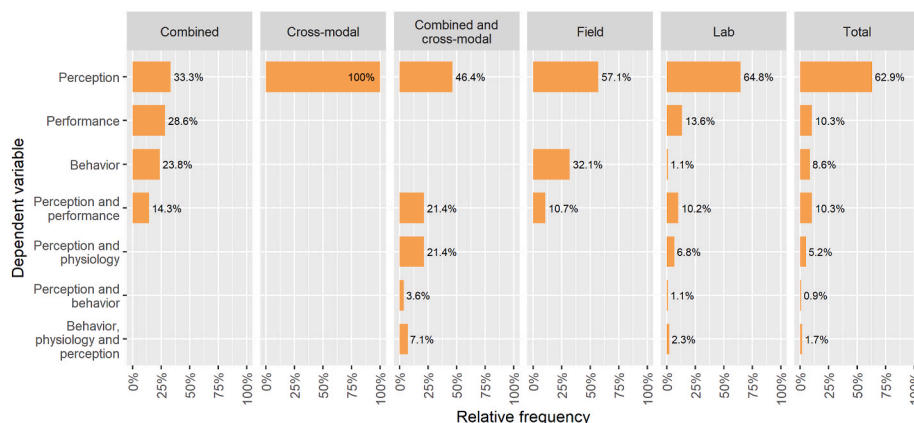

Fig. 6. Distribution of human response types in multi-domain studies according to the type of effect (combined, cross-modal) and the study type (field or lab).
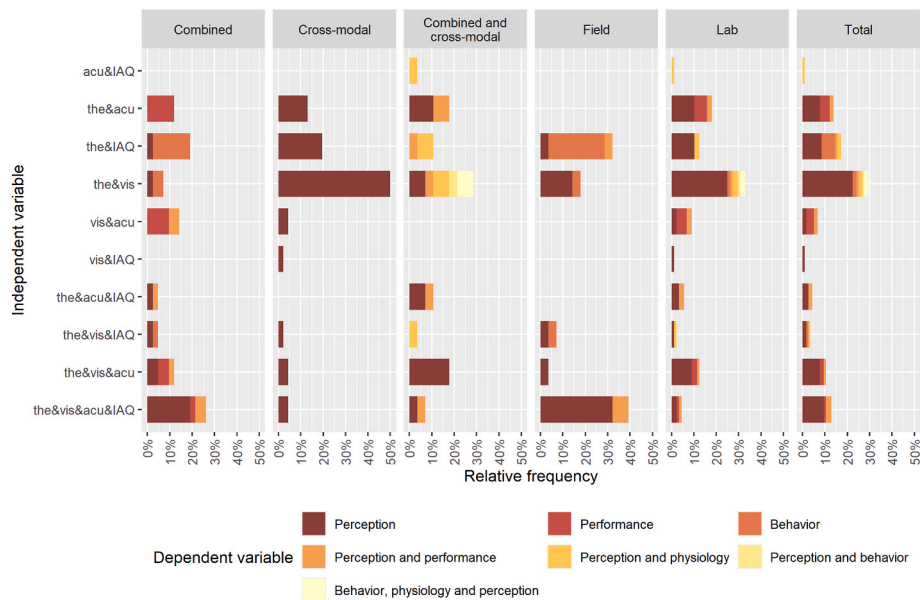
Fig. 7. Distribution of independent and dependent variables, according to the type of effect (combined, cross-modal), study type (lab, field) in the reviewed papers. Acu = Acoustics; IAQ = Indoor Air Quality; The = Thermal; Vis = Visual.

variables (air temperature, relative humidity, air velocity and Fanger's Predicted Mean Vote - PMV) were the most considered independent variables, investigated to assess their influence on all the non-thermal domains. This outcome can be expected given the strong interest in thermal studies previously highlighted. For all independent variables, extreme values were commonly used in experimental investigations. The choice of extreme stimuli can be justified because if a cross-modal effect is not observed for extreme stimuli, it is unlikely that it will occur in normal conditions (if it assumed that the relationship between the dependent and independent variable is linear). Interestingly, when the same independent variable was tested on different sensory domains (e.g., air temperature effect on acoustic, IAQ and visual perception), the distribution and median of its values were consistent across domains.

Fig. 8 highlights the least and more explored combinations or range of independent variables tested in cross-modal investigations, an information that can be used to guide future multi-domain studies. Ventilation rate was not represented, as only one value (30 l/s influence on thermal and acoustic responses) was present in the considered studies.

The great majority of the reviewed studies reporting experimental investigations about combined effects clearly indicated the type of independent environmental variables. Design values were specified in most of the studies as well (98 % of studies reporting thermal stimuli, 88 % visual, 95 % IAQ and acoustic). Level values were less frequently reported for each environmental variable: 71 % for thermal and 76 % for visual, IAQ, and acoustic. Fig. 9 shows the combination of the independent environmental variables reported in experimental studies investigating combined effects. It can be observed that air temperature and illuminance were the most studied variables. Fig. 9 also indicates the dependent variables, confirming the overwhelming focus on overall comfort and performance as discussed before and highlighted in Fig. 7. The range of considered values broadly varied between variables and the investigated human response. Fig. 9, similarly as Fig. 8 for cross-modal effects, highlights the least and most explored environmental stimuli combinations tested in combined effects research, a piece of information that could be used for future multi-domain studies.

Finally, in most of the reviewed multi-domain investigations, the independent variable values were continuous, only rarely categorical (e. g., natural versus electrical light, wall colors, good vs. bad light comfort conditions).

4.1.3. Research hypothesis

Only 53 % of the considered articles reported the research hypothesis, divided into those where the hypothesis was "with direction" or "without direction" (Fig. 10). Studies carried out in laboratories had the highest percentage of hypothesis statements (59 %) with almost the same percentage for "with direction" (28 %) and "without direction" (30 %). In addition, most articles with a hypothesis statement belonged to "cross-modal" experiments, mainly carried out in laboratories. In research on the combined effect, only 26 % of the papers stated the hypothesis. Among them, the study by Lin [116] can be considered as a best practice of the category "with direction" because the author clearly stated the hypothesis of the work: "higher noise intensity and either too low or too high illumination intensity will reduce visual performance". The papers on the combined effect not reporting the hypothesis might be due to the lack of research and data on the topic [84,107,108,117–119].

More than 60 % of field studies did not state the hypothesis. This may be due to the number of uncontrolled variables that make it difficult to formulate a clear hypothesis. In this case, the research was based on generic assumptions that needed to be verified in the current conditions.

4.1.4. Setting feature

The considered setting features and their presence in the literature are summarized in Fig. 11 and discussed in the following.

Despite the fundamental importance of a comprehensive description of all the environmental conditions (besides the ones varied as independent variables), most of the considered studies did not report them. Only about 20 % reported a comprehensive overview (e.g., Refs. [54,55, 120]) (i.e., with all environmental stimuli described), while an additional 37 % included a partial description. The description was often present in lab studies, especially when it was comprehensive (Fig. 11). Many studies described only the features that were relevant in the investigated domains, neglecting the potential cross-modal influence of other domain-related features.

The building or space type was not reported in 47 % of all the studies. In laboratory studies, the "emulated" space type was not reported in 60 % of cases. From the studies that did report the building or space type, it can be observed that multi-domain studies were mainly carried out in offices (34 %), followed by educational (10 %) and residential buildings (5 %).

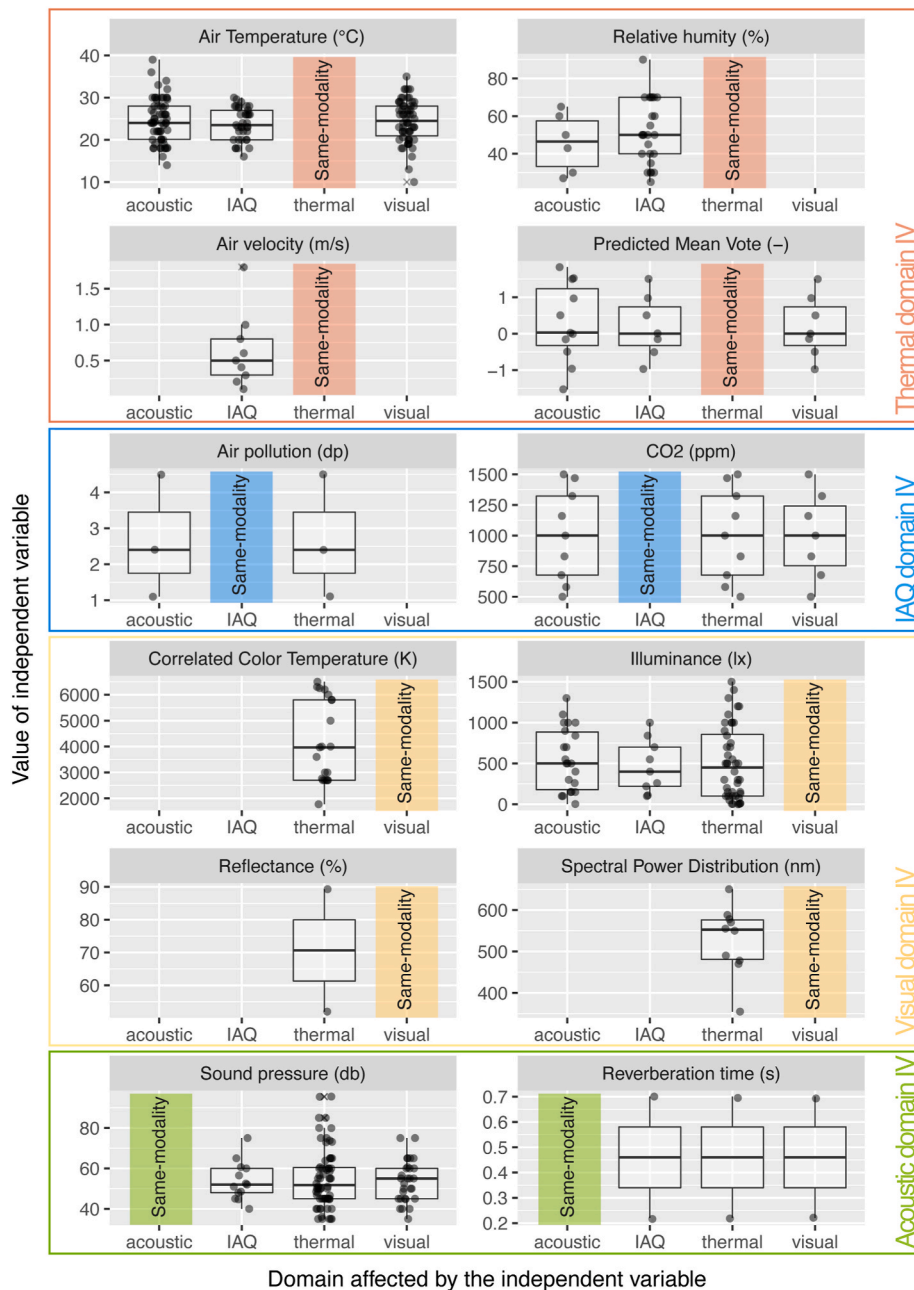In the investigated studies, 48 % omitted space pictures and 35 %

Fig. 8. Number of cross-modal studies depending on the domain and reported value of the Independent variable (IV). Each dot represents the value of the independent variable investigated in the literature. Dots are randomly jittered to discern more values and their left or right position with respect to the vertical line in each boxplot has no additional meaning.

reported it without participants (ethical issues may play a role in this case). A good reference for description can be found in several studies [83,121–124]. Best practices of pictures can be found in Refs. [94,105, 125]. 55 % of studies did not report any information about the heating and cooling systems, and only 50 % provided information on ventilation type. Examples of these systems descriptions can be found in Tiller et al. [84] and Yang and Moon [126]. Description of ventilation type can be found in Skwarczynski et al. [127]. Lighting information was provided in 55 % of studies, with a large prevalence using electric lighting (37 %). The reduced number of studies on daylight could be explained by the challenging experimental conditions that such an environmental variable entails. Winzen et al. [131] and Chinazzo et al. [55] described the lighting system. Among the investigated studies, information about the fenestration system was only accounted for in *22%* of papers. Reference descriptions can be found in Haldi and Robinson [124] and Garretón

et al. [132].

Among the studies considered in this work, 86 % provided information on control opportunities, especially in laboratory experiments. Discrepancies between laboratory and field studies can also be recognized in terms of occupants' level of control over the environment since lab experiments were largely characterized by the lack of control by occupants (92 %). The same situation can be found in only 11 % of field experiments. Reporting exhaustive information on occupants' possible interactions with all available interfaces was not common since studies usually provided insights solely about actions that affected the investigated variables.

Most of the studies (88 %) provided details on the experiment location (e.g., reporting the city and country), offering the possibility of interpreting results with a more accurate consideration of local climatic conditions as well as sociological attitudes of the population [54,114,
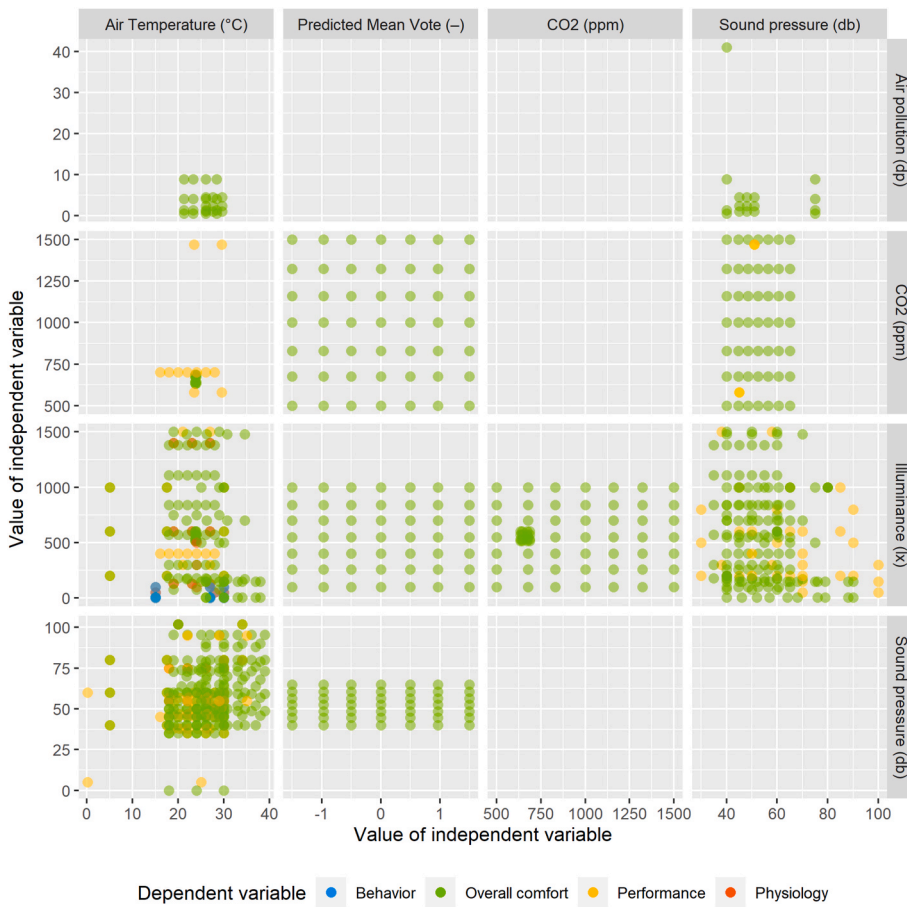
Fig. 9. Combination of independent variable values employed in experimental investigations studying combined effects, considering the dependent variables (indicated with colors). Ventilation rate, air velocity, relative humidity, CCT, and VOC (Volatile Organic Compounds) are not represented as only a few data points were present in the considered studies. Some outliers of the represented independent variables were excluded as well (i.e., 3000, 4000 lx). Each dot represents an investigated independent variable. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
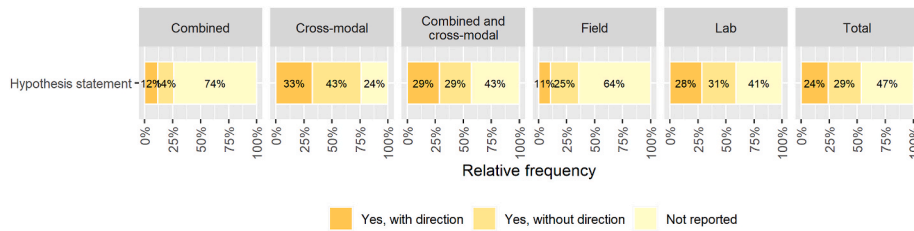

Fig. 10. Relative frequencies of hypothesis statements in the considered studies.
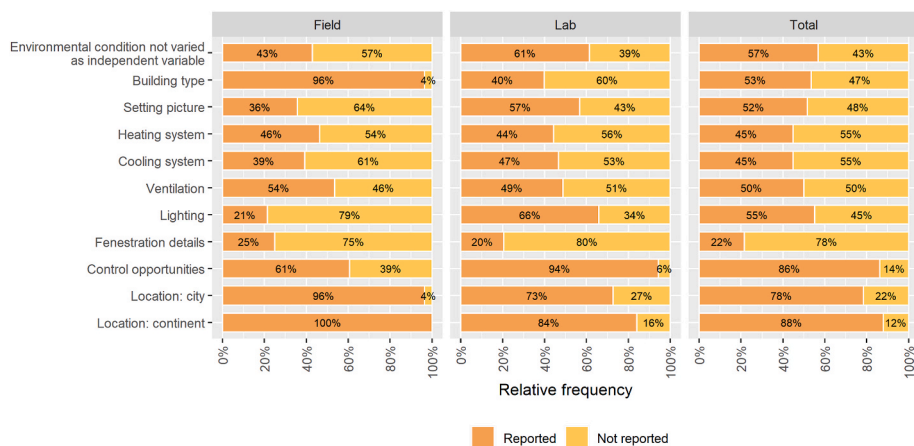

Fig. 11. Relative frequencies of the experimental setting features in the considered studies.

133]. Europe and Asia hosted most of the studies (38 % and 35 %, respectively), followed by North America (11 %), South America and Oceania (about 1 %).

4.1.5. Exposure feature

In the analyzed studies, the most frequent design was within-subjects (40 % of studies), particularly common in lab studies, followed by between-subjects (18 %) and mixed designs (15 %). However, many papers did not clearly report on their study design (27 %), especially in field studies, which might be due to the fact that field studies normally work with between-subjects-design as they measure existing environmental conditions without modifying them. A within-subject design in a field study would be called an intervention study. It is challenging to summarize the number and combination of tested experimental conditions in a concise manner as they vary highly across studies. For example, Huebner et al. [92] reported several conditions tested within-subjects, with all subjects experiencing dynamic temperature variations, and two conditions experienced between subjects (two CCTs). Laurentin et al. [134] tested six conditions within-subjects (two temperatures and three light types).

What is important to notice was the lack of reporting of exposure characteristics in many studies. While some missing information can be justified by the study type (e.g., the length of exposure for each experimental condition was rarely reported in field studies due to the lack of clear exposures), others should be reported in all studies to increase replicability and better understand study results. It was the case of the total length of the experiment per participant, not reported in 82 % of field studies and 15 % of lab studies, which greatly influences the outcome of the experiment given the potential fatigue of longer experimental sessions, especially in laboratory settings. It is surprising to see that the timing of the experiment during both the day and the year was not reported in many field studies (40 % and 25 %, respectively), and even less in lab studies in which the time of the day was not reported in about 55 % of the studies and the time of the year in 61 % of them.

The last analyzed aspect of the exposure feature is the adaptation time. More than half of the studies reported the adaptation time, especially in lab settings (Fig. 12). There was a tendency in most of the laboratory studies to use 30 min as an adaptation time; however, the time ranged from 5 to 55 min among the experiments, indicating a lack of consensus regarding this parameter.

4.1.6. Experimental design quality

As shown in Fig. 13, there were substantive gaps in reporting across all the elements of good experimental design analyzed here. Half of the reviewed papers did not report how the participants were assigned to the experimental conditions, especially in field studies where 82 % did not indicate this information. The risk of bias due to participants' expectations during the experimental sessions was reduced through single-blind and double-blind procedures in 34 % and 2 %, respectively. The rest, mostly field studies, did not mention blinding. In IEQ studies, a procedure can be considered blind when the experimental conditions are not directly explained to participants (i.e., another goal is introduced instead of presenting the study as "the effect of *x* conditions on *y* human response"). It must be highlighted that it is very challenging to make some conditions blinded (e.g., temperature or light conditions), especially in repeated measures. Hence, a truly blind procedure might be hard to achieve in IEQ studies, especially with extreme environmental conditions.

To reach the internal validity of the results, the experimental design must account for confounding variables. The most common variables controlled during data collection involved thermal stimuli (clothing insulation, relative humidity, and air velocity), followed by illuminance. Such variables can be controlled during the experiments or in the subsequent statistical analysis. The number of studies that did not report this information is high, especially in field studies. This is a surprising result considering the more numerous confounding factors present in

real buildings than those found while performing controlled experiments. A null condition was reported in 28 % of the studies, all of them developed in a laboratory setting. Depending on the type of stimuli investigated, different null conditions were used, such as comfortable indoor temperature or daylight transmitted through uncolored filters [55]. In a repeated stimulus design, the consistency of the responses to the same stimuli can be tested, which is a good practice to verify the reliability of the results [47,67]. Yet, this approach did not seem to be common in the considered studies.

4.2. Review of study deployment and analysis

4.2.1. Data collection and processing

Table 4 shows the frequency of the studies reporting the measured environmental parameters. The thermal parameters (i.e., temperature and relative humidity) were the most frequently measured and reported for both field and lab studies. The predominance of thermal measurements is linked to the numerous experiments concerning thermal aspects. However, it must be noted that such measurement was also present in other studies (approximately in 71 % of all the reviewed studies). This outcome is potentially due to the great influence that thermal conditions play on occupants' experience of space and the relative ease of measuring thermal parameters due to the availability of low-cost sensors [135]. The visual domain was the second most frequently measured aspect, with 47 % of studies reporting illuminance values.

Overall, general information for reproducibility was scarcely reported in the considered papers, as shown in Fig. 14. For instance, most studies did not report the frequency with which measurements were taken (78 % of studies), the processing method used after data collection (59 %), or the comparison between measured and design conditions (83 %). These results include both field and lab studies. This lack of information on environmental measurements is a severe limitation of existing multi-domain studies. The location of the measurements was the only information that was reported more often, presented in 66 % of the studies. Environmental measurements at the proximity of each participant were more common in lab studies than in field experiments, where sensors were usually deployed to measure the average room condition.

4.2.2. Participants

Fig. 15 highlights the percentage of studies reporting the participant characteristics. Overall, field studies had a higher number of participants (mean = 141) compared to laboratory studies (mean = 35). Distribution by sex was reported in most laboratory studies (91 %) and approximately half of the field studies (46 %). As shown in Fig. 15, age is reported more than most other single characteristics (73 %). The origin of the participants was reported in only 18 % of the analyzed papers. The verification of physical conditions before the experiment (e.g., sleep, vision, food/alcohol/caffeine intake) was reported in more than half of the laboratory papers (55 %), but rarely in field studies (11 %). Indications about the subjects' health status, height, weight, and origin were reported in one-third or fewer of the papers. Finally, participants' involvement in experiments was more frequently reported in laboratory studies than in field studies across all measures. Of the measures, the description of tasks/activities was the most commonly reported (77 %). In the described tasks/activities, the predominant activities were office activity (29 %) and class activity (7 %), while in laboratory studies, the most reported activities were reading (17 %), sitting (15 %), and conducting performance tests (13 %). Participants' payment for taking part in the project is reported in 44 % of the papers. None of the field studies foresaw a payment to the participants, while 47 % of the laboratory studies remunerated the participants. Surprisingly, information on the ethical approval and whether a tailored information sheet was distributed to the participants was reported only in 21 % of the analyzed studies (7 % and 25 % in field and laboratory studies, respectively).

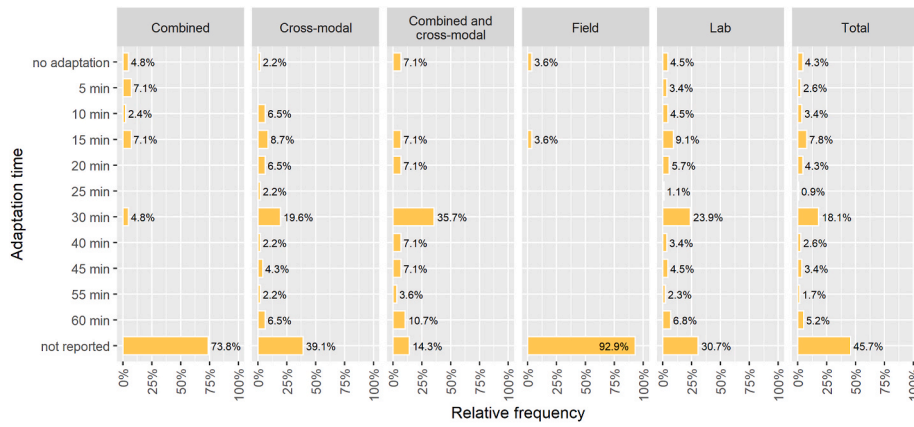While most studies provided detailed information on the number of

Fig. 12. Adaptation time in minutes reported in the studies (y-axis) in laboratory experiments.
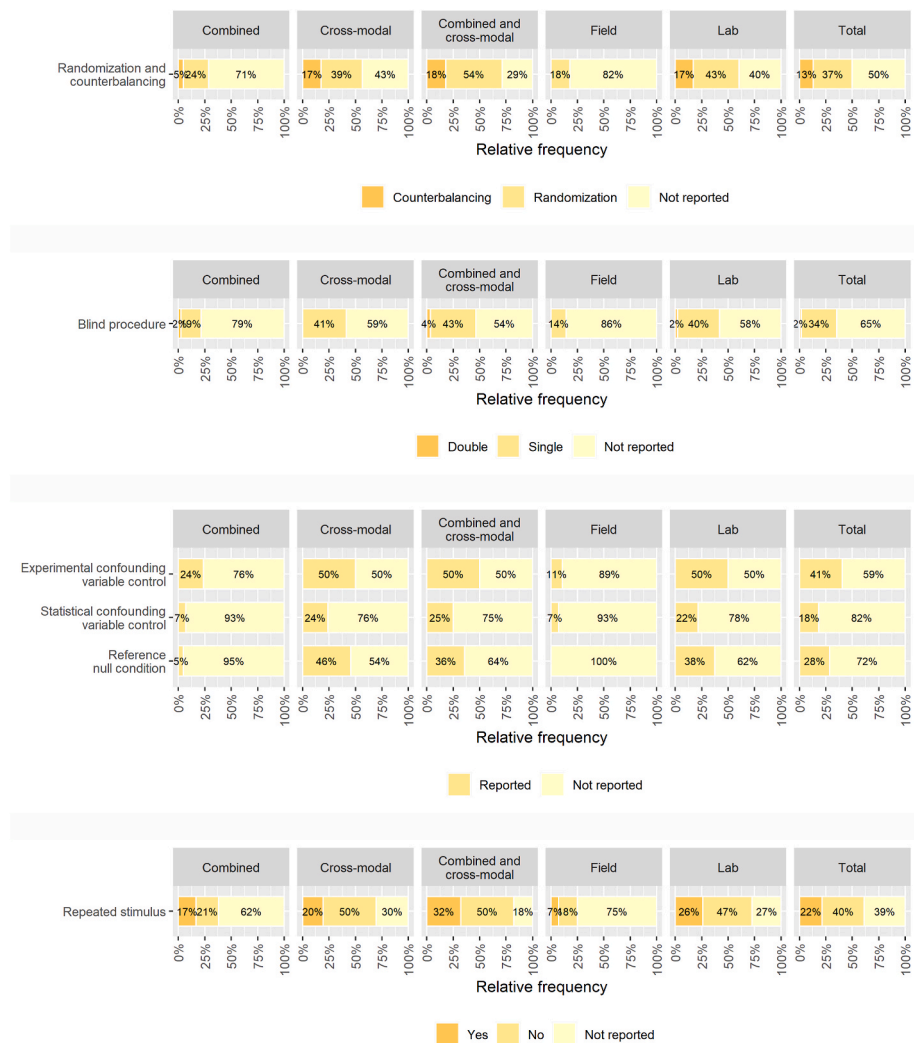

Fig. 13. Relative frequencies of information about the experimental design quality reported in the considered studies by effect type and study type.

participants, most of the described participant-related aspects seem to be underreported or not clearly stated in the papers. This leads to the risk that readers will make assumptions about certain aspects (e.g., assume that all participants were nationals from the country where the study was conducted). In future studies, researchers should report participants' characteristics in detail to clearly define to whom the study's findings apply. As best practice references, the studies that, according to

our review, reported most of the relevant aspects related to participants' characteristics and their involvement were Kim and Tokura [93], Chinazzo et al. [128], Golasi et al. [136], and Wang et al. [137].

4.2.3. Statistical analysis

Among the considered publications, 44 statistical methods were used to analyze the combined and cross-modal effects. Fig. 16 shows the main

Table 4
Number of reviewed studies reporting to measure the environmental parameters.

Environmental measurements	Effect type			Study type		Total
	Combined	Cross-modal	Combined and cross-modal	Field	Lab	
Air temperature	26	33	21	22	58	80
Air velocity/speed	9	16	10	12	23	35
Global radiation	0	1	0	1	0	1
Globe temperature	5	4	3	4	8	12
Humidity	1	3	0	0	4	4
Local outdoor temperature	0	1	0	1	0	1
Mean radiant temperature	3	1	0	4	0	4
Operative temperature	0	0	4	0	4	4
Outdoor relative humidity	4	0	0	4	0	4
Relative humidity	18	22	17	18	39	57
Surface temperature	0	0	3	0	3	3
Wet bulb temperature	0	0	3	0	3	3
Clearness index	0	1	0	1	0	1
Correlated colour temperature	0	4	0	0	4	4
Illuminance level	21	17	17	13	42	55
Illumination intensity	1	0	0	0	1	1
Luminance	1	0	0	0	1	1
CO2 concentration	13	2	7	15	7	22
Particulate matter	4	0	0	4	0	4
Ventilation rate	0	3	1	1	3	4
Sound/noise level	12	3	3	3	15	18

Fig. 14. Relative frequency of reviewed studies reporting information on environmental stimuli measurements. The label "other" includes, e.g., per desk row, and in the corner desk.

statistical methods used in the reviewed studies and the percentage of the studies adopting different methods. The most used statistical methods were the analysis of variance (ANOVA), linear regression, and *t*-test. The least used methods were categorized in the "other" group, which includes, for example, Mann-Whitney-U test [138], change-point regression [97], and permutation test [105]. The methods were also analyzed and categorized based on their *appropriate* use. For example, the *t*-test was deemed as "not appropriate" if multiple *t*-tests were applied directly as the primary test and not as a follow-up test of a

higher-order test such as ANOVA. In addition, the absence of a statistical analysis was categorized as "not appropriate".

In Fig. 16, it can be seen that mixed-effect models (also commonly referred to as multilevel or hierarchical models), although used, are not applied often. However, these models are valuable tools developed to address the violation of the independence assumption (required by traditional statistical analyzes such as ANOVA and ordinary least-squares regression). This assumption is violated whenever the observations are nested and/or clustered. For example, nested and/or
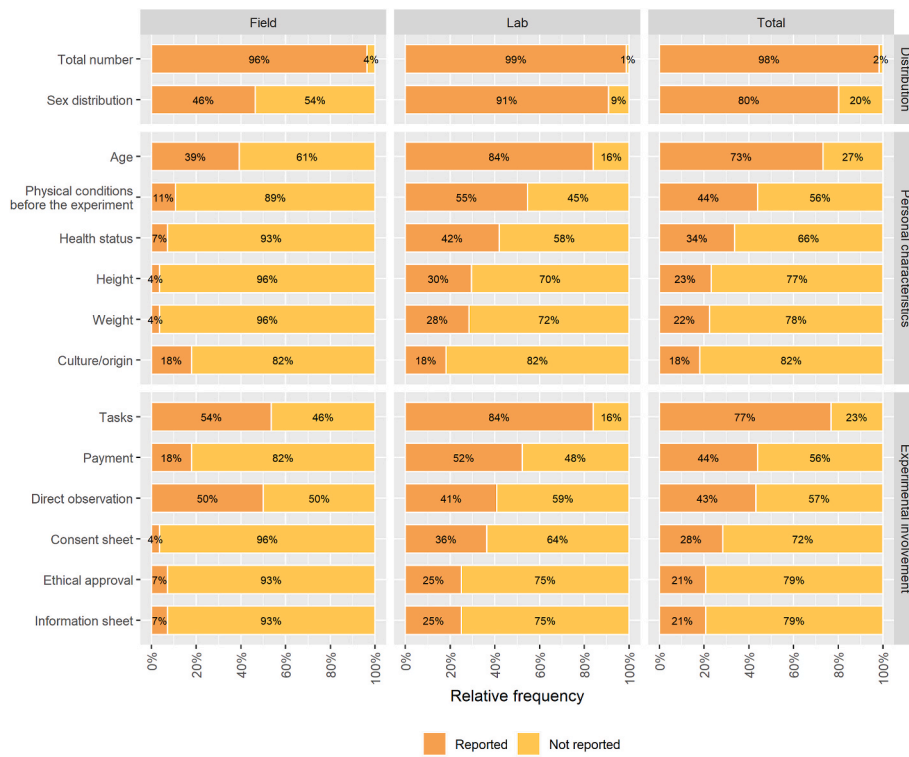
Fig. 15. Relative frequencies of information about participants reported in the considered studies.
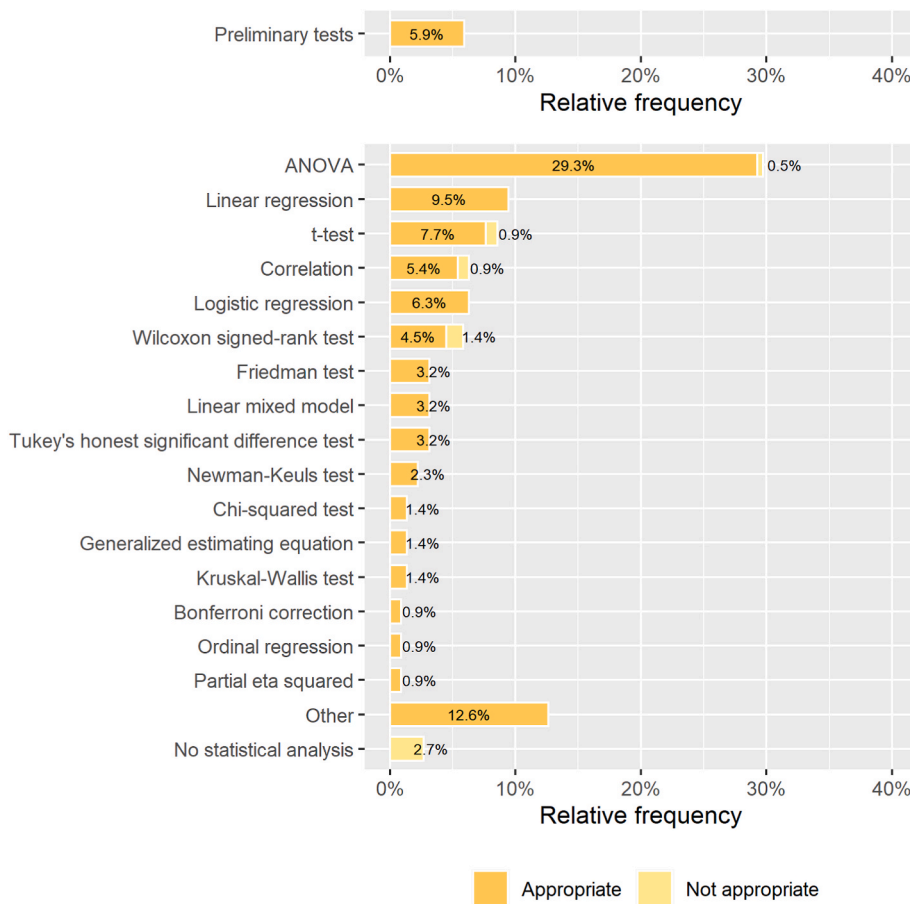

Fig. 16. The percentage of different statistical methods used (thereinto, ANOVA includes repeated measures ANOVA, one-way ANOVA, two-way ANOVA, three-way ANOVA, factorial ANOVA, mixed model ANOVA, Welch's ANOVA, ANCOVA, MANOVA, MANCOVA; generalized estimating equations includes a model assuming a binomial distribution with logistic link, a model assuming a normal distribution with identity link function; correlation includes partial correlation analysis, Pearson's correlation coefficient, Spearman's rank correlation coefficient).

clustered observations can arise from temporal and spatial autocorrelation. In the context of multi-domain studies, an application of these methods can be found in Refs. [55,128–130,139]. In Fig. 16, it can also be observed that only 5.9 % of the statistical methods used (14 out of 236) performed preliminary tests to assess the collected data (e.g., Shapiro-Wilk to check the data distribution).

Adopting a specific statistical method was justified in only 40 % of the papers. This result shows that the authors either assumed the readers could infer the statistical reasoning or considered it not an important aspect of the manuscript.

Only 4 % of the studies reported a power analysis, both in field and lab studies. This aspect leads to quite an interesting outcome because, in most cases, either the experimental design was not entirely reported in the publication, or the minimum number of observations of an experiment was simply stated but not justified.

Despite its importance, only 22 % of the studies explicitly reported the effect size, both in field and lab studies. It means that most of the studies referred only to statistical significance testing to evaluate their results.

While the domain outcomes of the reviewed studies are of paramount importance and contribute to the development of the field knowledge, unfortunately, the description of the statistical methodology was often approximate or missing. In most cases, statistical methods were applied without a dedicated description of data acquisition, analysis, curation, storage, and usage. In some cases, even validity and representativity of outcomes cannot be inferred due to missing information on data accuracy, completeness, consistency, relevance, and uniformity.

4.3. Review of study outcome

4.3.1. Reporting results

To our knowledge, the definitions of the results and results reporting style are described for the first time in this study. Therefore, it is difficult to analyze the presence of such information in the considered papers. Most of the time, we observed that results were reported in an incomplete way (e.g., only statistically significant results were described, or not all the effects of all the considered stimuli were reported). In

addition, the direction of the effect in cross-modal studies and the type of combined effect were rarely stated. Finally, a graphical representation of the cross-modal and combined effects was reported in only a few studies (e.g., Refs. [130,140,141]).

4.3.2. Study discussion and conclusion

Fig. 17 shows the relative frequency of data-informed conclusions and frequency of reporting future studies, study limitations, mechanism explanations, and practical implications.

Most of the articles (88 %) presented conclusions based on data, while the remainder seems to be speculative. Such distribution was similar across effect types, but not across laboratory versus field studies: the percentage of conclusions based on data is higher in research carried out in laboratory than in-field, 90 % against 82 %, respectively. This difference can be related to the opportunity to control some potential confounding factors in laboratory that are not always detectable in a real case.

Roughly half of the studies did not identify future studies, limitations or practical implications, although there were some differences within the sub-types. For instance, limitations were related to the study type, with some of them only relevant for field studies (e.g., limited control) and others for lab studies (e.g., limited exposure time). Also, in studies carried out in the field, the percentage of papers with mechanisms explanation was lower than those in a laboratory, 64 % and 86 %, respectively. The results of these studies can be influenced by variables that cannot be controlled, making it difficult to reach an unambiguous result [142]. However, in many cases, authors were able to provide a description of the mechanism [97,121], even with a step forward from the initial hypothesis [143]. In research carried out in laboratory, the use of a wide range of sensors and the control of variables allowed some authors to explain the results while also considering a physiological point of view [90,93,127,144,145]. In other studies, authors deepened the effect of specific stimuli on the perception of comfort [146] or on performance [116].

In the articles presenting future studies several authors propose further research in the form of new configurations of existing independent variables or expanding their ranges and identifying new parameters of the same independent variables or new environmental factors. These

Fig. 17. Relative frequencies of information about conclusions and discussions reported in the considered studies, according to the effect type and study type.

future developments are more visible in cross-modal analysis where the interaction among the independent variables are often partials. Other future studies include the investigation of different size, age, and origins of the participant group, of new building typologies or settings, different exposure time and experimental length, and of new computational models.

Practical implications were not reported in 43 % of the analyzed papers. Examples of good descriptions of practical implications can be found in several papers [85,116,147].

5. Conclusions and recommendations

5.1. Key observations

The premise of this paper, as well as that of most of the work it assesses, is that people's experience of and response to indoor environmental conditions involve multiple domains. Nonetheless, the bulk of regulatory resources for building professionals is single-domain. This may be attributed to the complexity of multi-domain exposures and the mechanisms by which they influence buildings' occupants and implies a need for increased multi-domain research. Moreover, while additional studies are necessary, they are not sufficient for progress in this area. To achieve a deeper understanding of the nature of multi-domain exposure implications for occupants' health, comfort, and productivity, the related research must also satisfy several qualitative requirements. Such research must be designed, conducted, and documented in a systematic and transparent manner, such that the results are reproducible and suitable for meta-analyses. This paper's assessment of the past research efforts in this area identified several shortcomings, notwithstanding the studies' general relevance, importance, and in some cases, pioneering significance. Therefore, as the following summary of the observed key challenges implies, necessary quality improvements of future multi-domain research need to address both the studies' design, deployment, and reporting. The key observations are divided into those related to each aspect of the critical review and those associated with a transversal analysis of the results.

Key observations of the critical review:

- Dependent variables: existing studies mainly focused on the investigation of subjective perceptual responses, most commonly through numeric scales (including 3-point, 5-point, and 7-point scales) to capture test participants' responses regarding perception, comfort, satisfaction, and preference. At times, a different number of points and different labels were used, even though the same assessment category was involved. This, as well as the inconsistent use of dimensions in analogue scales, disables the comparison of results from different studies and poses a problem for conducting large-scale meta-analyses. Performance, behavior, and physiology are still untapped research venues that could lead to new breakthroughs in multi-domain studies.
- Independent variables: thorough documentation of the prevailing values of the independent variables is a basic requirement for doing multi-domain studies. Most reviewed research generally provided such documentation, even though the types and design values in some same-modality independent variables were not reported. Future comparative studies and meta-analyses could benefit from a more consistent choice of the design values for independent variables. It is recommended to always adopt numerical design values which will enable future replication studies and meta-analyses. Moreover, documentation of non-environmental independent variables (e.g., relevant information on participants and outdoor conditions) could strengthen the interpretation scope of the studies' findings.
- Research hypothesis: the comprehension and utility of results from experimental research, would be arguably higher when research hypotheses are explicitly stated, including their "direction."

Surprisingly, about 40 % of the laboratory studies and 60 % of field studies did not state the research hypotheses. Whenever the hypothesis was stated, only a fraction indicated the direction – a very small one in field studies.

- Setting features: the description of the settings is a key aspect, yet not sufficiently reported in most reviewed studies. Such information includes building location, type, space layout, HVAC, building elements (e.g., windows and shades), control interfaces, and lighting systems. Consequently, confounding factors and potential cross-modal effects of other features could be overlooked.
- Exposure features: in many instances, characteristics of the exposure situation (e.g., type, timing, and length of exposure) were not reported in many studies. This represents a problem when trying to replicate a study or include its findings in an overarching meta-analysis of multiple investigations. The analysis of previous studies also shows a lack of consistency regarding the adaptation time, which might influence the results of the experiments.
- Experimental design quality: the consideration of experimental design criteria/principles is of critical importance to assure high standards of scientific quality. The reviewed studies were analyzed regarding randomization, counterbalance, experimental procedure (single or double blind, at least when explaining the goal of the study), experimental and statistical confounding variables, reporting of null condition, and repetition of certain experimental conditions. The reviewed studies did not consistently report these aspects. For instance, 82 % of the reviewed field studies did not include information on how participants were assigned to specific experimental conditions.
- Data collection and processing: the measurement and data processing of environmental conditions (not only explicitly targeted independent variables, but other elements of the experiments' boundary conditions) in the course of multi-domain studies is of high importance, especially in view of reproducibility criteria. A sufficient level of reporting on environmental measurements and their analysis was provided only in a small number of multi-domain studies. This implies the need for streamlined assessment and reporting procedures for both environmental conditions and human responses.
- Participants: studies involving human participants should provide detailed information on their distribution, relevant personal characteristics, and their role/involvement in the experiments. The assessment of the reviewed studies regarding this criterion yields a rather unsatisfactory picture. Aside from their number (almost always reported), essential information regarding participants was either underreported or not clearly stated. This circumstance undermines the credibility of the studies concerning, among other things, their representativeness and generalizability. In addition, information about the ethical approval and the related documentation (consent and information sheet) is lacking in almost 80 % of the publications, raising concerns about the ethics of the performed studies.
- Statistical analysis: a considerable number (N = 44) of different statistical methods were employed in the reviewed studies (mostly ANOVA). Among the formal tests of the distribution of the data, it is striking that the Shapiro-Wilk test, although recommended among the possible formal tests (e.g., Kolmogorov-Smirnov, Lilliefors and Anderson-Darling) [148], is only used in 5.9 % of the cases, while the tests where the normality distribution should be verified are much more (more than 55 % if we consider the sum of the papers where ANOVA, *t*-test and linear regression are used). Future studies should adopt a statistical approach that first checks the distribution of the sample and then applies tests where the normal distribution is an underlying assumption that corresponds to the main hypothesis. About 60 % of the studies did not include any justification for the choice of the applied statistical method. A low fraction of the studies conducted a power analysis (4 %) and reported effect sizes (22 %).

This hampers the reproducibility of experiments, feasibility of meta-analyses, and review of collective insights.

- Reporting results: the reporting of the results in published studies is inconsistent and sometimes incomplete (e.g., not all the results are reported, graphical representations are missing). The use of the same terminology to describe the type of effect investigated (i.e., cross-modal or combined) and their results is paramount to conduct future meta-analyses on multi-domain studies. For cross-modal effects, the direction of the effect (i.e., positive, negative or no effect) must be reported for each of the levels of the considered stimuli. For combined effects, the results can be described following the terminology described in the ASHRAE Guideline 10–2016 [39]. In future studies, researchers are invited to describe the results comprehensively and adopt the suggested reporting style for both cross-modal and combined effects (including terminology and the suggested tabular representation). In addition, considering that understanding cross-modal and combined effects solely based on the outcome of statistical analysis (e.g., model coefficients) may be a complex task for those without a solid background in statistics, we advise the complimentary usage of as simple as possible graphical representations of the cross-modal and combined effects (as depicted in Fig. 1).
- Study discussion and conclusions: despite always presenting the conclusions (mostly based on the data), a large part of the considered papers does not include future studies (43 %), limitations (55 %), explanation of the mechanisms behind the results (69 %), and practical implications (43 %). The lack of such information reduces the possibility to advance the knowledge on the topic and understanding its relevance for people and society.

Transversal key observations:

- Multi-domain studies have been reported to rarely carryover previous studies' findings and to lack foundational theories to formulate and test research hypothesis [40]. Therefore, introductory sections were not reviewed in this study. Future multi-domain investigations should build upon previous findings to generate theoretical assumptions or start from theory-based motivations based on human perceptual and behavioral processes to formulate their research hypotheses.
- Field studies were less likely to report features (e.g., site, location, equipment etc.), hypotheses, assumptions, and variables. Laboratory and field experiments have intrinsic differences, but this is not a justification for leaving out the information required for valid, generalizable, replicable, and reproducible studies.
- The low fraction of the studies that conducted a power analysis, followed a good experimental design, described sufficient population characteristics, and effect sizes, suggests a possible replication crisis identified elsewhere [65,66]. The adjacent field of psychology serves as a reservoir of a decade's worth of scientific discussion and proposed methodological improvements (e.g., pre-registration prior to the start of the study, transparent data processing practices, and reporting effects sizes) [149] that should serve as example in future studies. It has been suggested that the social-structural factors that contribute to the replication crisis are not limited to psychology [150] and may apply to other fields [151].

It can be concluded that multi-domain studies were often not thoroughly documented and reported in a systematic and detailed manner or did not adhere to paramount research quality criteria. These issues may be rooted in the lack of robust schemes for conceptualizing and reporting both cross-modal and combined effects. This study aimed to establish sound guidelines and recommendations for designing, deploying and reporting multi-domain studies for addressing this challenge and foster more structured and coherent future multi-domain studies. Standardizing methods and reporting formats for multi-domain studies will enhance the rigor in reviewing these studies and enable future meta-analyses.

5.2. Future multi-domain studies

Although the provided recommendations were developed for investigations about (indoor) environmental stimuli, their application can be extended to studies investigating personal (e.g., sex, age, culture) and contextual aspects (e.g., time of the day, season, building typology, control opportunities). These aspects can be considered as additional domains influencing human responses in multi-domain studies [40].

The publications and context covered by this work outline momentum towards characterizing the multi-dimensional impact of the built environment on occupants. This foundation and the lessons learned provide the context for future work. Research in this area going forward could focus on filling the gaps of information about indoor environmental stimuli and human responses through innovative technologies and methods. For example, the use of continuous, field-based biosensing methods, like those being developed in mobile health research, can enable the detection of a broader range of human physiological responses [152]. The human response can be captured in a more scalable way using innovative interfaces that are integrated specifically into mobile devices and wearables [153]. There are, moreover, relatively new statistical techniques for testing causal claims relevant to multi-domain studies from a properly designed field study setup. For an overview of some of the recent developments in techniques, see Ref. [154]. Many of the proposed quality criteria are complementary to the rigorous study design required for a causal framework. The quality criteria summarized in Fig. 2 and their description in section 3 can therefore serve as guidance for study design and reporting in future multi-domain studies.

During the reviewing process, we uncovered a wide range of possible interdisciplinary research opportunities through collaboration with the research communities of machine learning, building controls, wellness, public health, and real estate communities, as well as between research fields such as psychology, physiology, engineering, and architecture. The methodological best quality criteria uncovered during the review process can be further enhanced by these interdisciplinary collaborations to create hybrid approaches that accelerate the transfer of IEQ research results into actionable outputs, such as the amendment of building design and operation standards and guidelines. Future work may also consider the increasingly dynamic nature in which buildings are used, especially in office spaces where a larger diversity of activities can occur due to the enhanced workplace flexibility.

CRediT authorship contribution statement

Giorgia Chinazzo: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rune Korsholm Andersen:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Elie Azar:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Verena M. Barthelmes:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Cristina Becchio:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Lorenzo Belussi:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Christiane Berger:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Salvatore Carlucci:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Stefano Paolo Corgnati:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Sarah Crosby:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Ludovico Danza:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Luiza de**

Castro: Formal analysis, Data curation. **Matteo Favero:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation. **Stephanie Gauthier:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Runa T. Hellwig:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Quan Jin:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Joyce Kim:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Mandana Sarey Khanie:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Dolaana Khovalyg:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Carola Lingua:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Alessandra Luna-Navarro:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Ardeshir Mahdavi:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Clayton Miller:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Isabel Mino-Rodriguez:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Ilaria Pigliautile:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Anna Laura Pisello:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Ricardo Forgiarini Rupp:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Abdul-Manan Sadick:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Francesco Salamone:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation. **Marcel Schweiker:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Marc Syndicus:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Giorgia Spigliantini:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Natalia Giraldo Vasquez:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Donna Vakalis:** Writing – review & editing, Writing – original draft, Validation, Data curation. **Marika Vellei:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Shen Wei:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A

Ref.	List of considered papers
[111]	A chamber-experiment investigation of the interaction between perceptions of noise and odor in humans
[155]	A comparative study of discomfort caused by indoor air pollution, thermal load and noise
[51]	A field study investigation on the influence of light level on subjective thermal perception in different seasons
[156]	A multiple linear regression approach to correlate the Indoor Environmental Factors to the global comfort in a Zero-Energy building
[157]	A multivariate-logistic model for acceptance of indoor environmental quality (IEQ) in offices
[133]	A new index combining thermal, acoustic, and visual comfort of moderate environments in temperate climates
[158]	A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices
[159]	A weighting procedure to analyze the Indoor Environmental Quality of a Zero-Energy Building
[88]	Air movement and perceived air quality
[81]	An applied framework to evaluate the impact of indoor office environmental factors on occupants' comfort and working conditions
[160]	An evaluation model for indoor environmental quality (IEQ) acceptance in residential buildings
[161]	Can colour and noise influence man's thermal comfort?
[94]	Colour as a psychological agent to manipulate perceived indoor thermal environment for effective energy usage
[107]	Combined effects of acoustic and visual distraction on cognitive performance and well-being
[56]	Combined effects of acoustic, thermal, and illumination conditions on the comfort of discrete senses and overall indoor environment
[55]	Combined effects of daylight transmitted through coloured glazing and indoor temperature on thermal responses and overall comfort
[108]	Combined effects of noise and air temperature on human neurophysiological responses in a simulated indoor environment
[84]	Combined Effects of noise and temperature on human comfort and performance
[162]	Combined effects of short-term noise exposure and hygrothermal conditions on indoor environmental perceptions
[163]	Combined effects of sound and illuminance on indoor environmental perception
[164]	Combined effects of temperature and noise on human discomfort
[165]	Correlations between thermal satisfaction and non-thermal conditions of indoor environmental quality: Bayesian inference of a field study of offices
[147]	Cross-modal effects of illuminance and room temperature on indoor environmental perception

(continued on next page)

(*continued*)

Ref.	List of considered papers
[166]	Cross-modal effects of noise and thermal conditions on indoor environmental perception and speech recognition
[140]	Cross-modal effects of thermal and visual conditions on outdoor thermal and visual comfort perception
[128]	Daylight affects human thermal perception
[167]	Decision support for improving occupant environmental satisfaction in office buildings: The relationship between sub-set of IEQ satisfaction and overall environmental satisfaction
[168]	Determining the Indoor Environment Quality for an Educational Building
[169]	Developing an indoor environment quality tool for assessment of mechanically ventilated office buildings in the UK – A preliminary study
[170]	Development of a multivariate regression model for overall satisfaction in public buildings based on field studies
[171]	Development of equi-comfort charts constituted with temperature and noise at 150 and 3 lx
[118]	Effect of coloured illumination upon perceived temperature
[130]	Effect of Indoor Temperature and Glazing with Saturated Color on Visual Perception of Daylight
[116]	Effect of noise intensity and illumination intensity on visual performance
[134]	Effect of thermal conditions and light source type on visual comfort appraisal
[145]	Effects of different light intensities during the forenoon on the afternoon thermal sensation in mild cold
[172]	Effects of indoor temperature and background noise on floor impact noise perception
[173]	Effects of noise and heat stress on primary and subsidiary task performance
[144]	Effects of noise type, noise intensity, and illumination intensity on reading performance
[119]	Effects of noise, heat and indoor lighting on cognitive performance and self-reported affect
[132]	Effects of perceived indoor temperature on daylight glare perception
[126]	Effects of recorded water sounds on intrusive traffic noise perception under three indoor temperatures
[174]	Effects of steady-state noise and temperature conditions on environmental acceptability
[175]	Effects of thermal discomfort in an office on perceived air quality, SBS symptoms, physiological responses, and human performance
[110]	Evaluation of the Visual Stimuli on Personal Thermal Comfort Perception in Real and Virtual Environments Using Machine Learning Approaches
[137]	Experimental investigation about thermal effect of colour on thermal sensation and comfort
[99]	Experimental study on occupants' interaction with windows and lights in Mediterranean offices during the non-heating season
[176]	Facilitatory effects of environmental sounds on hue-heat phenomena
[120]	First SenseLab studies with primary school children: exposure to different environmental configurations in the experience room
[54]	How correlated colour temperature manipulates human thermal perception and comfort
[177]	Impact of individual IEQ factors on passengers' overall satisfaction in Chinese airport terminals
[127]	Impact of individually controlled facially applied air movement on perceived air quality at high humidity
[142]	Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance
[178]	Impact of Temperature and Humidity on Perception of Indoor Air Quality During Immediate and Longer Whole-Body Exposures
[179]	Impact of temperature and humidity on the perception of indoor air quality
[180]	In search of evidence for the hue-heat hypothesis in the aircraft cabin
[181]	Incandescent affect: turning on the hot emotional system with bright light
[182]	Influence of air temperature on preference for color temperature of general lighting in the room
[93]	Influence of different light intensities during the daytime on evening dressing behavior in the cold
[129]	Influence of indoor temperature and daylight illuminance on visual perception
[90]	Influence of Light Intensities on Dressing Behavior in Elderly People
[136]	Influence of lighting colour temperature on indoor thermal perception: A strategy to save energy from the HVAC installations
[91]	Influence of Two Different Light Intensities from 16:00 to 20:30 Hours on Evening Dressing Behavior in the Cold
[183]	Influence of visual factors on noise annoyance evaluation caused by road traffic noise in indoor environment
[146]	Interactions and comprehensive effect of indoor environmental quality factors on occupant satisfaction
[184]	Interactions and range effects in experiments on pairs of stresses: mild heat and low frequency noise
[139]	Interactions between the perception of light and temperature
[138]	Interrelations of Comfort Parameters in a Simulated Aircraft Cabin
[185]	Investigating the effect of CO2 concentration on reported thermal comfort
[186]	Investigation of the relationships between thermal, acoustic, illuminous environments and human perceptions
[187]	Investigation of the subjective evaluation of indoor illumination level on perceived air quality
[86]	Irrelevant speech and indoor lighting: effects on cognitive performance and self-reported affect
[188]	Light intensity and thermal responses
[189]	Linear, non-linear and alternative algorithms in the correlation of IEQ factors with global comfort: a case study
[100]	Modeling occupant behavior of the manual control of windows in residential buildings
[96]	Monitoring and modelling of manually-controlled venetian blinds in private offices: A pilot study
[190]	New comfort index during combined conditions of moderate low ambient temperature and traffic noise
[115]	New index of combined effect of temperature and noise on human comfort: summer experiments on hot ambient temperature and traffic noise
[191]	Nonlinear relationships between individual IEQ factors and overall workspace satisfaction
[97]	Occupant behavior regarding the manual control of windows in residential buildings
[192]	Occupant response to different correlated colour temperatures of white LED lighting
[101]	Occupants' interactions with windows in 8 residential apartments in Beijing and Nanjing, China
[106]	Office noise and illumination effects on reading comprehension
[193]	On the interaction between lighting and thermal comfort: an integrated approach to IEQ
[124]	On the unification of thermal perception and adaptive actions
[194]	Perceived air quality and the thermal environment
[98]	Probability of occupant operation of windows during transition seasons in office buildings
[195]	Quantification of the synthesized evaluation of the combined environment
[92]	Saving energy with light? Experimental studies assessing the impact of colour temperature on thermal comfort
[87]	Sensory and physiological effects on humans of combined exposures to air temperatures and volatile organic compounds
[196]	Simultaneous effects of irrelevant speech, temperature and ventilation rate on performance and satisfaction in open-plan offices
[83]	Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms
[197]	Study on human responses under different CO2 concentration and illuminance in underground refuge chamber
[198]	The combined effects of many different indoor environmental factors on acceptability and office work performance
[199]	The combined effects of noise and illumination on the performance efficiency of visual search and neuromotor task components
[200]	The combined effects of temperature, background noise and lighting on the non-physical task performance of university students
[201]	The effect of correlated colour temperature of lighting on thermal sensation and thermal comfort in a simulated indoor workplace
[85]	The effects of moderate heat stress and open-plan office noise distraction on SBS symptoms and on the performance of office work

(*continued*)

Ref.	List of considered papers
[122]	The effects of temperature, light, and sound on perceived work environment
[105]	The impact of a view from a window on thermal comfort, emotion, and cognitive performance
[117]	The impact of human perception of simultaneous exposure to thermal load, low frequency ventilation noise and indoor air pollution
[125]	The impact of thermal environment on occupant IEQ perception and productivity
[202]	The influence of coloured light in the aircraft cabin on passenger thermal comfort
[82]	The influence of exposure to multiple indoor environmental parameters on human perception
[89]	The influence of heat, air jet cooling and noise on performance in classrooms
[103]	The interaction of noise and mild heat on cognitive performance and serial reaction time
[203]	The Relationship between Thermal Comfort and Light Intensity with Sleep Quality and Eye Tiredness in Shift Work Nurses
[95]	Understanding window behaviour in a mixed-mode buildings and the impact on energy performance
[204]	Upper limits of air humidity for preventing warm respiratory discomfort
[205]	Ventilation requirements in buildings—I. Control of occupancy odor and tobacco smoke odor
[206]	Visual effects of wood on thermal perception of interior environments
[207]	Warmth, glare and a background of quiet speech: A comparison of their effects on performance
[114]	What's So Hot About Red?
[208]	What's so hot about sound?-influence of HVAC sounds on thermal comfort
[102]	Window opening behavior of occupants in residential buildings in Beijing

Appendix B

The described exclusion criteria lead to the exclusion of studies involving contextual, personal or other behavior (all sections besides 4.1 and 5.1 in Schweiker et al. [40]). In particular, the following studies were excluded from the analysis:

- Studies focusing on the effect of personal control [209];
- Studies focusing on physiological responses only[3] (e.g., Ref. [210]);
- Studies in which the independent variables are not physical measurements - such as those in which overall comfort/index or performance are evaluated on the basis of subjective evaluations of the indoor environmental stimuli (e.g., Refs. [211,211–218]);
- Studies reporting results of experts' questionnaires [219];
- Studies where interactions are analyzed just looking at the correlation between human responses [220];
- Studies investigating the effect of the combined presence of multiple indoor stimuli on the measurements of another factor [123];
- Studies focusing neither on cross-modal nor on combined effects [133];
- Preliminary studies in which the quantitative results described are not the goal of the study [189];
- Proof-of-concept studies [221].
- Experiments in Virtual Reality [222,223].

References

[1] N.E. Klepeis, et al., The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants, J. Expo. Sci. Environ. Epidemiol. 11 (3) (2001) 231.

[2] P.M. Bluyssen, Towards new methods and ways to create healthy and comfortable buildings, Build. Environ. 45 (4) (Apr. 2010) 808–818, https://doi.org/10.1016/j.buildenv.2009.08.020.

[3] F. Stazi, F. Naspi, M. D'Orazio, A literature review on driving factors and contextual events influencing occupants' behaviours in buildings, Build. Environ. 118 (Jun. 2017) 40–66, https://doi.org/10.1016/j.buildenv.2017.03.021.

[4] M. Aries, M. Aarts, J. van Hoof, Daylight and health: a review of the evidence and consequences for the built environment, Light. Res. Technol. 47 (1) (Feb. 2015) 6–27, https://doi.org/10.1177/1477153513509258.

[5] M. Amundadottir, S. Lockley, M. Andersen, Unified framework to evaluate non-visual spectral effectiveness of light for human health, Light. Res. Technol. 49 (6) (Oct. 2017) 673–696, https://doi.org/10.1177/1477153516655844.

[6] A. Leaman, B. Bordass, Are users more tolerant of 'green' buildings? Build. Res. Inf. 35 (6) (Sep. 2007) 662–673, https://doi.org/10.1080/09613210701529518.

[7] D. Clements-Croome, Creating the Productive Workplace, Taylor & Francis, 2006.

[8] D. Clements-Croome, L. Baizhan, Productivity and indoor environment, in: Proceedings of Healthy Buildings, vol. 1, 2000, pp. 629–634. Accessed: Nov. 09, 2015. [Online]. Available: http://www.senseair.se/wp-content/uploads/2011/05/31.pdf.

[9] A. Soriano, M.W. Kozusznik, J.M. Peiró, C. Mateo, Mediating role of job satisfaction, affective well-being, and health in the relationship between indoor environment and absenteeism: work patterns matter, Work 61 (2) (Jan. 2018) 313–325, https://doi.org/10.3233/WOR-182802.

[10] J.A. Veitch, K.E. Charles, K.M.J. Farley, G.R. Newsham, A model of satisfaction with open-plan office conditions: COPE field findings, J. Environ. Psychol. 27 (3) (Sep. 2007) 177–189, https://doi.org/10.1016/j.jenvp.2007.04.002.

[11] G. Newsham, J. Brand, C. Donnelly, J. Veitch, M. Aries, K. Charles, Linking indoor environment conditions to job satisfaction: a field study, Build. Res. Inf. 37 (2) (Apr. 2009) 129–147, https://doi.org/10.1080/09613210802710298.

[12] G. Chinazzo, Investigating the indoor environmental quality of different workplaces through web-scraping and text-mining of Glassdoor reviews, Build. Res. Inf. 49 (6) (Aug. 2021) 695–713, https://doi.org/10.1080/09613218.2021.1908879.

[13] Z. Yu, B.C.M. Fung, F. Haghighat, H. Yoshino, E. Morofsky, A systematic procedure to study the influence of occupant behavior on building energy consumption, Energy Build. 43 (6) (2011) 1409–1417, https://doi.org/10.1016/j.enbuild.2011.02.002.

[14] H.B. Rijal, P. Tuohy, M.A. Humphreys, J.F. Nicol, A. Samuel, J. Clarke, Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings, Energy Build. 39 (7) (Jul. 2007) 823–836, https://doi.org/10.1016/j.enbuild.2007.02.003.

[15] O. Guerra-Santin, L. Itard, Occupants' behaviour: determinants and effects on residential heating consumption, Build. Res. Inf. 38 (3) (Jun. 2010) 318–338, https://doi.org/10.1080/09613211003661074.

[16] W. Fisk, O. Seppanen, O. Fisk Seppanen, Providing Better Indoor Environmental Quality Brings Economic Benefits, 2007.

[17] J.G. Allen, J.D. Macomber, Healthy Buildings: How Indoor Spaces Drive Performance and Productivity, Harvard University Press, 2020.

[18] P.O. Fanger, Thermal Comfort: Analysis and Applications in Environmental Engineering, Danish Technical Press, Copenhagen, 1970 [Online]. Available: http://books.google.ch/books?id=S0FSAAAAMAAJ.

[19] J. Wienold, Daylight Glare in Offices, Fraunhofer-Verlag, 2009.

[20] ASHRAE, ANSI/ASHRAE, Standard 62.1-2016: Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, USA, 2016.

[21] ASHRAE, ANSI/ASHRAE 55-2020: Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, USA, 2020. Standard 55-2020.

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[3] Physiological responses are analyzed in papers where this type of response is reported together with other perceptual, behavioral, and cognitive responses.

[22] H. Levin, Emmerich, Dissecting interactions among IEQ factors, ASHRAE J. 55 (9) (2013) 66–72.

[23] ASHRAE, ANSI/ASHRAE Guideline 10P: Interactions Affecting the Achievement of Acceptable Indoor Environments, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, USA, 2011.

[24] S. Shimojo, L. Shams, Sensory modalities are not separate modalities: plasticity and interactions, Curr. Opin. Neurobiol. 11 (4) (2001) 505–509.

[25] R.B. Welch, Intersensory Interactions, vol. 1, John Wiley and Sons, New York, 1986.

[26] J. Driver, C. Spence, Multisensory perception: beyond modularity and convergence, Curr. Biol. 10 (20) (Oct. 2000) R731–R735, https://doi.org/10.1016/S0960-9822(00)00740-5.

[27] D. Alais, F.N. Newell, P. Mamassian, Multisensory processing in review: from physiology to behaviour, Seeing Perceiving 23 (1) (2010) 3–38.

[28] G.M. Wyburn, Human Senses and Perception, University of Toronto Press, 1964.

[29] G. Calvert, C. Spence, B.E. Stein, The Handbook of Multisensory Processes, MIT press, 2004.

[30] M.O. Ernst, H.H. Bülthoff, Merging the senses into a robust percept, Trends Cognit. Sci. 8 (4) (2004) 162–169.

[31] P. Bertelson, B. De Gelder, The Psychology of Multimodal Perception, Crossmodal Space Crossmodal Atten., 2004, pp. 141–177.

[32] E.T. Hall, The Hidden Dimension, vol. 609, Doubleday, Garden City, NY, 1966.

[33] A. Rapoport, El Sayegh, Culture, Architecture, and Design, Locke science publishing Company Washington, 2005.

[34] J. Ward, Synesthesia, Annu. Rev. Psychol. 64 (1) (2013) 49–75, https://doi.org/10.1146/annurev-psych-113011-143840.

[35] C. Karmann, S. Schiavon, E. Arens, Percentage of commercial buildings showing at least 80% occupant satisfied with their thermal comfort, in: Presented at the Proceedings of 10th WIndsor Conference: Rethinking Comfort, Windsor, UK, Apr. 2018.

[36] C. Huizenga, S. Abbaszadeh, L. Zagreus, E.A. Arens, Air quality and thermal comfort in office buildings: results of a large indoor environmental quality survey, Proceeding Healthy Build 3 (Jan. 2006) (2006). Accessed: Oct. 22, 2015. [Online]. Available: http://escholarship.org/uc/item/7897g2f8.

[37] G. Brager, L. Baker, Occupant satisfaction in mixed-mode buildings, Build. Res. Inf. 37 (4) (Aug. 2009) 369–380, https://doi.org/10.1080/09613210902899785.

[38] L.T. Graham, T. Parkinson, S. Schiavon, Lessons learned from 20 years of CBE's occupant surveys, Build. Cities 2 (1) (Feb. 2021), https://doi.org/10.5334/bc.76. Art. no. 1.

[39] ASHRAE, ANSI/ASHRAE Guideline 10P: Interactions Affecting the Achievement of Acceptable Indoor Environments, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, USA, 2016.

[40] M. Schweiker, et al., Review of multi-domain approaches to indoor environmental perception and behaviour, Build. Environ. 176 (Jun. 2020) 106804, https://doi.org/10.1016/j.buildenv.2020.106804.

[41] S. Torresin, G. Pernigotto, F. Cappelletti, A. Gasparella, Combined effects of environmental factors on human perception and objective performance: a review of experimental laboratory works, Indoor Air 28 (4) (2018) 525–538.

[42] H. Wu, Y. Wu, X. Sun, J. Liu, Combined effects of acoustic, thermal, and illumination on human perception and performance: a review, Build. Environ. 169 (2020), 106593.

[43] J. Van Hoof, M. Mazej, J.L. Hensen, Thermal comfort: research and practice, Front. Biosci. 15 (2) (2010) 765–788.

[44] A. Mahdavi, et al., Necessary conditions for multi-domain indoor environmental quality standards, Sustainability 12 (20) (Jan. 2020), https://doi.org/10.3390/su12208439. Art. no. 20.

[45] R.F. Rupp, N.G. Vásquez, R. Lamberts, A review of human thermal comfort in the built environment, Energy Build. 105 (2015) 178–205.

[46] S.C. Landis, et al., A call for transparent reporting to optimize the predictive value of preclinical research, Nature 490 (7419) (2012), https://doi.org/10.1038/nature11556. Art. no. 7419, Oct.

[47] H. Coolican, Research Methods and Statistics in Psychology, sixth ed., Psychology Press, 2014 [Online]. Available: https://books.google.ch/books?hl=it&lr=&id=8DJFAwAAQBAJ&oi=fnd&pg=PP1&dq=hugh+coolican&ots=BSeeshI8eW&sig=-W_waAGHMrmDl4VsNsd6ZuOFaA.

[48] A.L. Pisello, et al., Test rooms to study human comfort in buildings: a review of controlled experiments and facilities, Renew. Sustain. Energy Rev. 149 (Oct. 2021) 111359, https://doi.org/10.1016/j.rser.2021.111359.

[49] A.K. Mishra, M. Ramgopal, Field studies on human thermal comfort — an overview, Build. Environ. 64 (Jun. 2013) 94–106, https://doi.org/10.1016/j.buildenv.2013.02.015.

[50] R. Jacoby Cureau, et al., Bridging the gap from test rooms to field-tests for human indoor comfort studies: a critical review of the sustainability potential of living laboratories, Energy Res. Social Sci. 92 (Oct. 2022) 102778, https://doi.org/10.1016/j.erss.2022.102778.

[51] G. Chinazzo, L. Pastore, J. Wienold, M. Andersen, A Field Study Investigation on the Influence of Light Level on Subjective Thermal Perception in Different Seasons, 2018, p. 12.

[52] Z. Wang, et al., Individual difference in thermal comfort: a literature review, Build. Environ. 138 (Jun. 2018) 181–193, https://doi.org/10.1016/j.buildenv.2018.04.040.

[53] M. Schweiker, G.M. Huebner, B.R.M. Kingma, R. Kramer, H. Pallubinsky, Drivers of diversity in human thermal perception – a review for holistic comfort models, Temperature 5 (4) (Oct. 2018) 308–342, https://doi.org/10.1080/23328940.2018.1534490.

[54] A. Brambilla, W. Hu, R. Samangouei, R. Cadorin, W. Davis, How correlated colour temperature manipulates human thermal perception and comfort, Build. Environ. 177 (Jun. 2020) 106929, https://doi.org/10.1016/j.buildenv.2020.106929.

[55] G. Chinazzo, J. Wienold, M. Andersen, Combined effects of daylight transmitted through coloured glazing and indoor temperature on thermal responses and overall comfort, Build. Environ. 144 (Oct. 2018) 583–597, https://doi.org/10.1016/j.buildenv.2018.08.045.

[56] W. Yang, H.J. Moon, Combined effects of acoustic, thermal, and illumination conditions on the comfort of discrete senses and overall indoor environment, Build. Environ. 148 (Jan. 2019) 623–633, https://doi.org/10.1016/j.buildenv.2018.11.040.

[57] S.A. Sadeghi, P. Karava, I. Konstantzos, A. Tzempelikos, Occupant interactions with shading and lighting systems using different control interfaces: a pilot field study, Build. Environ. 97 (Feb. 2016) 177–195, https://doi.org/10.1016/j.buildenv.2015.12.008.

[58] J.K. Day, et al., A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort, Build. Environ. 178 (Jul. 2020) 106920, https://doi.org/10.1016/j.buildenv.2020.106920.

[59] R.T. Hellwig, Perceived control in indoor environments: a conceptual approach, Build. Res. Inf. 43 (3) (May 2015) 302–315, https://doi.org/10.1080/09613218.2015.1004150.

[60] L.M. Huiberts, K.C.H.J. Smolders, Y.A.W.D. Kort, Seasonal and time-of-day variations in acute non-image forming effects of illuminance level on performance, physiology, and subjective well-being, Chronobiol. Int. 34 (7) (Aug. 2017) 827–844, https://doi.org/10.1080/07420528.2017.1324471.

[61] M.G. Kent, Temporal effects on glare response from daylight, Build. Environ. (2017) 16.

[62] M. Vellei, G. Chinazzo, K.-M. Zitting, J. Hubbard, Human thermal perception and time of day: a review, Temperature (Oct. 2021) 1–22, https://doi.org/10.1080/23328940.2021.1976004, vol. 0, no. 0.

[63] A. Wagner, E. Gossauer, C. Moosmann, Th Gropp, R. Leonhart, Thermal comfort and workplace occupant satisfaction—results of field studies in German low energy office buildings, Energy Build. 39 (7) (Jul. 2007) 758–769, https://doi.org/10.1016/j.enbuild.2007.02.013.

[64] T. Goto, J. Toftum, R. de Dear, P.O. Fanger, Thermal sensation and thermophysiological responses to metabolic step-changes, Int. J. Biometeorol. 50 (5) (May 2006) 323–332, https://doi.org/10.1007/s00484-005-0016-5.

[65] Open Science Collaboration, Estimating the reproducibility of psychological science, Science 349 (6251) (Aug. 2015) aac4716, https://doi.org/10.1126/science.aac4716.

[66] M. Baker, 1,500 scientists lift the lid on reproducibility, Nature 533 (7604) (May 2016) 452–454, https://doi.org/10.1038/533452a.

[67] A. Field, J. Miles, Z. Field, Discovering Statistics Using R, SAGE Publications, 2012.

[68] A. Dean, D. Voss, D. Draguljić, Design and Analysis of Experiments, Springer, 2017.

[69] M. Schweiker, et al., Evaluating assumptions of scales for subjective assessment of thermal environments – do laypersons perceive them the way, we researchers believe? Energy Build. 211 (Mar. 2020) 109761, https://doi.org/10.1016/j.enbuild.2020.109761.

[70] P. Voigt, A. Von dem Bussche, The eu general data protection regulation (gdpr), Pract. Guide 1st Ed Cham Springer Int. Publ. 10 (3152676) (2017) 10–5555.

[71] A.P. Siddaway, A.M. Wood, L.V. Hedges, How to do a systematic review: a best practice guide for conducting and reporting narrative reviews, meta-analyses, and meta-syntheses, Annu. Rev. Psychol. 70 (2019) 747–770.

[72] H. Cooper, L.V. Hedges, J.C. Valentine, The Handbook of Research Synthesis and Meta-Analysis, Russell Sage Foundation, 2019.

[73] F. Faul, E. Erdfelder, A. Buchner, A.-G. Lang, Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses, Behav. Res. Methods 41 (4) (2009) 1149–1160, Nov, https://doi.org/10.3758/BRM.41.4.1149.

[74] M.B. Nuijten, J.R. Polanin, 'statcheck': automatically detect statistical reporting inconsistencies to increase reproducibility of meta-analyses, Res. Synth. Methods 11 (5) (2020) 574–579, https://doi.org/10.1002/jrsm.1408.

[75] S. Duval, R. Tweedie, Trim and fill: a simple funnel-plot–based method of testing and adjusting for publication bias in meta-analysis, Biometrics 56 (2) (2000) 455–463, https://doi.org/10.1111/j.0006-341X.2000.00455.x.

[76] R.C.M. van Aert, J.M. Wicherts, M.A.L.M. van Assen, Conducting meta-analyses based on p values: reservations and recommendations for applying p-uniform and p-curve, Perspect. Psychol. Sci. 11 (5) (Sep. 2016) 713–729, https://doi.org/10.1177/1745691616650874.

[77] J. Langevin, Longitudinal dataset of human-building interactions in U.S. offices, Sci. Data 6 (1) (Nov. 2019) 288, https://doi.org/10.1038/s41597-019-0273-5.

[78] M. Schweiker, et al., The Scales Project, a cross-national dataset on the interpretation of thermal perception scales, Sci. Data 6 (1) (Nov. 2019) 289, https://doi.org/10.1038/s41597-019-0272-6.

[79] T.D. Sterling, Publication decisions and their possible effects on inferences drawn from tests of significance–or vice versa, J. Am. Stat. Assoc. 54 (285) (1959) 30–34, https://doi.org/10.2307/2282137.

[80] J.D. Perezgonzalez, Fisher, Neyman-Pearson or NHST? A tutorial for teaching data testing, Front. Psychol. 6 (2015). Accessed: Apr. 28, 2022. [Online]. Available: https://www.frontiersin.org/article/10.3389/fpsyg.2015.00223.

[81] M.S. Andargie, E. Azar, An applied framework to evaluate the impact of indoor office environmental factors on occupants' comfort and working conditions, Sustain. Cities Soc. 46 (Apr. 2019) 101447, https://doi.org/10.1016/j.scs.2019.101447.

[82] I. Balazova, G. Clausen, D.P. Wyon, The Influence of Exposure to Multiple Indoor Environmental Parameters on Human Perception, Performance and Motivation, 2007, p. 8.

[83] M.C. Lee, K.W. Mui, L.T. Wong, W.Y. Chan, E.W.M. Lee, C.T. Cheung, Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms, Build. Environ. 49 (Mar. 2012) 238–244, https://doi.org/10.1016/j.buildenv.2011.10.001.

[84] D. Tiller, L. Wang, A. Musser, M. Radik, AB-10-017: Combined Effects of Noise and Temperature on Human Comfort and Performance (1128-RP), Archit. Eng. – Fac. Publ., Jan. 2010 [Online]. Available: https://digitalcommons.unl.edu/archengfacpub/40.

[85] T. Wittersch, D.P. Wyon, G. Clausen, The effects of moderate heat stress and open-plan office noise distraction on SBS symptoms and on the performance of office work, Indoor Air 14 (s8) (Dec. 2004) 30–40, https://doi.org/10.1111/j.1600-0668.2004.00305.x.

[86] I. Knez, S. Hygge, Irrelevant speech and indoor lighting: effects on cognitive performance and self-reported affect, Appl. Cogn. Psychol. 16 (6) (2002) 709–718, https://doi.org/10.1002/acp.829.

[87] L. Mølhave, Z. Liu, A.H. Jørgensen, O.F. Pedersen, S.K. Kjægaard, Sensory and physiological effects on humans of combined exposures to air temperatures and volatile organic Compounds, Indoor Air 3 (3) (1993) 155–169, https://doi.org/10.1111/j.1600-0668.1993.t01-1-00002.x.

[88] A.K. Melikov, J. Kaczmarczyk, Air movement and perceived air quality, Build. Environ. 47 (Jan. 2012) 400–409, https://doi.org/10.1016/j.buildenv.2011.06.017.

[89] A. Kabanshi, H. Wigö, M.K. van de Poll, P. Ljung, P. Sörqvist, The influence of heat, air jet cooling and noise on performance in classrooms, Int. J. Vent. 14 (3) (Dec. 2015) 321–332, https://doi.org/10.1080/14733315.2015.11684089.

[90] H.E. Kim, H. Tokura, Influence of light intensities on dressing behavior in elderly people, J. Physiol. Anthropol. Appl. Hum. Sci. 19 (1) (2000) 13–19, https://doi.org/10.2114/jpa.19.13.

[91] C. Kim, H. Tokura, Influence of Two Different Light Intensities from 16:00 to 20:30 Hours on Evening Dressing Behavior in the Cold, 2007.

[92] G.M. Huebner, D.T. Shipworth, S. Gauthier, C. Witzel, P. Raynham, W. Chan, Saving energy with light? Experimental studies assessing the impact of colour temperature on thermal comfort, Energy Res. Social Sci. 15 (May 2016) 45–57, https://doi.org/10.1016/j.erss.2016.02.008.

[93] H. Eun Kim, H. Tokura, Influence of different light intensities during the daytime on evening dressing behavior in the cold, Physiol. Behav. 58 (4) (Oct. 1995) 779–783, https://doi.org/10.1016/0031-9384(95)00129-7.

[94] A. Hettiarachchi, R. Emmanuel, Colour as a Psychological Agent to Manipulate Perceived Indoor Thermal Environment for Effective Energy Usage; Cases Implemented in Sri Lanka, 2017, p. 9. Edinburgh.

[95] G. Giakoumis, S. Gauthier, Understanding window behaviour in a mixed-mode buildings and the impact on energy performance, Accessed: Jul. 23, 2020. [Online]. Available: https://eprints.soton.ac.uk/414904/, Sep. 2016.

[96] V. Inkarojrit, Monitoring and modelling of manually-controlled Venetian blinds in private offices: a pilot study, J. Build. Perform. Simul. 1 (2) (Jun. 2008) 75–89, https://doi.org/10.1080/19401490802021012.

[97] B. Jeong, J.-W. Jeong, J.S. Park, Occupant behavior regarding the manual control of windows in residential buildings, Energy Build. 127 (Sep. 2016) 206–216, https://doi.org/10.1016/j.enbuild.2016.05.097.

[98] N. Li, J. Li, R. Fan, H. Jia, Probability of occupant operation of windows during transition seasons in office buildings, Renew. Energy 73 (Jan. 2015) 84–91, https://doi.org/10.1016/j.renene.2014.05.065.

[99] F. Naspi, M. Arnesano, L. Zampetti, F. Stazi, G.M. Revel, M. D'Orazio, Experimental study on occupants' interaction with windows and lights in Mediterranean offices during the non-heating season, Build. Environ. 127 (Jan. 2018) 221–238, https://doi.org/10.1016/j.buildenv.2017.11.009.

[100] J. Park, C.-S. Choi, Modeling occupant behavior of the manual control of windows in residential buildings, Indoor Air 29 (2) (2019) 242–251, https://doi.org/10.1111/ina.12522.

[101] S. Shi, B. Zhao, Occupants' interactions with windows in 8 residential apartments in Beijing and Nanjing, China, Build. Simulat. 9 (2) (Apr. 2016) 221–231, https://doi.org/10.1007/s12273-015-0266-z.

[102] M. Yao, B. Zhao, Window opening behavior of occupants in residential buildings in Beijing, Build. Environ. 124 (Nov. 2017) 441–449, https://doi.org/10.1016/j.buildenv.2017.08.035.

[103] S. Hygge, The interaction of noise and mild heat on cognitive performance and serial reaction time, Environ. Int. 17 (4) (Jan. 1991) 229–234, https://doi.org/10.1016/0160-4120(91)90007-D.

[104] G. Clausen, D.P. Wyon, The combined effects of many different indoor environmental factors on acceptability and office work performance, HVAC R Res. 14 (1) (Jan. 2008) 103–113, https://doi.org/10.1080/10789669.2008.10390996.

[105] W.H. Ko, et al., The impact of a view from a window on thermal comfort, emotion, and cognitive performance, Build. Environ. 175 (May 2020), 106779, https://doi.org/10.1016/j.buildenv.2020.106779.

[106] J.A. Veitch, Office noise and illumination effects on reading comprehension, J. Environ. Psychol. 10 (3) (Sep. 1990) 209–217, https://doi.org/10.1016/S0272-4944(05)80096-9.

[107] A. Liebl, J. Haller, B. Jödicke, H. Baumgartner, S. Schlittmeier, J. Hellbrück, Combined effects of acoustic and visual distraction on cognitive performance and well-being, Appl. Ergon. 43 (2) (Mar. 2012) 424–434, https://doi.org/10.1016/j.apergo.2011.06.017.

[108] A.M. Abbasi, M. Motamedzade, M. Aliabadi, R. Golmohammadi, L. Tapak, Combined effects of noise and air temperature on human neurophysiological responses in a simulated indoor environment, Appl. Ergon. 88 (Oct. 2020) 103189, https://doi.org/10.1016/j.apergo.2020.103189.

[109] R. Andersen, V. Fabi, J. Toftum, S.P. Corgnati, B.W. Olesen, Window opening behaviour modelled from measurements in Danish dwellings, Build. Environ. 69 (Nov. 2013) 101–113, https://doi.org/10.1016/j.buildenv.2013.07.005.

[110] F. Salamone, et al., Evaluation of the visual stimuli on personal thermal comfort perception in real and virtual environments using machine learning approaches, Sensors 20 (6) (1627, Mar) 2020, https://doi.org/10.3390/s20061627.

[111] Z. Pan, S.K. Kjaergaard, L. Mølhave, A chamber-experiment investigation of the interaction between perceptions of noise and odor in humans, Int. Arch. Occup. Environ. Health 76 (8) (Oct. 2003) 598–604, https://doi.org/10.1007/s00420-003-0464-3.

[112] I.S.O. En, EN ISO 2802-2012: Ergonomics of the Physical Environment – Assessment of Environments by Means of an Environmental Survey Involving Physical Measurements of the Environment and Subjective Responses of People, CEN, Brussels, 2012.

[113] I.S.O. En, Ergonomics of the Thermal Environment—Assessment of the Influence of the Thermal Environment Using Subjective Judgement Scales, ISO, 2019. *ISO 10551-2019:*.

[114] C.A. Bennett, P. Rey, What's so hot about red? Hum. Factors 14 (2) (Apr. 1972) 149–154, https://doi.org/10.1177/001872087201400204.

[115] K. Nagano, T. Horikoshi, New Index of Combined Effect of Temperature and Noise on Human Comfort: Summer Experiments on Hot Ambient Temperature and Traffic Noise, 2001.

[116] C.-C. Lin, Effect of noise intensity and illumination intensity on visual performance, Percept. Mot. Skills 119 (2) (Oct. 2014) 441–454, https://doi.org/10.2466/26.24.PMS.119c20z1.

[117] O. Alm, T. Wittersch, G. Clausen, J. Toftum, P.O. Fanger, The impact of human perception of simultaneous exposure to thermal load, low-frequency ventilation noise and indoor air pollution, in: Proc. Of 8th International Conference on Indoor Air Quality and Climate, 1999, pp. 270–275. Accessed: Aug. 14, 2020. [Online]. Available: https://orbit.dtu.dk/en/publications/the-impact-of-human-perception-of-simultaneous-exposure-to-therma.

[118] P.C. Berry, Effect of colored illumination upon perceived temperature, J. Appl. Psychol. 45 (4) (1961) 248.

[119] S. Hygge, I. Knez, Effects of noise, heat and indoor lighting on cognitive performance and self-reported affect, J. Environ. Psychol. 21 (3) (Sep. 2001) 291–299, https://doi.org/10.1006/jevp.2001.0222.

[120] P.M. Bluyssen, D. Zhang, D.H. Kim, A. Eijkelenboom, M. Ortiz-Sanchez, First SenseLab studies with primary school children: exposure to different environmental configurations in the experience room, Intell. Build. Int. (Sep. 2019) 1–18, https://doi.org/10.1080/17508975.2019.1661220, vol. 0, no. 0.

[121] J. Choi, A. Aziz, V. Loftness, Decision support for improving occupant environemntal satisfacton in office buildings: the relationship between sub-set of IEW satisfaction and overall environemntal satisfaction, Proc. Healthy Build. Conf. (2009) 1302–1305.

[122] K. Yamazaki, S. Nomoto, Y. Yokota, T. Murai, The effects of temperature, light, and sound on perceived work environment, Build. Eng. 104 (711) (1998).

[123] L. Fang, G. Clausen, P.O. Fanger, Impact of temperature and humidity on chemical and sensory emissions from building materials, Indoor Air 9 (3) (1999) 193–201, https://doi.org/10.1111/j.1600-0668.1999.t01-1-00006.x.

[124] F. Haldi, D. Robinson, On the unification of thermal perception and adaptive actions, Build. Environ. 45 (11) (2010) 2440–2457, Nov, https://doi.org/10.1016/j.buildenv.2010.05.010.

[125] Y. Geng, W. Ji, B. Lin, Y. Zhu, The impact of thermal environment on occupant IEQ perception and productivity, Build. Environ. 121 (Aug. 2017) 158–167, https://doi.org/10.1016/j.buildenv.2017.05.022.

[126] W. Yang, H.J. Moon, Effects of recorded water sounds on intrusive traffic noise perception under three indoor temperatures, Appl. Acoust. 145 (2019) 234–244.

[127] M.A. Skwarczynski, A.K. Melikov, J. Kaczmarczyk, V. Lyubenova, Impact of individually controlled facially applied air movement on perceived air quality at high humidity, Build. Environ. 45 (10) (Oct. 2010) 2170–2176, https://doi.org/10.1016/j.buildenv.2010.03.017.

[128] G. Chinazzo, J. Wienold, M. Andersen, Daylight affects human thermal perception, Sci. Rep. 9 (1) (Sep. 2019), https://doi.org/10.1038/s41598-019-48963-y. Art. no. 1.

[129] G. Chinazzo, J. Wienold, M. Andersen, Influence of indoor temperature and daylight illuminance on visual perception, Light. Res. Technol. 52 (3) (May 2020) 350–370, https://doi.org/10.1177/1477153519859609.

[130] G. Chinazzo, J. Wienold, M. Andersen, Effect of indoor temperature and glazing with saturated color on visual perception of daylight, Leukos (Mar. 2020) 1–22, https://doi.org/10.1080/15502724.2020.1726182, vol. 0, no. 0.

[131] J. Winzen, F. Albers, C. Marggraf-Micheel, The influence of coloured light in the aircraft cabin on passenger thermal comfort, Light. Res. Technol. 46 (4) (Aug. 2014) 465–475, https://doi.org/10.1177/1477153513484028.

[132] J.Y. Garretón, R. Rodriguez, A. Pattini, Effects of perceived indoor temperature on daylight glare perception, Build. Res. Inf. 44 (8) (Nov. 2016) 907–919, https://doi.org/10.1080/09613218.2016.1103116.

[133] C. Buratti, E. Belloni, F. Merli, P. Ricciardi, A new index combining thermal, acoustic, and visual comfort of moderate environments in temperate climates, Build. Environ. 139 (Jul. 2018) 27–37, https://doi.org/10.1016/j.buildenv.2018.04.038.

[134] C. Laurentin, V. Bermtto, M. Fontoynont, Effect of thermal conditions and light source type on visual comfort appraisal, Light. Res. Technol. 32 (4) (Dec. 2000) 223–233, https://doi.org/10.1177/096032710003200406.

[135] F. Salamone, G. Chinazzo, L. Danza, C. Miller, S. Sibilio, M. Masullo, Low-cost thermohygrometers to assess thermal comfort in the built environment: a laboratory evaluation of their measurement performance, Buildings 12 (5) (May 2022), https://doi.org/10.3390/buildings12050579. Art. no. 5.

[136] I. Golasi, F. Salata, E. de L. Vollaro, A. Peña-García, Influence of lighting colour temperature on indoor thermal perception: a strategy to save energy from the HVAC installations, Energy Build. 185 (Feb. 2019) 112–122, https://doi.org/10.1016/j.enbuild.2018.12.026.

[137] H. Wang, G. Liu, S. Hu, C. Liu, Experimental investigation about thermal effect of colour on thermal sensation and comfort, Energy Build. 173 (Aug. 2018) 710–718, https://doi.org/10.1016/j.enbuild.2018.06.008.

[138] G. Grün, R.T. Hellwig, M. Trimmel, A.H. Holm, Interrelations of Comfort Parameters in a Simulated Aircraft Cabin, 2008.

[139] M. te Kulve, L. Schlangen, W. van M. Lichtenbelt, Interactions between the perception of light and temperature, Indoor Air 28 (6) (2018) 881–891, https://doi.org/10.1111/ina.12500.

[140] C.K.C. Lam, et al., Cross-modal effects of thermal and visual conditions on outdoor thermal and visual comfort perception, Build. Environ. 186 (Dec. 2020) 107297, https://doi.org/10.1016/j.buildenv.2020.107297.

[141] S. Lechner, C. Moosmann, A. Wagner, M. Schweiker, Does thermal control improve visual satisfaction? Interactions between occupants' self-perceived control, visual, thermal, and overall satisfaction, Indoor Air 31 (6) (2021) 2329–2349, https://doi.org/10.1111/ina.12851.

[142] L. Fang, D.P. Wyon, G. Clausen, O. Fanger, Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance, Indoor Air 14 (Suppl 7) (Jan. 2004) 74–81, https://doi.org/10.1111/j.1600-0668.2004.00276.x.

[143] G. Chinazzo, L. Pastore, J. Wienold, M. Andersen, A Field Study Investigation on the Influence of Light Level on Subjective Thermal Perception in Different Seasons, 2018.

[144] T. Liu, C.-C. Lin, K.-C. Huang, Y.-C. Chen, Effects of noise type, noise intensity, and illumination intensity on reading performance, Appl. Acoust. 120 (May 2017) 70–74, https://doi.org/10.1016/j.apacoust.2017.01.019.

[145] Y. Teramoto, et al., Effects of different light intensities during the forenoon on the afternoon thermal sensation in mild cold, J. Therm. Biol. 21 (5) (Oct. 1996) 339–343, https://doi.org/10.1016/S0306-4565(96)00019-8.

[146] H. Tang, Y. Ding, B. Singer, Interactions and comprehensive effect of indoor environmental quality factors on occupant satisfaction, Build. Environ. 167 (Jan. 2020) 106462, https://doi.org/10.1016/j.buildenv.2019.106462.

[147] W. Yang, H.J. Moon, Cross-modal effects of illuminance and room temperature on indoor environmental perception, Build. Environ. 146 (Dec. 2018) 280–288, https://doi.org/10.1016/j.buildenv.2018.10.007.

[148] N.M. Razali, Y.B. Wah, Power comparisons of shapiro-wilk, Kolmogorov-smirnov, lilliefors and anderson-darling tests, J. Stat. Model. Anal. 2 (1) (2011) 21–33.

[149] P.E. Shrout, J.L. Rodgers, Psychology, science, and knowledge construction: broadening perspectives from the replication crisis, Annu. Rev. Psychol. 69 (1) (2018) 487–510, https://doi.org/10.1146/annurev-psych-122216-011845.

[150] N.C. Nelson, J. Chung, K. Ichikawa, M.M. Malik, Psychology exceptionalism and the multiple discovery of the replication crisis, Rev. Gen. Psychol. 26 (2) (Jun. 2022) 184–198, https://doi.org/10.1177/10892680211046508.

[151] F. Romero, Philosophy of science and the replicability crisis, Philos. Compass 14 (11) (2019), e12633, https://doi.org/10.1111/phc3.12633.

[152] E. Rich, A. Miah, Mobile, wearable and ingestible health technologies: towards a critical research agenda, Health Sociol. Rev. 26 (1) (2017) 84–97, https://doi.org/10.1080/14461242.2016.1211486. Gennaio.

[153] D. Sheikh Khan, J. Kolarik, P. Weitzmann, Design and application of occupant voting systems for collecting occupant feedback on indoor environmental quality of buildings – a review, Build. Environ. 183 (Ottobre 2020) 107192, https://doi.org/10.1016/j.buildenv.2020.107192.

[154] T.A. Glass, S.N. Goodman, M.A. Hernán, J.M. Samet, Causal inference in public health, Annu. Rev. Publ. Health 34 (1) (2013) 61–75, https://doi.org/10.1146/annurev-publhealth-031811-124606.

[155] G. Clausen, L. Carrick, P.O. Fanger, S.W. Kim, T. Poulsen, J.H. Rindel, A comparative study of discomfort caused by indoor air pollution, thermal load and noisec, Indoor Air 3 (4) (1993) 255–262, https://doi.org/10.1111/j.1600-0668.1993.00006.x.

[156] L. Danza, L. Belussi, F. Salamone, A multiple linear regression approach to correlate the Indoor Environmental Factors to the global comfort in a Zero-Energy building, E3S Web Conf. 197 (2020), 04002, https://doi.org/10.1051/e3sconf/202019704002.

[157] L.T. Wong, K.W. Mui, P.S. Hui, A multivariate-logistic model for acceptance of indoor environmental quality (IEQ) in offices, Build. Environ. 43 (1) (Jan. 2008) 1–6, https://doi.org/10.1016/j.buildenv.2007.01.001.

[158] L. Huang, Y. Zhu, Q. Ouyang, B. Cao, A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices, Build. Environ. 49 (Mar. 2012) 304–309, https://doi.org/10.1016/j.buildenv.2011.07.022.

[159] L. Danza, et al., A weighting procedure to analyse the indoor environmental quality of a zero-energy building, Build. Environ. 183 (Oct. 2020) 107155, https://doi.org/10.1016/j.buildenv.2020.107155.

[160] A.C.K. Lai, K.W. Mui, L.T. Wong, L.Y. Law, An evaluation model for indoor environmental quality (IEQ) acceptance in residential buildings, Energy Build. 41 (9) (Sep. 2009) 930–936, https://doi.org/10.1016/j.enbuild.2009.03.016.

[161] O. Fanger, N.O. Breum, E. Jerking, Can colour and noise influence man's thermal comfort? Ergonomics 20 (1) (Jan. 1977) 11–18, https://doi.org/10.1080/00140137708931596.

[162] W. Yang, H.J. Moon, M.-J. Kim, Combined effects of short-term noise exposure and hygrothermal conditions on indoor environmental perceptions, Indoor Built Environ. 27 (8) (Oct. 2018) 1119–1133, https://doi.org/10.1177/1420326X17703774.

[163] W. Yang, H.J. Moon, Combined effects of sound and illuminance on indoor environmental perception, Appl. Acoust. 141 (Dec. 2018) 136–143, https://doi.org/10.1016/j.apacoust.2018.07.008.

[164] N. Pellerin, V. Candas, Combined effects of temperature and noise on human discomfort, Physiol. Behav. 78 (1) (2003) 99–106.

[165] S. Crosby, A. Rysanek, Correlations between thermal satisfaction and non-thermal conditions of indoor environmental quality: bayesian inference of a field study of offices, J. Build. Eng. (Dec. 2020) 102051, https://doi.org/10.1016/j.jobe.2020.102051.

[166] W. Yang, H.J. Moon, Cross-modal effects of noise and thermal conditions on indoor environmental perception and speech recognition, Appl. Acoust. 141 (2018) 1–8.

[167] Choi Joon-Ho, A. Aziz, and V. Loftness, "Decision support for improving occupant environmental satisfaction in office buildings: the relationship between sub-set of IEQ satisfaction and overall environmental satisfaction.," Presented at the Conference Healthy Buildings, Syracuse, NY USA.

[168] T. Mihai, V. Iordache, Determining the indoor environment quality for an educational building, Energy Proc. 85 (2016) 566–574.

[169] M. Ncube, S. Riffat, Developing an indoor environment quality tool for assessment of mechanically ventilated office buildings in the UK – a preliminary study, Build. Environ. 53 (Jul. 2012) 26–33, https://doi.org/10.1016/j.buildenv.2012.01.003.

[170] B. Cao, Q. Ouyang, Y. Zhu, L. Huang, H. Hu, G. Deng, Development of a multivariate regression model for overall satisfaction in public buildings based on field studies in Beijing and Shanghai, Build. Environ. 47 (Jan. 2012) 394–399, https://doi.org/10.1016/j.buildenv.2011.06.022.

[171] K. Nagano, T. Horikoshi, Development of equi-comfort charts constituted with temperature and noise at 150 and 3 lx, in: Proceedings of Indoor Air, 2014.

[172] W. Yang, M.-J. Kim, H.J. Moon, Effects of indoor temperature and background noise on floor impact noise perception, Indoor Built Environ. 28 (4) (Apr. 2019) 454–469, https://doi.org/10.1177/1420326X17753708.

[173] P.A. Bell, Effects of noise and heat stress on primary and subsidiary task performance, Hum. Factors 20 (6) (Dec. 1978) 749–752, https://doi.org/10.1177/001872087802000614.

[174] N. Pellerin, V. Candas, Effects of steady-state noise and temperature conditions on environmental perception and acceptability, Indoor Air 14 (2) (Apr. 2004) 129–136, https://doi.org/10.1046/j.1600-0668.2003.00221.x.

[175] L. Lan, P. Wargocki, D.P. Wyon, Z. Lian, Effects of thermal discomfort in an office on perceived air quality, SBS symptoms, physiological responses, and human performance, Indoor Air 21 (5) (2011) 376–390.

[176] N. Matsubara, A. Gassho, Y. Kurazumi, Facilitatory effects of environmental sounds on hue-heat phenomena, in: 18th Int. Congr. Acoust, vol. 2, 2004, pp. 1775–1778.

[177] Y. Geng, J. Yu, B. Lin, Z. Wang, Y. Huang, Impact of individual IEQ factors on passengers' overall satisfaction in Chinese airport terminals, Build. Environ. 112 (Feb. 2017) 241–249, https://doi.org/10.1016/j.buildenv.2016.11.040.

[178] L. Fang, G. Clausen, P.O. Fanger, Impact of temperature and humidity on perception of indoor air quality during immediate and longer whole-body exposures, Indoor Air 8 (4) (1998) 276–284, https://doi.org/10.1111/j.1600-0668.1998.00008.x.

[179] L. Fang, G. Clausen, P.O. Fanger, Impact of temperature and humidity on the perception of indoor air quality, Indoor Air 8 (2) (1998) 80–90, https://doi.org/10.1111/j.1600-0668.1998.t01-2-00003.x.

[180] F. Albers, J. Maier, C. Marggraf-Micheel, In search of evidence for the hue-heat hypothesis in the aircraft cabin, Light. Res. Technol. 47 (4) (2015) 483–494.

[181] A.J. Xu, A.A. Labroo, Incandescent affect: turning on the hot emotional system with bright light, J. Consum. Psychol. 24 (2) (Apr. 2014) 207–216, https://doi.org/10.1016/j.jcps.2013.12.007.

[182] H. Nakamura, M. Oki, Influence of air temperature on preference for color temperature of general lighting in the room, 人間-生活環境系学会英文誌 4 (1) (2000) 41–47, https://doi.org/10.1618/jhes.4.41.

[183] H. Ma, W. Nie, Influence of visual factors on noise annoyance evaluation caused by road traffic noise in indoor environment, in: INTER-NOISE and NOISE-CON Congress and Conference Proceedings, vol. 249, 2014, pp. 6308–6315, no. 1.

[184] E.C. Poulton, R.S. Edwards, Interactions and range effects in experiments on pairs of stresses: mild heat and low-frequency noise, J. Exp. Psychol. 102 (4) (1974) 621–628, https://doi.org/10.1037/h0036319.

[185] S. Gauthier, B. Liu, G. Huebner, D. Shipworth, Investigating the effect of CO2 concentration on reported thermal comfort, in: Proceedings of CISBAT 2015 International Conference on Future Buildings and Districts - Sustainability from Nano to Urban Scale -, vol. I, Sep. 2015, pp. 315–320 [Online]. Available: https://eprints.soton.ac.uk/381850/. (Accessed 23 July 2020).

[186] H. Wu, X. Sun, Y. Wu, Investigation of the relationships between thermal, acoustic, illuminous environments and human perceptions, J. Build. Eng. 32 (Nov. 2020) 101839, https://doi.org/10.1016/j.jobe.2020.101839.

[187] Y.T. Jiang, C.Z. Yang, Investigation of the subjective evaluation of indoor illumination level on perceived air quality, Proc. ISHVAC 2 (2011) 453–458.

[188] M. te Kulve, L. Schellen, L. Schlangen, A.J.H. Frijns, W.D. van Marken Lichtenbelt, Light intensity and thermal responses, in: Making Comfort Relevant: Proceedings of 9th Windsor Conference, 2016, pp. 1–8.

[189] F. Fassio, A. Fanchiotti, R.D.L. Vollaro, Linear, non-linear and alternative algorithms in the correlation of IEQ factors with global comfort: a case study, Sustainability 6 (11) (Nov. 2014), https://doi.org/10.3390/su6118113. Art. no. 11.

[190] K. Nagano, T. Horikoshi, New comfort index during combined conditions of moderate low ambient temperature and traffic noise, Energy Build. 37 (3) (Mar. 2005) 287–294, https://doi.org/10.1016/j.enbuild.2004.08.001.

[191] J. Kim, R. de Dear, Nonlinear relationships between individual IEQ factors and overall workspace satisfaction, Build. Environ. 49 (Mar. 2012) 33–40, https://doi.org/10.1016/j.buildenv.2011.09.022.

[192] J. Toftum, A. Thorseth, J. Markvart, Á. Logadóttir, Occupant response to different correlated colour temperatures of white LED lighting, Build. Environ. 143 (Oct. 2018) 258–268, https://doi.org/10.1016/j.buildenv.2018.07.013.

[193] L. Bellia, F.R. d'Ambrosio Alfano, F. Fragliasso, B.I. Palella, G. Riccio, On the interaction between lighting and thermal comfort: an integrated approach to IEQ, Energy Build. 231 (Jan. 2021) 110570, https://doi.org/10.1016/j.enbuild.2020.110570.

[194] L.G. Berglund, W.S. Cain, Perceived air quality and the thermal environment, in: Proceedings of IAQ, vol. 89, 1989, pp. 93–99.

[195] Y. Sakurai, T. Noguchi, G. Horie, N. Matsubara, Quantification of the synthesized evaluation of the combined environment, Energy Build. 14 (3) (1990) 169–173.

[196] J. Varjo, V. Hongisto, A. Haapakangas, H. Maula, H. Koskela, J. Hyönä, Simultaneous effects of irrelevant speech, temperature and ventilation rate on performance and satisfaction in open-plan offices, J. Environ. Psychol. 44 (Dec. 2015) 16–33, https://doi.org/10.1016/j.jenvp.2015.08.001.

[197] Z. Tu, S. Geng, Y. Li, Study on human responses under different CO2 concentration and illuminance in underground refuge chamber, IOP Conf. Ser. Earth Environ. Sci. 510 (Jul. 2020), 052026, https://doi.org/10.1088/1755-1315/510/5/052026.

[198] G. Clausen and D. Wyon, "The combined effects of many different indoor environmental factors on acceptability and office work performance," in Proc of Indoor Air 2005, vol. 2005, pp. 351–356.

[199] S.K. Bhattacharya, S.R. Tripathi, S.K. Kashyap, The combined effects of noise and illumination on the performance efficiency of visual search and neuromotor task components, J. Hum. Ergol. 18 (1) (1989) 41–51, https://doi.org/10.11183/jhe1972.18.41.

[200] L. Pronk, "The combined effects of temperature, background noise and lighting on the non-physical task performance of university students," p. 209.

[201] R.R. Baniya, E. Tetri, J. Virtanen, L. Halonen, The effect of correlated colour temperature of lighting on thermal sensation and thermal comfort in a simulated indoor workplace, Indoor Built Environ. 27 (3) (Mar. 2018) 308–316, https://doi.org/10.1177/1420326X16673214.

[202] J. Winzen, F. Albers, C. Marggraf-Micheel, The influence of coloured light in the aircraft cabin on passenger thermal comfort, Light. Res. Technol. Lond. 46 (4) (Aug. 2014) 465–475, https://doi.org/10.1177/1477153513484028.

[203] H. Azmoon, H. Dehghan, J. Akbari, S. Souri, The relationship between thermal comfort and light intensity with sleep quality and eye tiredness in shift work nurses, J. Environ. Public Health 2013 (Feb. 2013), e639184, https://doi.org/10.1155/2013/639184.

[204] J. Toftum, A.S. Jørgensen, P.O. Fanger, Upper limits of air humidity for preventing warm respiratory discomfort, Energy Build. 28 (1) (Aug. 1998) 15–23, https://doi.org/10.1016/S0378-7788(97)00018-2.

[205] W.S. Cain, et al., Ventilation requirements in buildings—I. Control of occupancy odor and tobacco smoke odor, Atmos. Environ. 17 (6) (Jan. 1983) 1183–1197, https://doi.org/10.1016/0004-6981(83)90341-4, 1967.

[206] D. Blackenberger, K.V.D. Wymelenberg, J. Stenson, Visual Effects of Wood on Thermal Perception of Interior Environments, ARCC Conf. Repos., May 2019.

Accessed: Nov. 30, 2020. [Online]. Available: https://www.arcc-journal.org/index.php/repository/article/view/619.

[207] R.D. Pepler, Warmth, glare and a background of quiet speech: a comparison of their effects on performance, Ergonomics 3 (1) (1960) 68–73.

[208] V. Roussarie, E. Siekierski, S. Viollon, and S. Ségrétain, and S. Bojago, "What's So Hot about Sound? – Influence of HVAC Sounds on Thermal Comfort," p. 11.

[209] G. Newsham, et al., Control strategies for lighting and ventilation in offices: effects on energy and occupants, Intell. Build. Int. 1 (2) (Feb. 2009) 101–121, https://doi.org/10.3763/inbi.2009.0004.

[210] K. Ishibashi, S. Arikura, T. Kozaki, S. Higuchi, A. Yasukouchi, Thermoregulatory effect in humans of suppressed endogenous melatonin by pre-sleep bright-light exposure in a cold environment, Chronobiol. Int. 27 (4) (May 2010) 782–806, https://doi.org/10.3109/07420521003794069.

[211] S. Lamb, K.C.S. Kwok, A longitudinal investigation of work environment stressors on the performance and wellbeing of office workers, Appl. Ergon. 52 (Jan. 2016) 104–111, https://doi.org/10.1016/j.apergo.2015.07.010.

[212] A. Astolfi, F. Pellerey, Subjective and objective assessment of acoustical and overall environmental quality in secondary school classrooms, J. Acoust. Soc. Am. 123 (1) (Jan. 2008) 163–173, https://doi.org/10.1121/1.2816563.

[213] N.D. Dahlan, Perceptive-cognitive aspects investigation in relation to indoor environment satisfaction collected from naturally ventilated multi-storey student accommodations in Malaysia, Indoor Built Environ. 24 (1) (Feb. 2015) 116–127, https://doi.org/10.1177/1420326X13506449.

[214] M. Frontczak, R.V. Andersen, P. Wargocki, Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing, Build. Environ. 50 (Apr. 2012) 56–64, https://doi.org/10.1016/j.buildenv.2011.10.012.

[215] M.A. Humphreys, Quantifying occupant comfort: are combined indices of the indoor environment practicable? Build. Res. Inf. 33 (4) (2005) 317–325, https://doi.org/10.1080/09613210500161950.

[216] F. Martellotta, A. Simone, S. Della Crociata, M. D'Alba, Global comfort and indoor environment quality attributes for workers of a hypermarket in Southern Italy, Build. Environ. 95 (Jan. 2016) 355–364, https://doi.org/10.1016/j.buildenv.2015.09.029.

[217] P.S. Nimlyat, Indoor environmental quality performance and occupants' satisfaction [IEQPOS] as assessment criteria for green healthcare building rating, Build. Environ. 144 (Oct. 2018) 598–610, https://doi.org/10.1016/j.buildenv.2018.09.003.

[218] R.M. Reffat, E.L. Harkness, Environmental comfort criteria: weighting and integration, J. Perform. Constr. Facil. 15 (3) (Aug. 2001) 104–108, https://doi.org/10.1061/(ASCE)0887-3828(2001)15:3(104).

[219] C.-M. Chiang, C.-M. Lai, A study on the comprehensive indicator of indoor environment assessment for occupants' health in Taiwan, Build. Environ. 37 (4) (2002) 387–392.

[220] S.C. Sekhar, S.E. Goh, Thermal comfort and IAQ characteristics of naturally/mechanically ventilated and air-conditioned bedrooms in a hot and humid climate, Build. Environ. 46 (10) (Oct. 2011) 1905–1916, https://doi.org/10.1016/j.buildenv.2011.03.012.

[221] A. Jamrozik, et al., A novel methodology to realistically monitor office occupant reactions and environmental conditions using a living lab, Build. Environ. 130 (Feb. 2018) 190–199, https://doi.org/10.1016/j.buildenv.2017.12.024.

[222] G. Ozcelik, B. Becerik-Gerber, R. Chugh, Understanding human-building interactions under multimodal discomfort, Build. Environ. 151 (Mar. 2019) 280–290, https://doi.org/10.1016/j.buildenv.2018.12.046.

[223] G. Chinazzo, K. Chamilothori, J. Wienold, M. Andersen, Temperature–color interaction: subjective indoor environmental perception and physiological responses in virtual reality, Hum. Factors (Jan. 2020), https://doi.org/10.1177/0018720819892383, 0018720819892383.