Quality criteria for multi-domain studies in the indoor environment: Critical review towards research guidelines and recommendations

A framework for multi-domain human studies in the indoor environment

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Abstract

Building occupants are simultaneously exposed to multiple environmental stimuli, i.e., visual, thermal, acoustic, and air quality, whose combination and interaction influence human perception, physiology, behavior, and performance. The literature on multi-domain studies is extensive, but presents heterogeneous methodological approaches or inconsistent study reporting, which hinders direct comparison between studies or meta-analyses. This paper defines a framework for designing, deploying, and reporting future multi-domain studies aiming to unravel the effects of multiple indoor environmental stimuli on human responses. Through the review and analysis of past investigations on the topic and the definition of a framework, this study identifies several shortcomings in the design, deployment, and documentation of multi-domain studies and defines which aspects should be considered and included in future investigations. The lack of key information can explain the inconsistent results found in the literature and the inability to conduct meta-analyses comprehensively and adequately. The adoption of the framework and the best practices reported in this paper is expected to foster future studies on the topic and their meta-analyses. Although the present work focuses on environmental stimuli, its application can be extended to personal and contextual aspects that can be considered additional domains influencing human responses. The ultimate goal is to consolidate our knowledge on multi-domain effects on human responses for its integration into standards and guidelines.

Keywords: IEQ; Human Comfort; Combined effects; Cross-modal effects; Transparent reporting; Research quality assurance

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 study 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., [20], [21]), and provide comfort requirements for temperature, light, noise and air quality separately. Consequently, buildings and current technologies devoted to control 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 & Gelder [31], while anthropological and architectural approaches 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 human senses are equally involved (think of a visual acuity test such as 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, 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., [46]).

To address this need, the present work reviews previous studies on human response to multi-domain stimuli with the aim of identifying the key aspects that should be considered when designing, conducting, and reporting these studies. Based on the review, a framework encompassing these key aspects is proposed for studies investigating the effects of multiple indoor environmental stimuli on human responses. It is necessary to highlight that this work reviews existing multi-domain investigations for the purpose of developing a framework and not for conducting a meta-analysis of previous 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 developed framework will 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 research framework analysis is described, through the review of (1) study categorization (type of effect, study type, frequency of effect and study type), (2) study set-up (dependent and independent variables, hypothesis, setting features, exposure features, experimental design quality), (3) study deployment and analysis (data collection and processing, participants, data analysis), (4) study outcome (reporting results, study discussion and conclusion) (see details in Figure 1). Finally, the results on the analysis are summarized and future directions are highlighted.

2 Methods

Two steps are introduced and followed for the definition of the framework: (i) multi-domain studies selection, (ii) framework setup and definitions based on the content of the selected studies. The two steps are detailed in Subsections 2.1 and 2.2, respectively, and constitute the setup for the analysis of past multi-domain studies conducted in Section 3. This latter section dissects each aspect of the proposed framework analyzing whether and how it is considered and reported in past studies.

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 is 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 are included in the analysis. Three main criteria are used in the paper selection, namely the selection of studies: (i) involving the response of people (i.e., no simulations, no physical measurements only); (ii) focusing on perception, behavior, and/or performance (i.e., not on physiology only); and (iii) having 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 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 Framework aspects for multi-domain studies

The selected studies are reviewed to identify the main aspects that allow understanding the investigations' goal, method, and results. These obtained aspects are categorized into four main groups (i.e., categorization, set-up, deployment and analysis, and outcome) and constitute the framework for multi-domain studies. The framework and its constituting aspects are shown in Figure 1 and detailed in the following section.

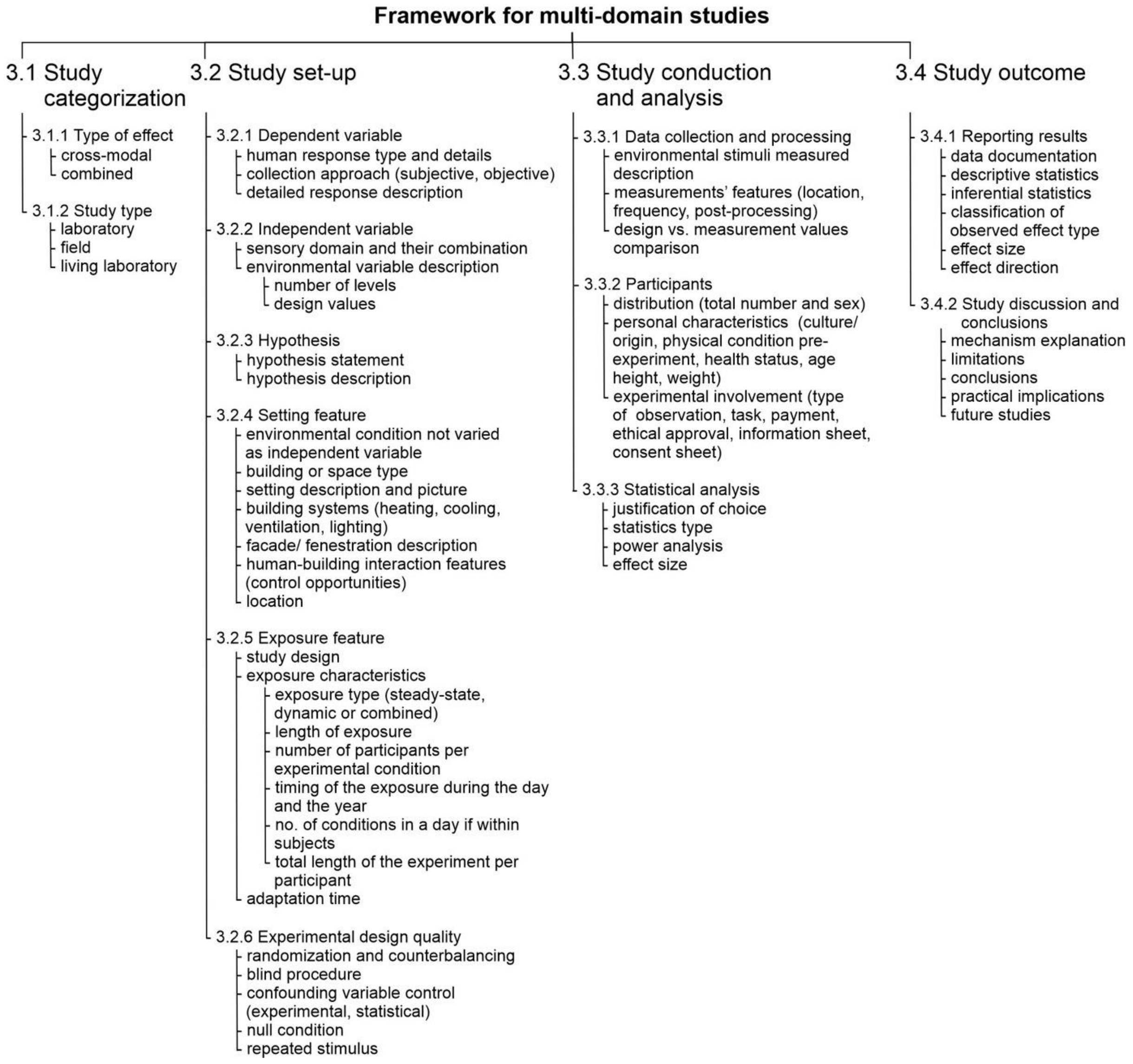

Figure 1: Framework for multi-domain studies defining the aspects to be considered when designing, deploying, and reporting multi-domain investigations.

3 Research framework analysis

The following sections describe and analyze the aspects defined in the proposed framework (Figure 1) based on the content of the considered multi-domain studies. Each section presents a transversal analysis of the percentage of studies reporting the specific framework aspect. Each aspect, in fact, is reported in at least some studies but rarely in all studies. Some aspects are common to all experimental investigations, while others are specific to multi-domain studies. However, in this research, all aspects are reported and analyzed in the same way to guide future researchers on what to consider while designing, deploying, and reporting multi-domain investigations.

3.1 Study categorization

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

3.1.1 Types of effects

Two types of effects are considered in this research, 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 Figure 2 for a graphical representation of the cross-modal effects. This further sub-categorization is reported to provide a complete framework, but it is not used to analyze the results of the reviewed literature. However, the authors believe that a comprehensive description of the type of effects could benefit the reporting and interpretation of future multi-domain studies.

Figure 2 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.

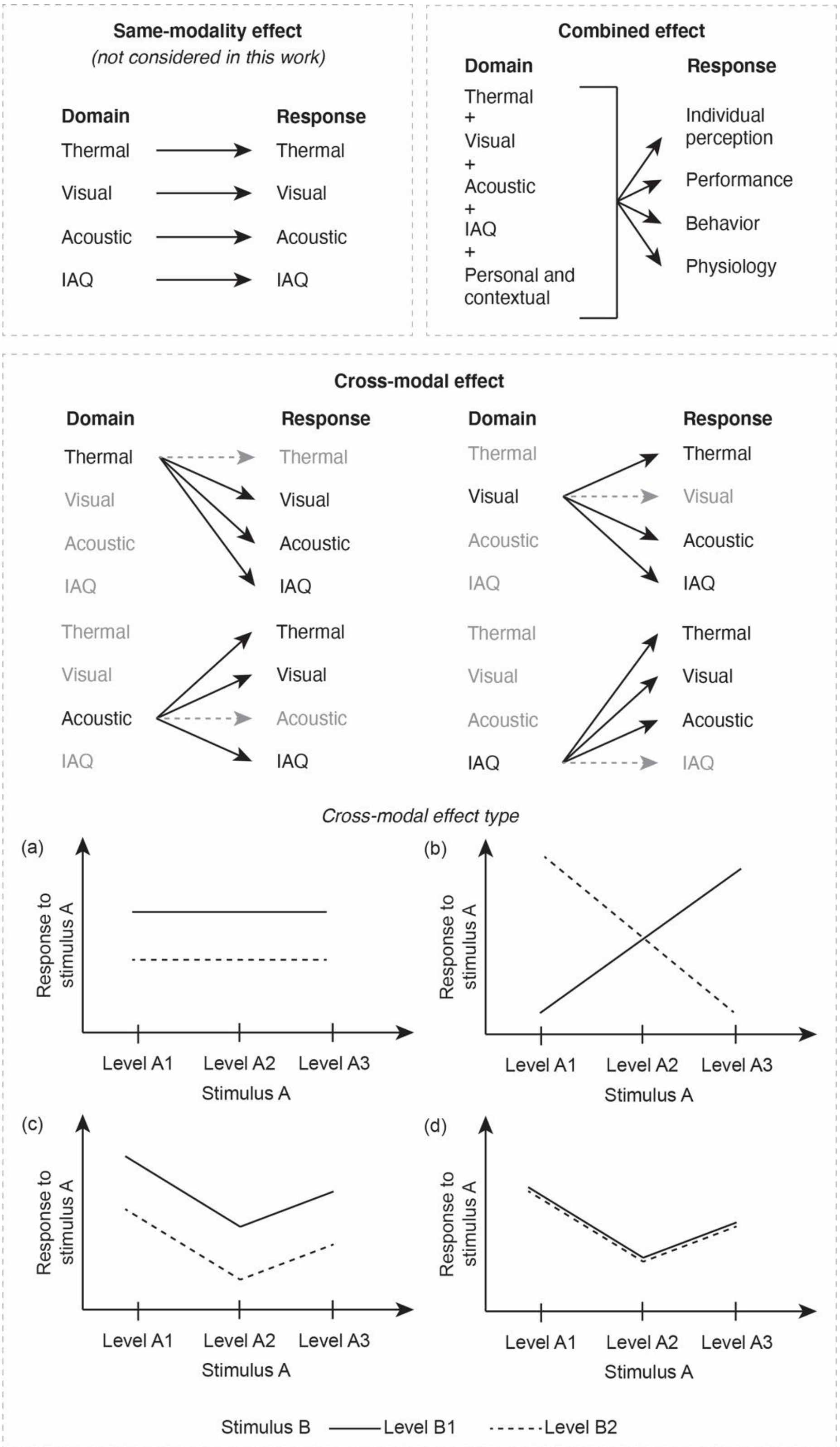

Figure 2: Schematic description of the type of effect: cross-modal, combined and same-modality effects. Bottom: Graphic representation of the types of cross-modal effects between two stimuli. a) Cross-modal <u>main</u> effect of stimulus B and no effect of stimulus A; b) cross-modal <u>main</u> effect 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].

Beside the type of cross-modal effect, it is possible to indicate the "direction" (i.e., positive, negative or no effect). Figure 3 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 Figure 3 a and b), positive effect (i.e., weaken a negative or strengthen a positive response of stimulus A alone as in Figure 3 d and e) or no effect (i.e., response to stimulus A is not affected by the presence of stimulus B as in Figure 3c) on the response to stimulus A.

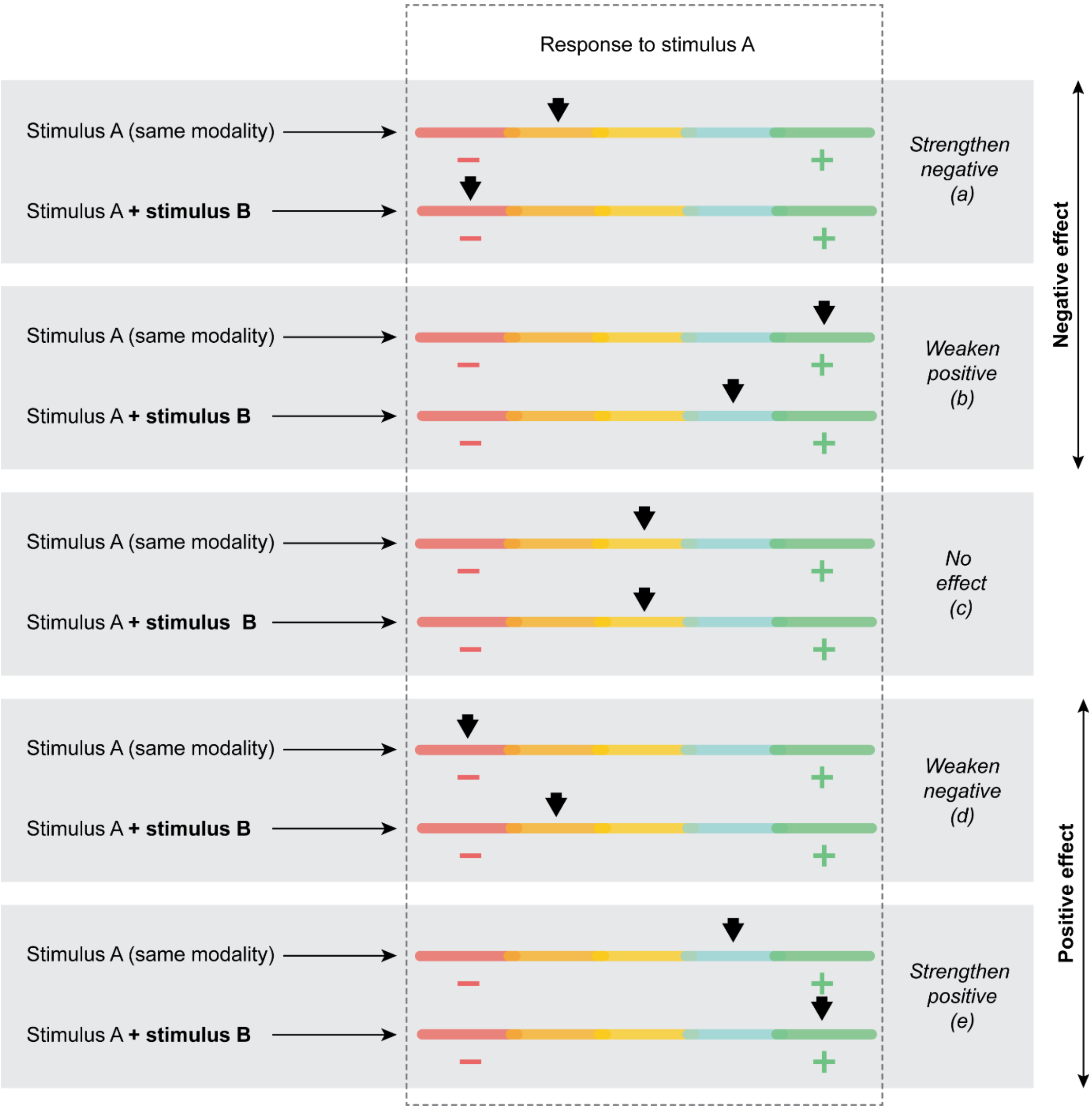

Figure 3: Schematic example of cross-modal effects of stimulus B on the response to stimulus A and the resulting effect directions.

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. 10]. Figure 4 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).

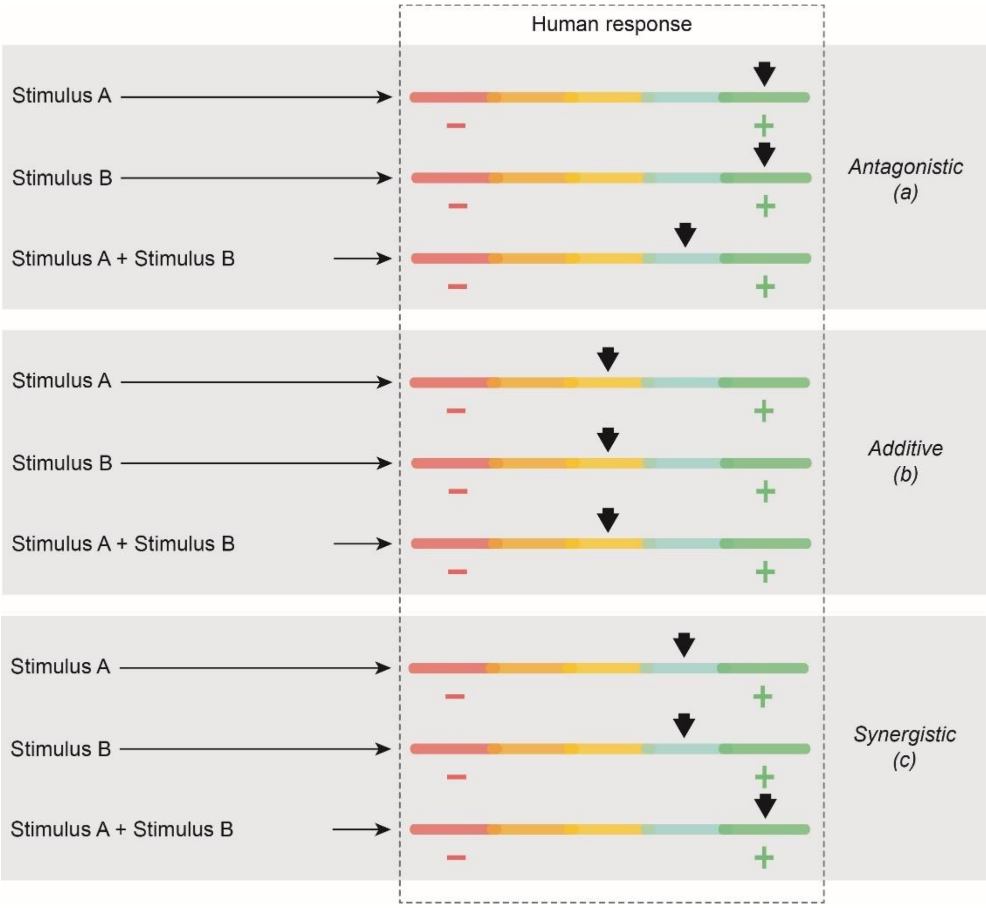

Figure 4: Schematic example of combined effects of stimuli A and B on human response and the resulting effect description.

3.1.2 Study types

The distinction between effect type is particularly important when analyzing the dependent and independent variables of a study. For the other aspects of the framework, however, the effect type is less relevant, and the distinction between the study type becomes more important. The study types considered in the analysis are describes as follows: (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 (Pisello et al. (Energy research and social science, under review)) is a study type not used in the considered papers.

3.1.3 Frequencies of effect and study types

Table 1 summarizes the distribution of the analyzed studies according to the effect type and study type. Lab studies outnumbered field studies, while the distribution of effect types was rather uniform across cross-modal and combined effects. Some studies reported both cross-modal and combined effect types, in the great majority of the cases when they were lab investigations. 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.

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

<table>
<tr><td></td><td></td><td colspan="3">Effect type</td><td rowspan="2">Total</td></tr>
<tr><td></td><td></td><td>Cross-modal</td><td>Combined</td><td>Combined and cross-modal</td></tr>
<tr><td rowspan="2">Study type</td><td>Lab</td><td>36%</td><td>17%</td><td>23%</td><td>76%</td></tr>
<tr><td>Field</td><td>4%</td><td>19%</td><td>1%</td><td>24%</td></tr>
<tr><td colspan="2">Total</td><td>40%</td><td>36%</td><td>24%</td><td>100%</td></tr>
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3.2 Study set-up

3.2.1 Dependent variable: human responses

The dependent variables in multi-domain studies refer to the different human responses that can be captured in experimental or observational settings. Figure 5 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).

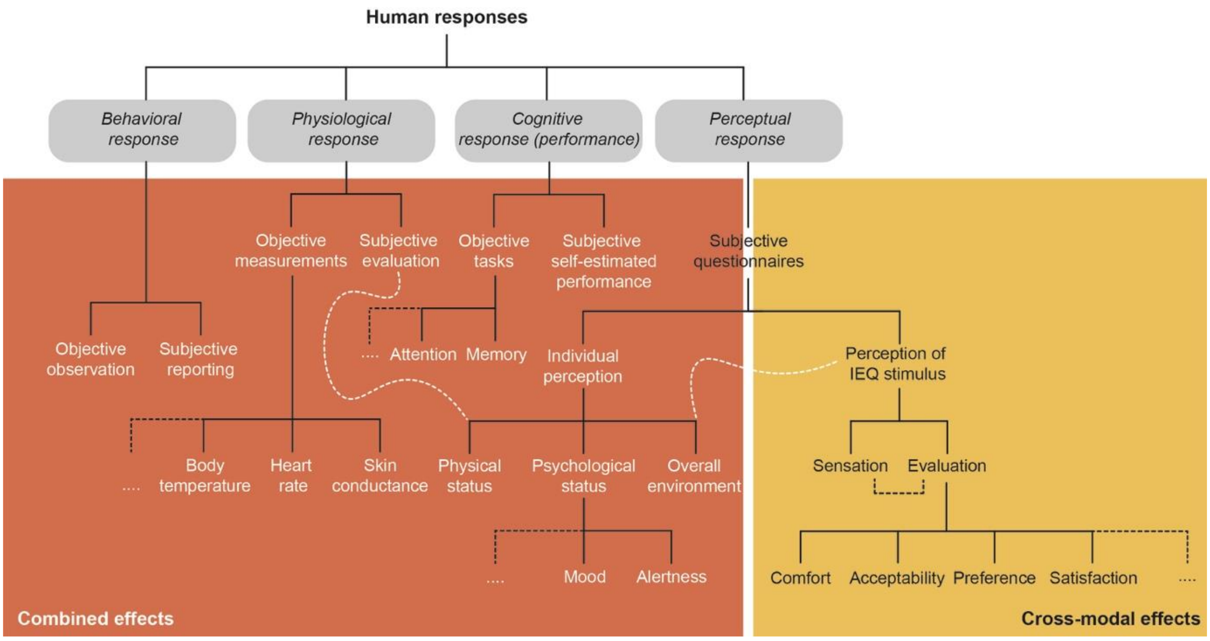

Figure 5: Schematic representation of the type of human responses that can be collected in studies investigating cross-modal or combined effects.

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). Besides a clear description of the human response type considered, studies should clearly report how these responses are gathered by specifying the method(s) of assessment and the adopted tools (e.g., questionnaire for perception responses, type of test for performance responses, sensing technology for behavior and physiology 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 analog (VAS), categorical scale combined with VAS (graphic CS), semantic differential, or dichotomous. To get comparable data and results, an 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. In this view, it is essential to report the original text of the adopted questionnaire, preferably both in the original and English language.

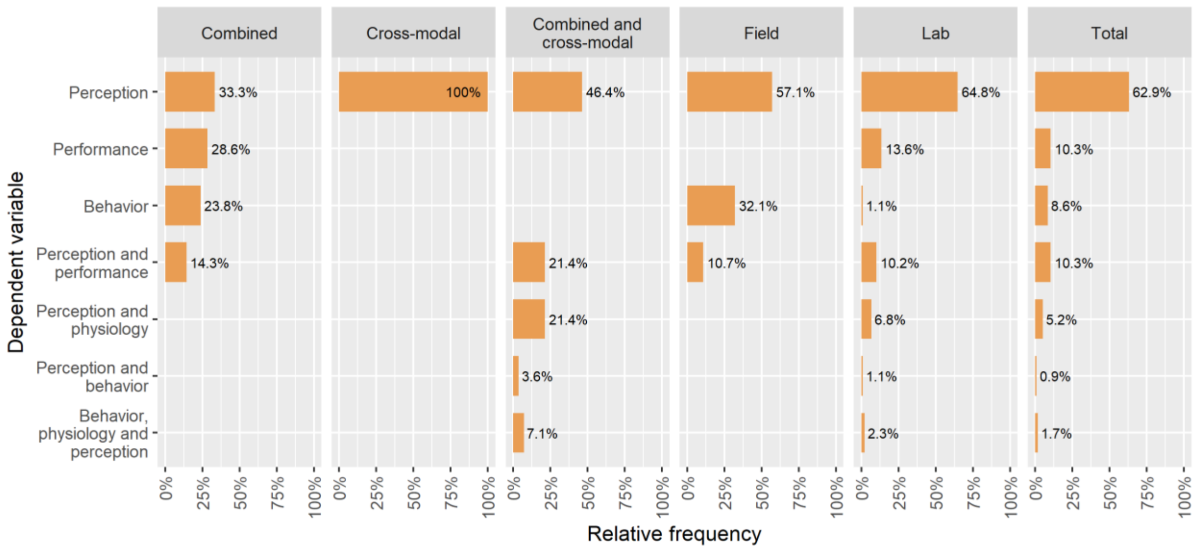

Figure 6: Distribution of human response types in multi-domain studies according to the type of effect (combined, cross-modal) and the study type (field or lab).

Figure 6, summarizing the distribution of human response types investigated in the considered multi-domain studies, shows that most of the studies investigated perceptual responses. Most of the time, perceptual responses were the only human responses considered in the study, and only in some studies human responses were considered in combination with performance (e.g., [50]–[54]), physiology (e.g., [55]–[57]), or behavior [58]–[60]. 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 selection of the papers considered in this research, although it included physiological responses in combination with other human responses only. Physiological responses were collected only in lab studies and never in field investigations. 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 [59]–[63]. Behavioral investigations in field studies were based on the collection of data on windows and blinds operations [64]–[71], thermostat setpoints [50] and ventilation speed settings [63]. Perception responses were equally collected in both lab and field studies.

When observing the distribution of 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 by submitting 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 [72]–[75]., the associated response time [53], [76], or both [77]. The subjective assessment of the performance was conducted through questionnaires [50]–[52], [78].

Methods for the objective evaluation of human behavior relied upon the experimenter's observations of subjects' clothing adaptation throughout the test (e.g., number of clothing items put on/off) [61], sensors to assess windows and blinds state [71], or equipment settings (e.g., selected fan speed level) [63]. Information on windows state was also commonly collected through physical measurements by means of sensors, especially in long-term field studies [64], [66], [70], [71].

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 [79]) were more rarely included in multi-domain studies [77], [80]. The subjective approach to collect physiological observations focused on direct questions about subjects' perception of health symptoms (e.g., eye irritation, throat irritation, and skin dryness) via questionnaires [56], [57], [81].

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 (which can be ordinal, nominal, interval, or ratio), 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 recognized, most probably due to the reference to standards related to human perception investigation through questionnaires [21], [82], [83]. It must be noted that sometimes, despite the same assessment category being evaluated (e.g., thermal sensation) and the same number of response categories being indicated, the used labels can be different [84]. Similarly, visual analogue scales can have different dimensions (e.g., from 0 to 100 or from 0 to 60) [81], [85]. These differences may lead to increased difficulties during results comparison between studies.

3.2.2 Independent variable: combined environmental stimuli

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. Figure 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.

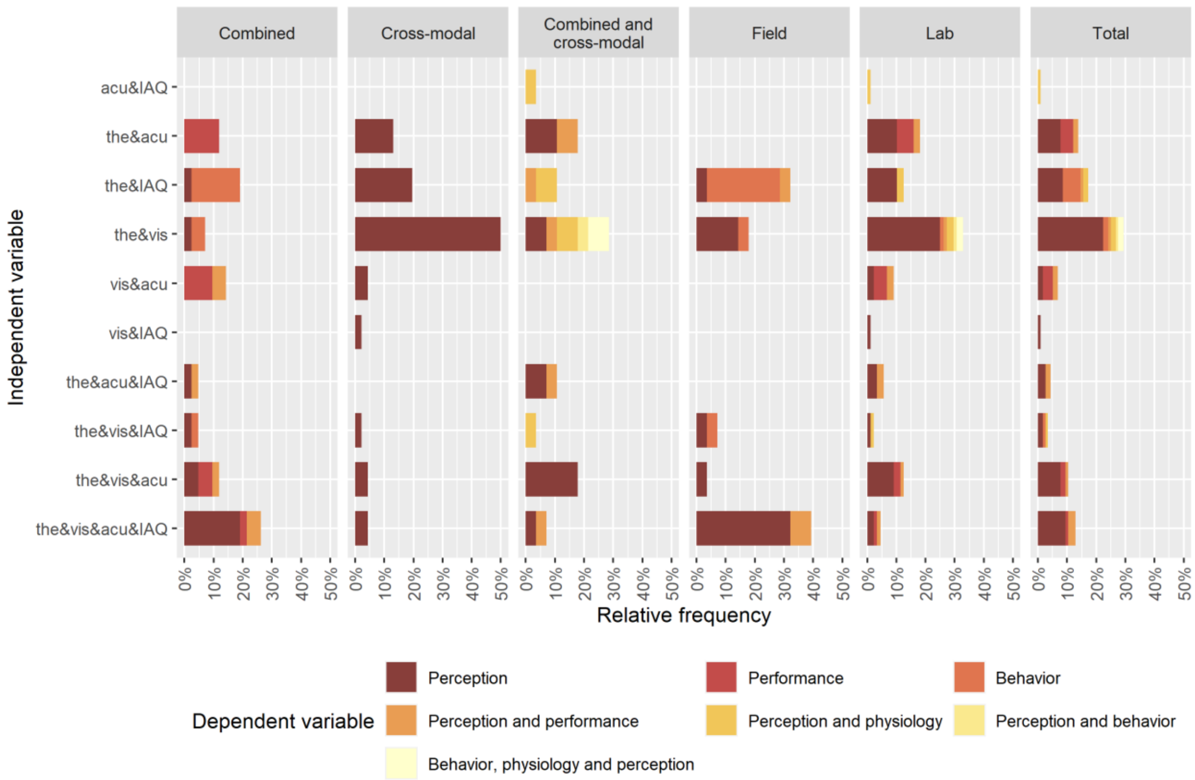

Figure 7: Distribution of independent and dependent variables, according to the type of effect (combined, cross-modal), study type (lab, field) in the reviewed papers. Acu = Acoustics; IAQ = Indoor Air Quality; The = Thermal; Vis = Visual.

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., [86]), 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 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.

The remainder of this subsection reports the detailed analysis of the independent variables of the considered studies focusing on experimental investigations only. Studies were divided according to the effect investigated, whether cross-modal or combined.

All the reviewed studies reporting experimental investigations about cross-modal effects indicated the type of the 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 did not describe the type (*12%*) and the design values (1*8%*). Figure 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. It can be observed that air temperature, relative humidity, air velocity and Fanger's Predicted Mean Vote (PMV) were the most considered independent variables. This outcome can be expected given the strong interest in thermal studies previously highlighted. For thermal and non-thermal 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. 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.

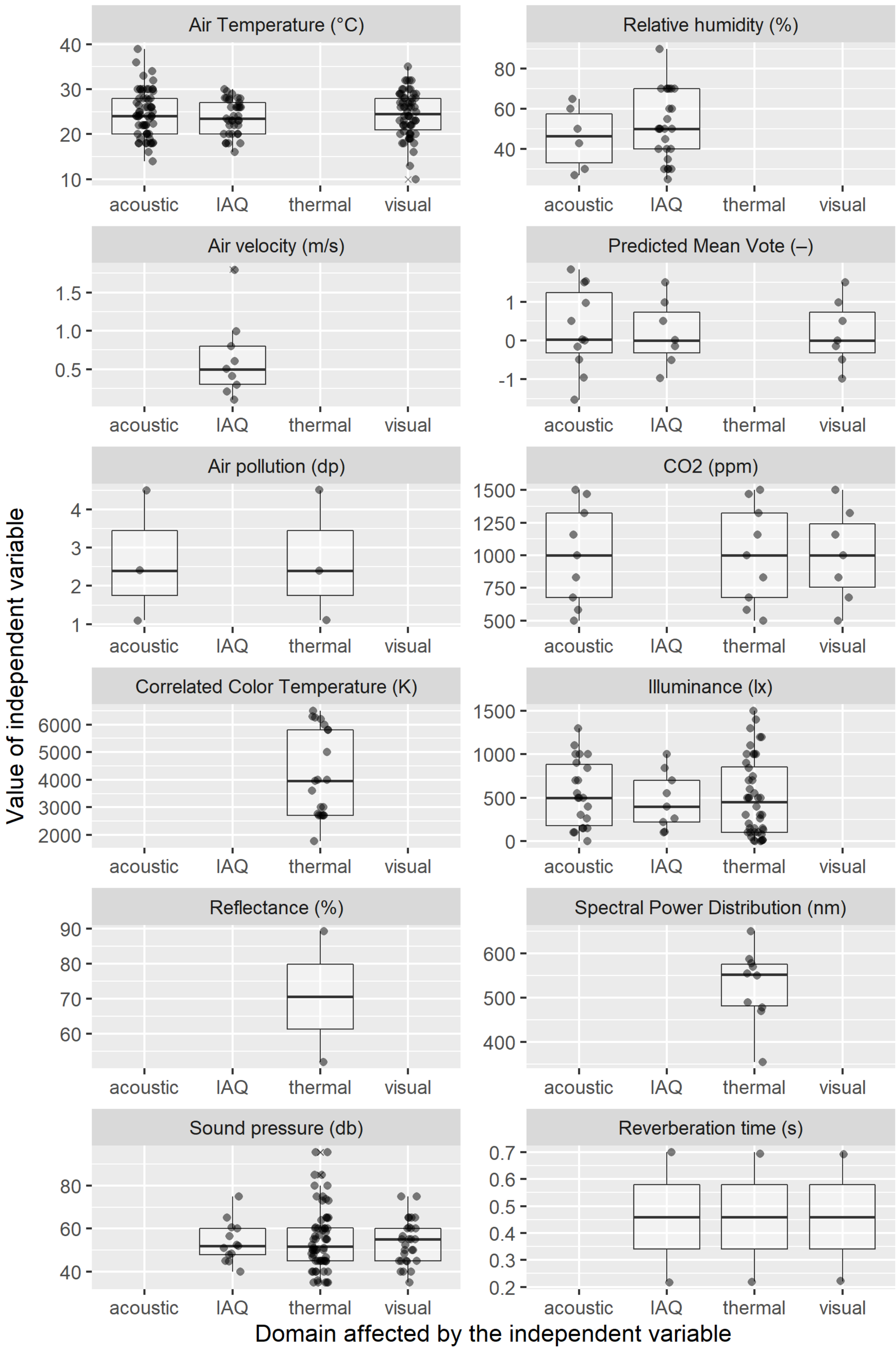

Figure 8: Independent variable values employed in experimental cross-modal investigations, considering the sensory domain on which their effect was tested on (indicated on the x-axis). Ventilation rate was not represented, as only one value (30 l/s influence on thermal and acoustic responses) was present 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. Figure 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. Figure 9 also indicates the dependent variables, confirming the overwhelming focus on overall comfort and performance as discussed before and highlighted in Figure 7. The range of considered values broadly varied between variables and the investigated human response. Figure 9 highlights the least and most explored environmental stimuli combinations, a piece of information that could be used for future multi-domain studies.

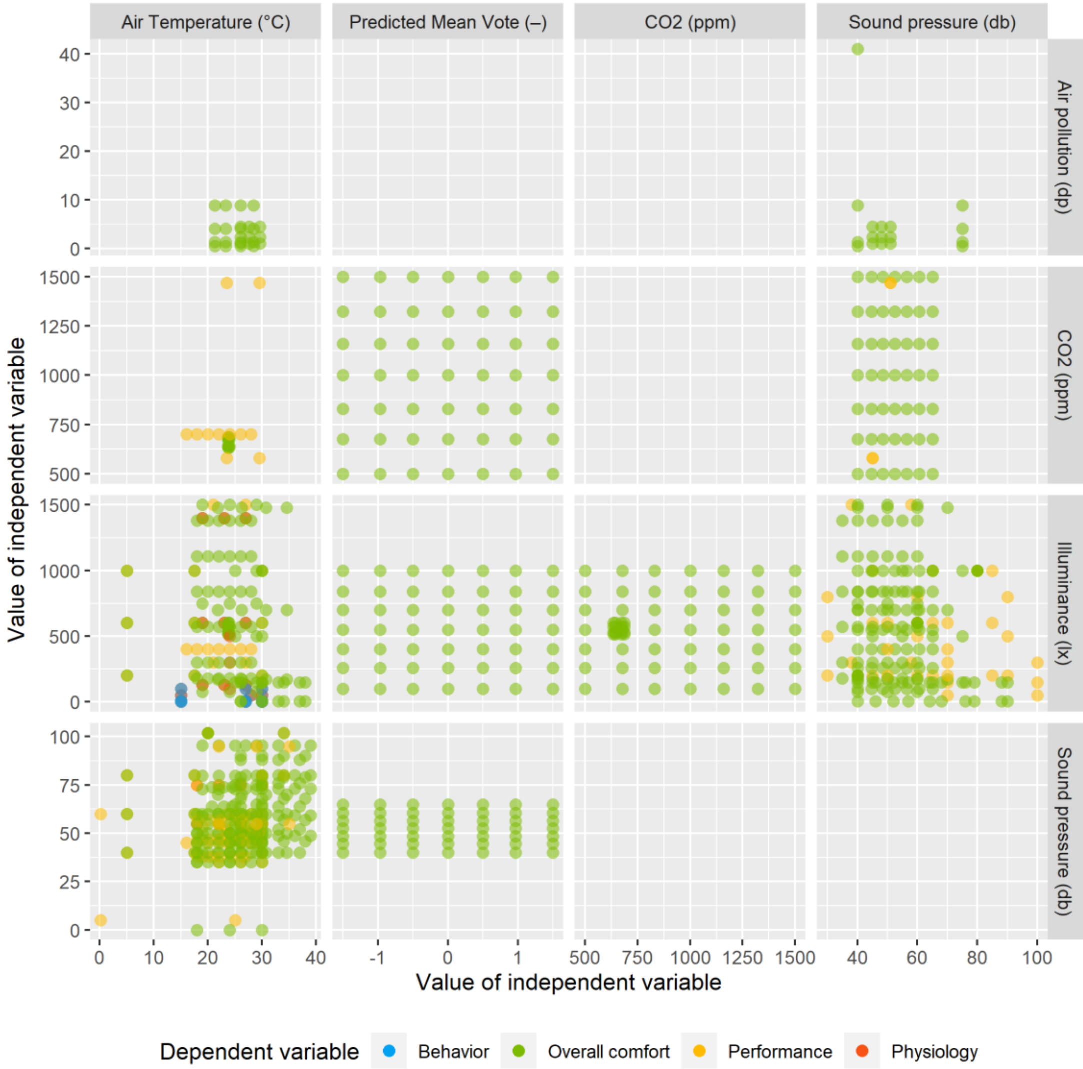

Figure 9: Combination of independent variable values employed in experimental investigations studying combined effects, considering the dependent variables (indicated with colors). Ventilation rate, air velocity, relative humidity, CCT, and VOC (Volatile Organic Compounds) are not represented as only 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).

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). It is recommended to opt for continuous design values 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. [87] or Schweiker et al. [88]) that are not environmental, for example, gender, age, and body mass index. Refer to 3.2.4 and 3.3.1 for further discussion on the topic.

3.2.3 Hypothesis

Hypothesis can be categorized by various means. For instance, causal hypotheses suggest that a cause-effect relationship exists between variables, while relational hypotheses suggest a relation. Stating and describing the hypotheses of a study leads to a better comprehension of the work. In general, all analyzed research articles move from the assumptions of previous studies reported in the scientific literature or from their analysis exploring new issues in the case of lack of data and research. Only *53%* of the considered articles reported the research hypothesis, divided into those where the hypothesis was "with direction" or "without direction" (Figure 10). The former expresses a direct or inverse relationship between dependent and independent variables: 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 [80], [89]. A hypothesis "without direction" expresses a general relationship between dependent and independent variables regarding the influence one may have on the other, such as the influence of thermal conditions on acoustic sensation and perception [90]. 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 the "cross-modal" or "combined and cross-modal" categories, whose experiments were 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 [91] 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 [53], [76], [77], [92]–[94].

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. Although there were some differences in the statement and description of the hypothesis within the examined articles, it can be concluded that the 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.

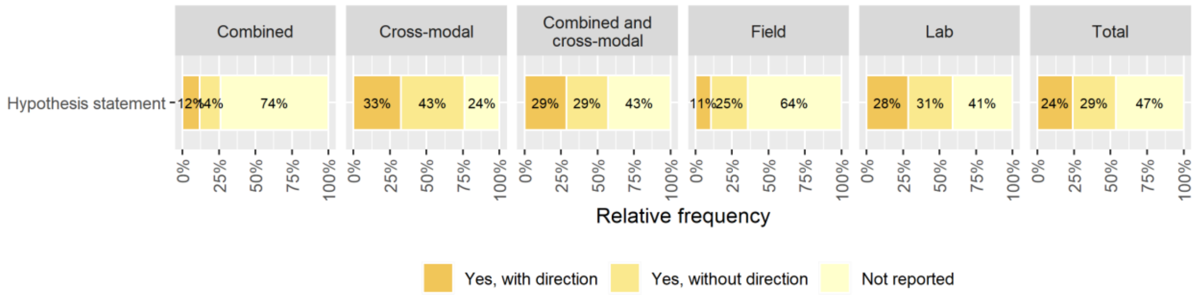

Figure 10: Relative frequencies of hypothesis statements in the considered studies.

3.2.4 Setting feature

Experimental setting features play a fundamental role in the combination and interaction of the variables investigated in multi-domain studies. For this reason, an accurate and complete description of variables should lead to better replicability and lower systematic errors because important covariates will be captured in the analysis [95]. A series of crucial features, summarized in Figure 11, are described in the following, and their presence in the considered papers is analyzed.

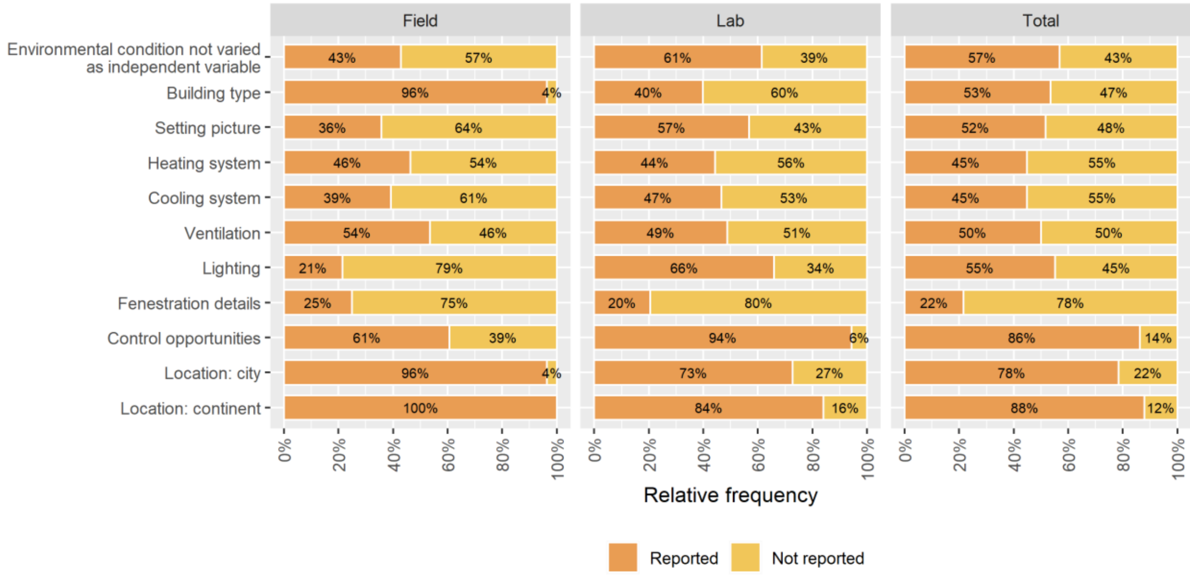

Figure 11: Relative frequencies of the experimental setting features in the considered studies.

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, including those that were not varied as independent variables. Such a comprehensive description of the indoor environment might help to understand potential differences across studies and detect confounding factors. Despite the fundamental importance of such a comprehensive description, most of the considered studies did not report these features. Only about *20%* reported a comprehensive overview (e.g., [80], [89], [96]) (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 (Figure 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 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; however, *47%* of all the studies analyzed here did not report such information. In laboratory studies, the "emulated" space type was not reported in *60%* of cases. From the studies that did report the building type, it can be observed that multi-domain studies were mainly carried out in offices (*34% of the total studies*), followed by educational (*10%*) and residential buildings (*5%*).

Besides indicating building 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). However, in the investigated studies, *48%* omitted space pictures and *35%* reported it without participants (ethical issues may play a role in this case). A good reference for description can be found in several studies [52], [97]–[100]. Best practices of pictures can be found in [63], [74], [101]. Describing relevant equipment (such as 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 [102]. Despite this, *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. [53] and Yang and Moon [103]. Description of ventilation type can be found in Skwarczynski et al. [104]. 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). Such information was provided in *55%* of studies, with a large prevalence using electric lighting (*37%*). The reduced number of studies on daylight [80], [86], [105]–[107] could be explained by the challenging experimental conditions that such an environmental variable entails. Winzen et al. [108] and Chinazzo et al. [80] described the lighting system. 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.). Among the investigated studies, such information was only accounted for in *22%* of papers. Reference descriptions can be found in Haldi and Robinson [100] and Garretón et al. [109].

Another relevant feature involves the interactions that occupants can have with building interfaces. Occupant controls can influence not only human interactions but also their satisfaction and behavior in different domains [110], [111]. Thus, reporting exhaustive information on control opportunities within the indoor space is highly recommended. Among the studies considered in this work, *86%* provided information on this topic, 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.

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. 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 [84], [89], [112]. Europe and Asia hosted most of the studies (*38%* and *35%*, respectively), followed by North America (*11%)*, South America and Oceania (about *1%*).

3.2.5 Exposure feature

This section covers the conditions that the subjects are exposed to (i.e., exposure features). Such information is essential to analyze the results and ease the replicability of the experiments. The first aspect to consider is study design, which describes if the experimenter measures responses to different exposures within-subjects (i.e., all participants are exposed to the same conditions), between-subjects (i.e., participants are exposed to different conditions), or a mix of the two. 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. An important aspect to report when describing the study design is the number and combination of tested experimental conditions (e.g., mixed design with one between-subjects condition and two within-subjects conditions). It is challenging to summarize the results in a concise manner as they vary highly across studies. For example, Huebner et al. [61] reported several conditions tested within-subjects, with all subjects experiencing dynamic temperature variations, and two conditions experienced between subjects (two CCTs). Laurentin et al. [113] tested six conditions within-subjects (two temperatures and three light types).

Once the study design is decided, it is necessary to define the characteristics of the exposure, which we can divide across the “exposure type” (i.e., steady-state, dynamic, or combined), the length of exposure for each experimental condition (e.g., exposure to warm temperature for 30 minutes and to each light condition for 10 minutes), the number of participants per experimental condition, and the timing of the exposure (during the day and the year). 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. Finally, it is 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. These exposure characteristics greatly varied in the considered studies. In addition, their description and presence depend on the type of study design and study type (i.e., lab or field).

What is important to notice was the lack of reporting of such 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. Seasonal variations are important to be recorded given their impact on several human responses [114]. In addition, publications suggest the potential variations of human responses during the day [115]–[117], highlighting the importance of recording and reporting the exact time of the day during which the experiment is conducted.

The last analyzed aspect of the exposure feature is the adaptation time (or acclimatization time), which is the time given to the participants to adapt to the experimental conditions. More than half of the studies reported the adaptation time, especially in lab settings (Figure 12). There was a tendency in most of the laboratory studies to use 30 minutes as an adaptation time; however, the time ranged from 5 to 55 minutes among the experiments, indicating a lack of consensus regarding this parameter. The consideration of the adaptation time is more relevant in studies involving the thermal domain since the human body requires time to reach steady-state thermal response in a new thermal condition and/or at a different activity level [118] and strongly depends on the temperature difference between experimental and natural condition.

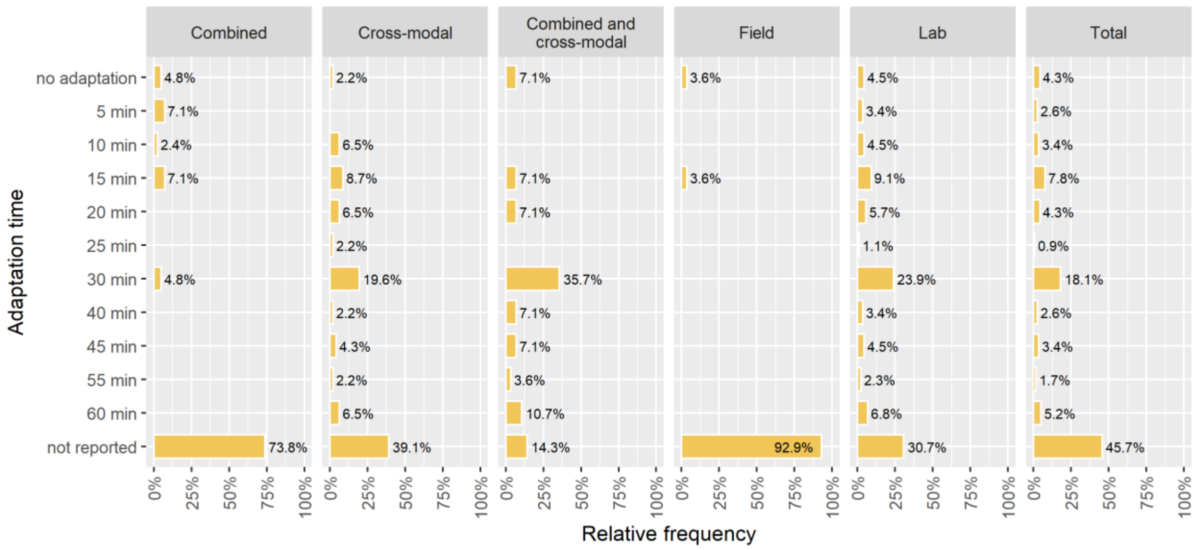

Figure 12: Adaptation time in minutes reported in the studies (Y- axis) in laboratory experiments.

3.2.6 Experimental design quality

Recently, a replication crisis has been in the spotlight of the scientific community [119], [120]. 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., [47], [121], [122]), such as randomization and control of confounding variables. An analysis of the quality of the experimental design reported in multi-domain studies was conducted considering whether: (i) the experimental conditions were randomly assigned or counterbalanced; (ii) the experimental procedure was blinded (single- or double-blind); (iii) confounding variables were controlled (experimentally or statistically); (iv) the study null condition was reported; and (v) one or more experimental conditions were repeated. Figure 13 summarizes the information reported by the authors of the analyzed papers considering points (i-v) of the previous list.

As shown in Figure 13, there were substantive gaps in reporting across all the elements of good study 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 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, 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 [80]. 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], [121]. Yet, this approach did not seem to be common in the considered studies.

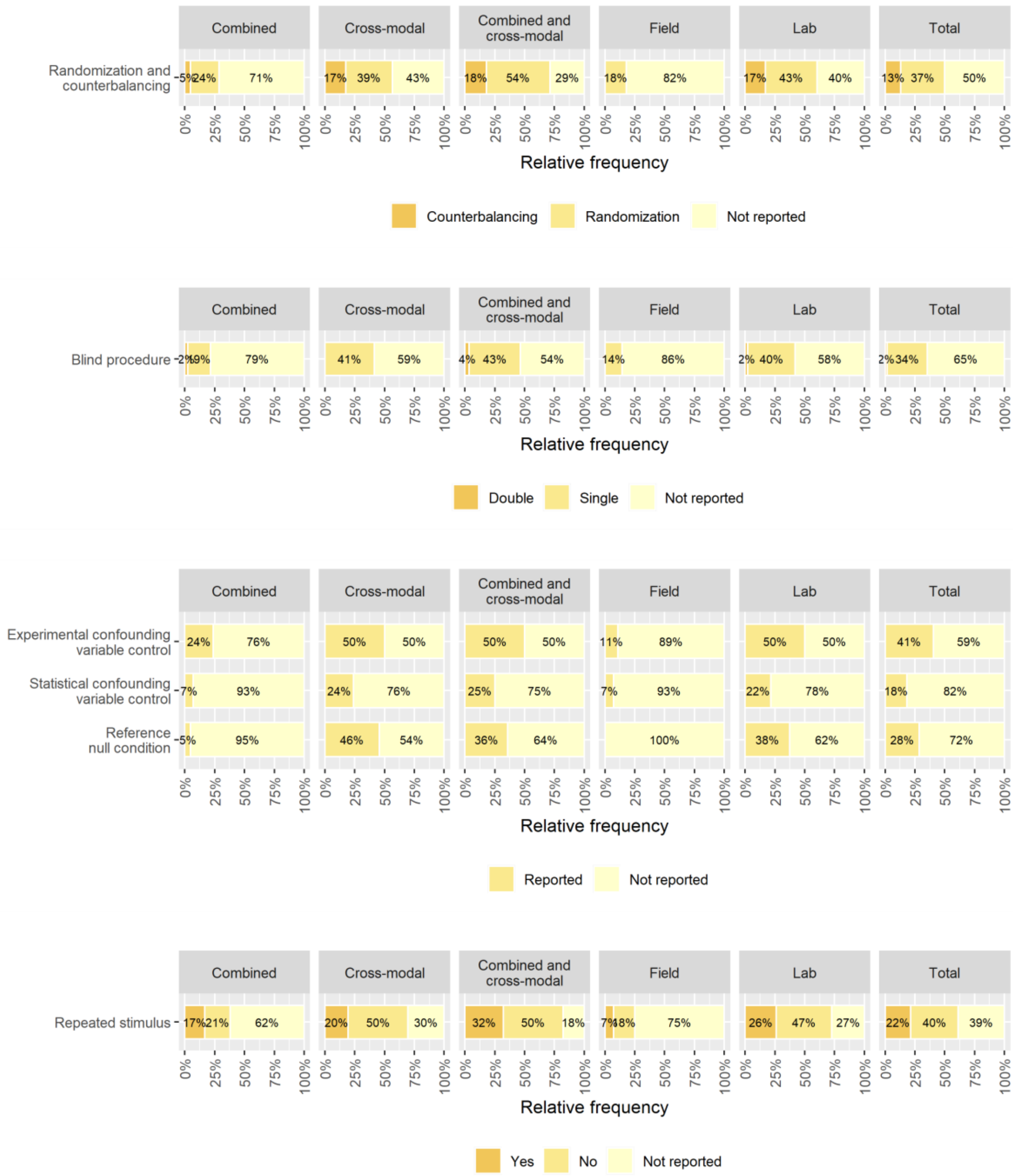

Figure 13: Relative frequencies of information about the experimental design quality reported in the considered studies by effect type and study type.

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. [123], which had been registered on osf.io.

3.3 Study deployment and analysis

3.3.1 Data collection and processing

In multi-domain studies, measuring the environmental stimuli – not only the investigated independent variables but additional factors that are hypothesized to be relevant – is essential. For example, in a study on the cross-modal effect of light on thermal perception, air quality, and acoustic conditions should be reported as well. Without measuring the possible confounders, the analysis necessarily excludes them, and therefore the results of the analysis are less valid. Moreover, comprehensive reporting facilitates comparison, meta-analysis, and the reproduction of an experiment. 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 are missing data treated?'), and differences from the design conditions should always be reported or discussed.

Table 2 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 [124]. The visual domain was the second most frequently measured aspect, with *47%* of studies reporting illuminance values.

	Effect type			Study type		Total
Environmental measurements	**Combined**	**Cross-modal**	**Combined and cross-modal**	**Field**	**Lab**	
Air temperature	26	33	21	22	58	80
Air velocity	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	0	1	0	1	0	1
Operative temperature	0	0	4	0	4	4
Outdoor relative humidity	4	0	0	4	0	4
Radiant temperature	3	0	0	3	0	3
Relative humidity	18	22	17	18	39	57
Skin temperature	0	3	0	0	3	3
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
Daylight	1	0	0	0	1	1
Illuminance level	20	17	17	13	41	54
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
Background noise	3	0	3	3	3	6
Noise level	7	3	0	0	10	10
Sound level	2	0	0	0	2	2

Table 2: Number of reviewed studies reporting to measure the environmental parameters.

Overall, general information for reproducibility was scarcely reported in the considered papers, as shown in Figure 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. Measurements should be taken in proximity to the occupant 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. 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.

Figure 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.

In general, very few studies reported sufficient information on the environmental measurements to allow for reproducibility. The number was the lowest for the field studies. This could partly be the expression of differing constraints for randomizing variables in field versus laboratory studies, yet moreover, there appears to be differing stringency of reporting: as noted earlier in the section on study design, field studies were less likely to report features (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. Best practices can be found in Lan et al. [125] and Chinazzo et al. [126]. Standardizing methods and reporting formats for multi-domain studies will enhance the rigor in reviewing these studies and enable future meta-analyses.

3.3.2 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. GDPR [127]) 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.

Figure 15 highlights the percentage of studies reporting these participant characteristics. Overall, field studies had a higher number of participants ($N_{\text{geometric mean}} = 141$) compared to laboratory studies ($N_{\text{geometric mean}} = 35$). Distribution by sex was reported in most laboratory studies (*91%*) and approximately half of the field studies (*46%*). As shown in Figure 15, age is reported far more than any other single characteristic. 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 almost half of the papers, 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 most frequently reported in lab studies than in field studies across all measures. Of the measures, the description of tasks/activities was the most common to be 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).

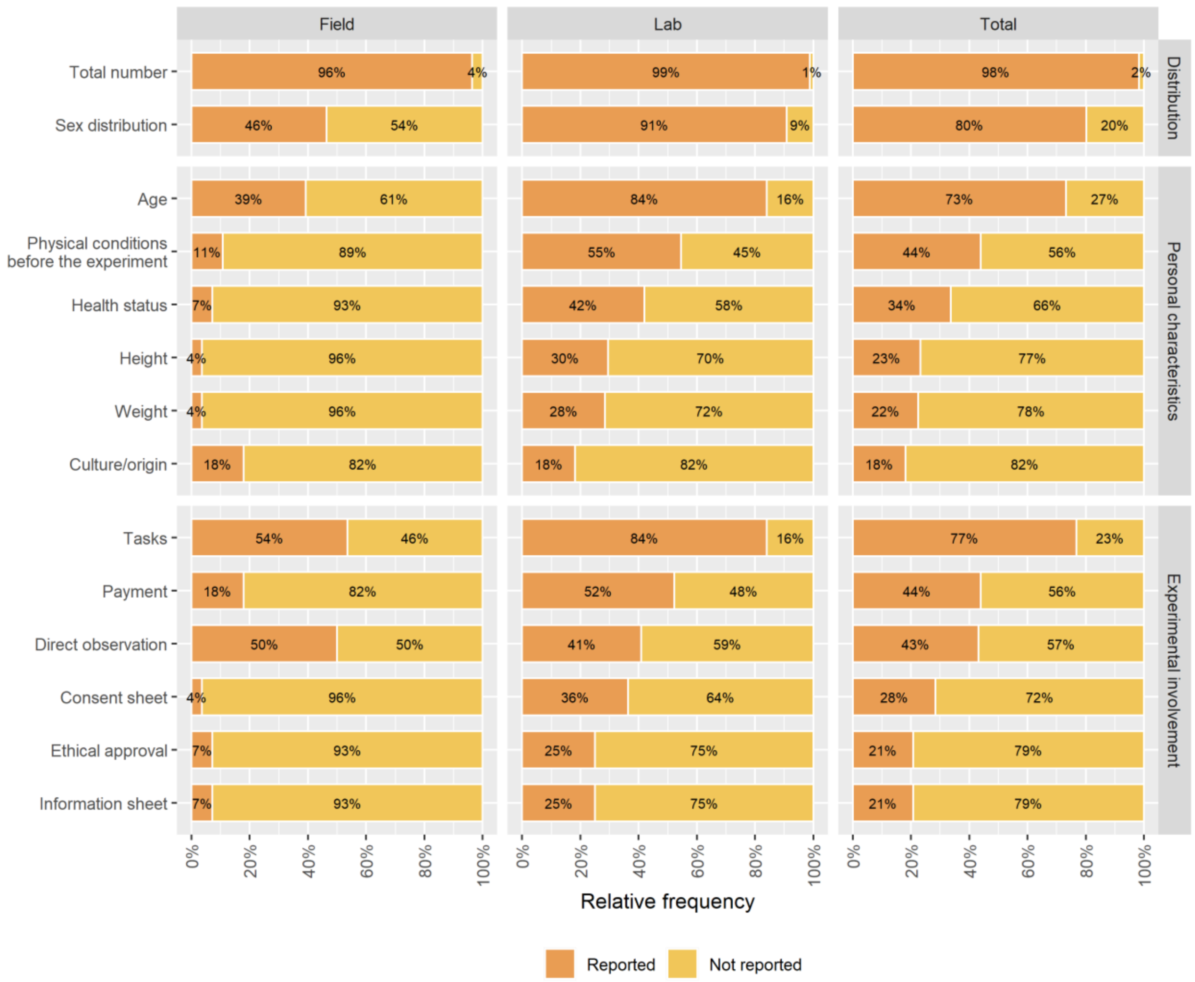

Figure 15: Relative frequencies of information about participants reported in the considered studies.

While most studies provided detailed information on the number of 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 [62], Chinazzo et al. [105], Golasi et al. [128], and Wang et al. [129].

3.3.3 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.

Among the publications considered, 36 statistical methods were used to analyze the combined and cross-modal effects. Figure 16 shows the main 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 logistic regression. The least used methods were categorized in the "other" group, which includes, for example, Mann-Whitney-U test [130], Kolmogorov-Smirnov test [131], and Tukey's Honest Significant Difference test [132]. Adopting a specified 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.

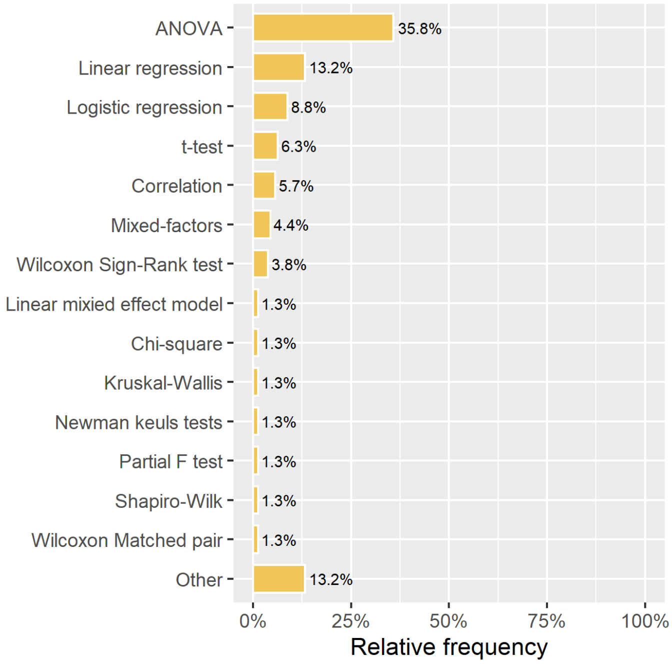

Figure 16: The percentage of studies adopting different statistical methods (thereinto, ANOVA includes ANOVA repeated measures, Friedman two-way ANOVA, Three-way mixed randomized repeated ANOVA, factorial ANOVA, multivariate analysis of variance, One-way ANOVA, Two-way ANOVA, Three-way ANOVA; logistic regression includes multivariable logistic regression; correlation includes partial correlation analysis, Pearson correlation, Spearman correlation).

Power analysis or other strategies to decide the minimum sample size required for an experimental study should be reported in parallel to the statistical analysis. Only *4%* of the studies reported a power analysis, both in field and lab studies. This aspect attracts a quite interesting outcome because, in most of the 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.

The effect size is another important indicator to evaluate and report. Besides indicating the strength of the statistical results, it puts a study into perspective by facilitating the comparison across different studies and helping in identifying sample sizes for future studies. In addition, and compared to significance, it is independent of the sample size. 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.

In summary, 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. Based on the analysis of the reviewed studies, to rely on the results of statistical methods, to promote transparency and reproducibility of experiments robustness against random and systematic errors, it is essential that studies clearly report the sample size, identified through an a priori power analysis or justified by any other method (e.g., resource constraints, accuracy, heuristics) to provide enough evidence of representativity. Also, the studies should communicate clearly the hypotheses tested and the assumptions set together with the adopted statistical test and the significance levels. Then, the studies should report the effect size as a measure of how meaningful the difference between different variables or groups is to prove the actual real-life significance of the experimental outcomes. Furthermore, when a variable depends on the value of another variable, interaction effects should also be discussed and plotted for supporting a proper interpretation of the phenomenon. 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 conclusions of the study.

3.4 Study outcome

3.4.1 Reporting results

The present section does not focus on the specific results obtained in the considered papers (e.g., ‘is temperature affecting visual sensation?’), but instead focuses on the content that should be present in the result section of each study. 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. [133], [134]. Unfortunately, as already pointed out earlier [40], so far, only a few papers in this field fulfill the requirements to enable their inclusion within meta-analyses.

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[1]: (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

[1] 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 variance like standard deviations.

inferential statistics, disregarding whether they are statistically significant or not (see reporting bias in science and the potential of misrepresentation of scientific results [135]). 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 $p < .05$) [136], 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 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). Readers can refer to the scheme and description reported in Section 3.1.1.

Table 3 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 Table 3, 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). In table Table 3, 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 Figure 2.

Also, in the case of combined effects, results could be described as illustrated in Table 4, according to the levels of the considered stimuli.

Table 3: Template for results reporting for cross-modal effects of 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*

Table 4: 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	e.g., additive		
	Comfort level			
	Higher level			

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. In future studies, researchers are invited to describe the results comprehensively and adopt the suggested reporting style for both cross-modal and combined effects. 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 (for examples see [107], [137], [138]).

3.4.2 Study discussion and conclusion

This section summarizes the trends among the final sections of the papers, namely the content of the conclusion and discussion sections. Figure 17 shows the relative frequency of data-informed conclusions and frequency of reporting future studies, study limitations, mechanism explanations, and practical implications.

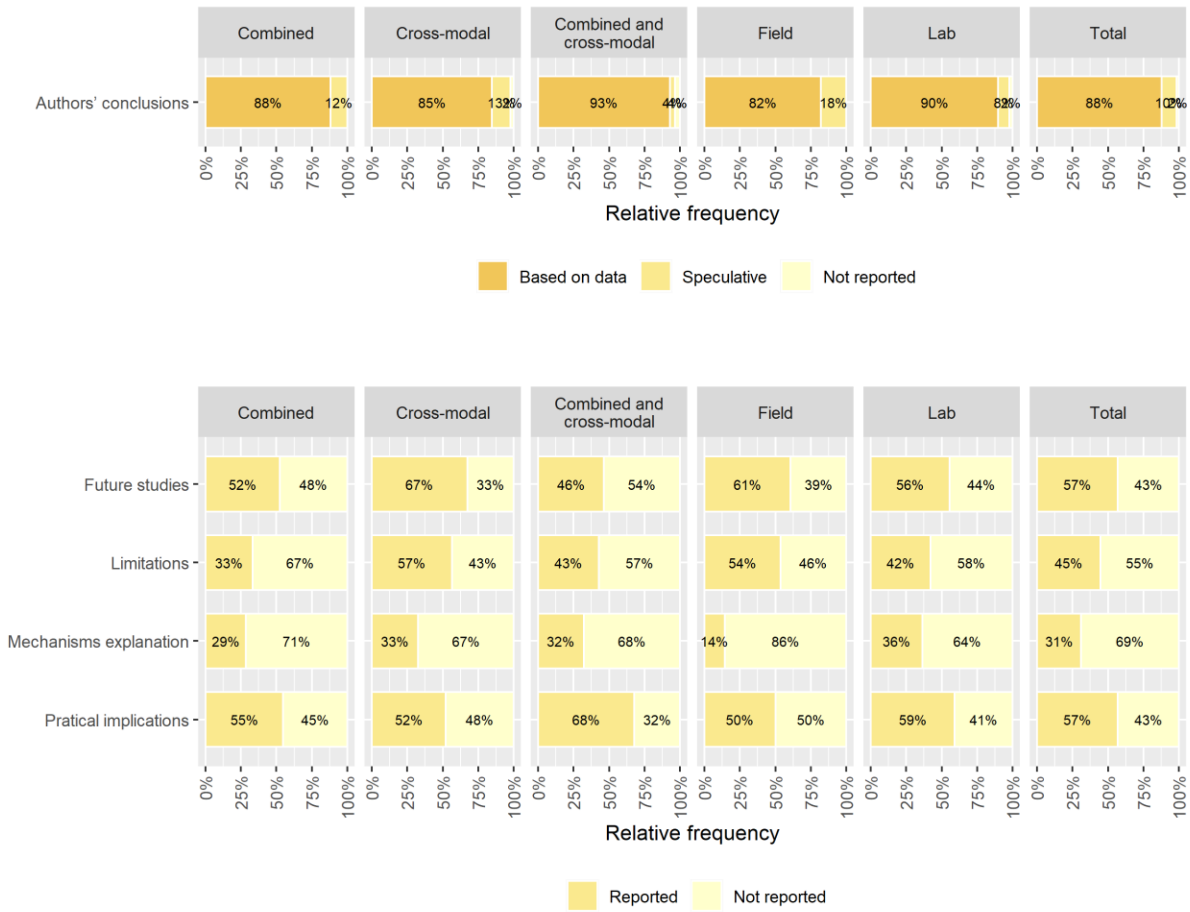

Figure 17: Relative frequencies of information about conclusions and discussions reported in the considered studies, according to the effect type and study type.

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. 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. In a 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 [59], [62], [104], [139], [140]. In other studies, authors deepened the effect of specific stimuli on the perception of comfort [141] or on performance [91].

Finally, the identification of practical implications of the research outcomes is an important task since it creates a direct link between the experiment and the impact on human life and society. Nevertheless, practical implications were not reported in 43% of the analyzed papers. Examples of good descriptions of practical implications can be found in several papers [54], [91], [142].

4 Conclusions

4.1 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 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 (ASHRAE 2016a, 10).

- 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.

- 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.

- The comprehension and utility of results from experimental research, would be arguably higher when hypotheses are explicitly stated. Surprisingly, about *40%* of the laboratory studies and *60%* of field studies did not state the hypotheses.

- 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.
- In many instances, exposure features were not consistently and comprehensively specified in the study designs. Likewise, 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 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.
- The measurement 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 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.

- Studies involving human participants should provide, detailed information on their composition, 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, 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.
- A considerable number (n=36) of different statistical methods were employed in the reviewed studies (mostly ANOVA). Thereby, the studies often lack a thorough description and documentation, for instance regarding data accuracy, consistency, relevance, uniformity, sample size, and significance levels. Moreover, about 60% of the studies did not include any justification for the choice of the applied statistical method. This hampers the reproducibility of experiments, feasibility of meta-analyses, and review of collective insights.
- The low fraction of the studies that conducted a power analysis (*4%*), reported a null hypothesis (*28%*), described sufficient population characteristics, and effect sizes (*22%*), suggests a possible replication crisis identified elsewhere (e.g., Open Science Collaboration 2015; Baker 2016). Future studies should align with the measures common in the adjacent field of psychology to address this shortcoming [143] (e.g., pre-registration prior to the start of the study, transparent data processing practices, and reporting effects sizes).
- Experimental studies were often not thoroughly documented and reported in a systematic and detailed manner. These issues may be rooted in the lack of robust schemes for the conceptualization and reporting of both cross-modal and combined effects. Consequently, establishing sound methods for structuring and reporting the findings of multi-domain

studies can be characterized as a major challenge. The present contribution (see Section 3.4.1) provided several recommendations for addressing this challenge in future multi-domain studies.

4.2 Future Directions

Although the proposed framework is developed from investigations about (indoor) environmental stimuli, its 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], however further factors may have to be considered in the framework depending on the aim of the study and type of contextual or personal aspects.

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 [144]. The human response can be captured in a more scalable way using innovative interfaces that are integrated specifically into mobile devices and wearables [145]. There are, moreover, relatively new statistical techniques for testing causal claims relevant to multi-domain frameworks from a properly designed field study setup. Many of the proposed framework elements are complementary to the rigorous study design required for a causal framework. For an overview of some of the recent developments in techniques, see [146].

The study 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 practices uncovered in this work 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 is also required to 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.

Declarations of competing interest

There are no known conflicts of interest.

Acknowledgements

This work was conducted within the framework of IEA-EBC Annex 79 "Occupant-Centric Building Design and Operation" (https://annex79.iea-ebc.org/).

Matteo Favero would like to thank the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN, Grant no. 257660) and the Research Council of Norway (Norges Forskingsrådet) for their support.

Stephanie Gauthier would like to thank the support of UK Engineering and Physical Sciences Research Council under Grant EP/T023074/1.

RunaT. Hellwig was supported by the Obelske Familiefond.

Ilaria Pigliautile acknowledgements go to the PON project "Red-To-Green" financed by the Italian Ministry of Research (D.M. 1062 PON Ricerca e Innovazione).

Anna Laura Pisello's acknowledgements go to the PRIN 2017 (Prot. 20172FSCH4) project entitled "Towards the NEXT generation of multiphysics and multidomain environmental COMfort models: theory elaboration and validation experiment".

Isabel Mino-Rodriguez is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), promotional reference 03EN1002A and 03EN1002B.

Marcel Schweiker is funded by a research grant (21055) by VILLUM FONDEN.

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Appendix A

Ref.	List of considered papers
[81]	A chamber-experiment investigation of the interaction between perceptions of noise and odor in humans
[147]	A comparative study of discomfort caused by indoor air pollution, thermal load and noise
[86]	A field study investigation on the influence of light level on subjective thermal perception in different seasons
[148]	A multiple linear regression approach to correlate the Indoor Environmental Factors to the global comfort in a Zero-Energy building
[149]	A multivariate-logistic model for acceptance of indoor environmental quality (IEQ) in offices
[112]	A new index combining thermal, acoustic, and visual comfort of moderate environments in temperate climates
[150]	A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices
[151]	A weighting procedure to analyse the Indoor Environmental Quality of a Zero-Energy Building
[57]	Air movement and perceived air quality
[50]	An applied framework to evaluate the impact of indoor office environmental factors on occupants’ comfort and working conditions
[152]	An evaluation model for indoor environmental quality (IEQ) acceptance in residential buildings
[153]	Can colour and noise influence man’s thermal comfort?
[63]	Colour as a psychological agent to manipulate perceived indoor thermal environment for effective energy usage
[76]	Combined effects of acoustic and visual distraction on cognitive performance and well-being

[90]	Combined effects of acoustic, thermal, and illumination conditions on the comfort of discrete senses and overall indoor environment
[80]	Combined effects of daylight transmitted through coloured glazing and indoor temperature on thermal responses and overall comfort
[77]	Combined effects of noise and air temperature on human neurophysiological responses in a simulated indoor environment
[53]	Combined Effects of noise and temperature on human comfort and performance
[154]	Combined effects of short-term noise exposure and hygrothermal conditions on indoor environmental perceptions
[155]	Combined effects of sound and illuminance on indoor environmental perception
[156]	Combined effects of temperature and noise on human discomfort
[157]	Correlations between thermal satisfaction and non-thermal conditions of indoor environmental quality: Bayesian inference of a field study of offices
[142]	Cross-modal effects of illuminance and room temperature on indoor environmental perception
[132]	Cross-modal effects of noise and thermal conditions on indoor environmental perception and speech recognition
[137]	Cross-modal effects of thermal and visual conditions on outdoor thermal and visual comfort perception
[105]	Daylight affects human thermal perception
[158]	Decision support for improving occupant environmental satisfaction in office buildings: The relationship between sub-set of IEQ satisfaction and overall environmental satisfaction
[159]	Determining the Indoor Environment Quality for an Educational Building
[160]	Developing an indoor environment quality tool for assessment of mechanically ventilated office buildings in the UK – A preliminary study
[161]	Development of a multivariate regression model for overall satisfaction in public buildings based on field studies
[162]	Development of equi-comfort charts constituted with temperature and noise at 150 and 3 lx
[93]	Effect of colored illumination upon perceived temperature
[107]	Effect of Indoor Temperature and Glazing with Saturated Color on Visual Perception of Daylight
[91]	Effect of noise intensity and illumination intensity on visual performance
[113]	Effect of thermal conditions and light source type on visual comfort appraisal
[140]	Effects of different light intensities during the forenoon on the afternoon thermal sensation in mild cold
[163]	Effects of indoor temperature and background noise on floor impact noise perception
[164]	Effects of noise and heat stress on primary and subsidiary task performance
[139]	Effects of noise type, noise intensity, and illumination intensity on reading performance

[94]	Effects of noise, heat and indoor lighting on cognitive performance and self-reported affect
[109]	Effects of perceived indoor temperature on daylight glare perception
[103]	Effects of recorded water sounds on intrusive traffic noise perception under three indoor temperatures
[165]	Effects of steady-state noise and temperature conditions on environmental perception and acceptability
[125]	Effects of thermal discomfort in an office on perceived air quality, SBS symptoms, physiological responses, and human performance
[79]	Evaluation of the Visual Stimuli on Personal Thermal Comfort Perception in Real and Virtual Environments Using Machine Learning Approaches
[129]	Experimental investigation about thermal effect of colour on thermal sensation and comfort
[68]	Experimental study on occupants' interaction with windows and lights in Mediterranean offices during the non-heating season
[166]	Facilitatory effects of environmental sounds on hue-heat phenomena
[96]	First SenseLab studies with primary school children: exposure to different environmental configurations in the experience room
[89]	How correlated colour temperature manipulates human thermal perception and comfort
[167]	Impact of individual IEQ factors on passengers ' overall satisfaction in Chinese airport terminals
[104]	Impact of individually controlled facially applied air movement on perceived air quality at high humidity
[168]	Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance
[169]	Impact of Temperature and Humidity on Perception of Indoor Air Quality During Immediate and Longer Whole-Body Exposures
[170]	Impact of temperature and humidity on the perception of indoor air quality
[171]	In search of evidence for the hue-heat hypothesis in the aircraft cabin
[172]	Incandescent affect: turning on the hot emotional system with bright light
[173]	Influence of air temperature on preference for color temperature of general lighting in the room
[62]	Influence of different light intensities during the daytime on evening dressing behavior in the cold
[106]	Influence of indoor temperature and daylight illuminance on visual perception
[59]	Influence of Light Intensities on Dressing Behavior in Elderly People
[128]	Influence of lighting colour temperature on indoor thermal perception: A strategy to save energy from the HVAC installations
[60]	Influence of Two Different Light Intensities from 16:00 to 20:30 Hours on Evening Dressing Behavior in the Cold

[174]	Influence of visual factors on noise annoyance evaluation caused by road traffic noise in indoor environment
[141]	Interactions and comprehensive effect of indoor environmental quality factors on occupant satisfaction
[175]	Interactions and range effects in experiments on pairs of stresses: mild heat and low frequency noise
[176]	Interactions between the perception of light and temperature
[130]	Interrelations of Comfort Parameters in a Simulated Aircraft Cabin
[177]	Investigating the effect of CO2 concentration on reported thermal comfort
[178]	Investigation of the relationships between thermal, acoustic, illuminous environments and human perceptions
[179]	Investigation of the subjective evaluation of indoor illumination level on perceived air quality
[55]	Irrelevant speech and indoor lighting: effects on cognitive performance and self-reported affect
[180]	Light intensity and thermal responses
[181]	Linear, non-linear and alternative algorithms in the correlation of IEQ factors with global comfort: a case study
[69]	Modeling occupant behavior of the manual control of windows in residential buildings
[65]	Monitoring and modelling of manually-controlled venetian blinds in private offices: A pilot study
[182]	New comfort index during combined conditions of moderate low ambient temperature and traffic noise
[85]	New index of combined effect of temperature and noise on human comfort: summer experiments on hot ambient temperature and traffic noise
[183]	Nonlinear relationships between individual IEQ factors and overall workspace satisfaction
[66]	Occupant behavior regarding the manual control of windows in residential buildings
[184]	Occupant response to different correlated colour temperatures of white LED lighting
[70]	Occupants' interactions with windows in 8 residential apartments in Beijing and Nanjing, China
[75]	Office noise and illumination effects on reading comprehension
[185]	On the interaction between lighting and thermal comfort: an integrated approach to IEQ
[100]	On the unification of thermal perception and adaptive actions
[186]	Perceived air quality and the thermal environment
[67]	Probability of occupant operation of windows during transition seasons in office buildings
[187]	Quantification of the synthesized evaluation of the combined environment

[61]	Saving energy with light? Experimental studies assessing the impact of colour temperature on thermal comfort
[56]	Sensory and physiological effects on humans of combined exposures to air temperatures and volatile organic compounds
[131]	Simultaneous effects of irrelevant speech, temperature and ventilation rate on performance and satisfaction in open-plan offices
[52]	Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms
[188]	Study on human responses under different CO2 concentration and illuminance in underground refuge chamber
[189]	The combined effects of many different indoor environmental factors on acceptability and office work performance
[190]	The combined effects of noise and illumination on the performance efficiency of visual search and neuromotor task components
[191]	The combined effects of temperature, background noise and lighting on the non-physical task performance of university students
[192]	The effect of correlated colour temperature of lighting on thermal sensation and thermal comfort in a simulated indoor workplace
[54]	The effects of moderate heat stress and open-plan office noise distraction on SBS symptoms and on the performance of office work
[98]	The effects of temperature, light, and sound on perceived work environment
[74]	The impact of a view from a window on thermal comfort, emotion, and cognitive performance
[92]	The impact of human perception of simultaneous exposure to thermal load, low frequency ventilation noise and indoor air pollution
[101]	The impact of thermal environment on occupant IEQ perception and productivity
[193]	The influence of coloured light in the aircraft cabin on passenger thermal comfort
[51]	The influence of exposure to multiple indoor environmental parameters on human perception
[58]	The influence of heat, air jet cooling and noise on performance in classrooms
[72]	The interaction of noise and mild heat on cognitive performance and serial reaction time
[194]	The Relationship between Thermal Comfort and Light Intensity with Sleep Quality and Eye Tiredness in Shift Work Nurses
[64]	Understanding window behaviour in a mixed-mode buildings and the impact on energy performance
[195]	Upper limits of air humidity for preventing warm respiratory discomfort
[196]	Ventilation requirements in buildings—I. Control of occupancy odor and tobacco smoke odor
[197]	Visual effects of wood on thermal perception of interior environments

[198]	Warmth, glare and a background of quiet speech: A comparison of their effects on performance
[84]	What's So Hot About Red?
[199]	What's so hot about sound?-influence of HVAC sounds on thermal comfort
[71]	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 [200];
- Studies focusing on physiological responses only[2] (e.g., [201]);
- 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., [202]–[210]);
- Studies reporting results of experts' questionnaires [211];
- Studies where interactions are analyzed just looking at the correlation between human responses [212];
- Studies investigating the effect of the combined presence of multiple indoor stimuli on the measurements of another factor [99];
- Studies focusing neither on cross-modal nor on combined effects [112];
- Preliminary studies in which the quantitative results described are not the goal of the study [181];
- Proof-of-concept studies [213]
- Experiments in Virtual Reality [214], [215].

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