Review of multi-domain approaches to indoor environmental perception and behaviour

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Abstract

Building occupants are continuously exposed to multiple indoor environmental stimuli, including thermal, visual, acoustic, and air quality related factors. Moreover, personal and contextual aspects can be regarded as additional domains influencing occupants' perception and behaviour. The scientific literature in this area typically deals with these multiple stimuli in isolation. In contrast to single-domain research, multi-domain research analyses at least two different domains, for example, visual and thermal. The relatively few literature reviews that have considered multi-domain approaches to indoor-environmental perception and behaviour covered only a few dozen articles each. The present contribution addresses this paucity by reviewing 219 scientific papers on interactions and cross-domain effects that influence occupants' indoor environmental perception and behaviour. The objective of the present review is to highlight motivational backgrounds, key methodologies, and major findings of multi-domain investigations of human perception and behaviour in indoor environments. The in-depth review of these papers provides not only an overview of the state of the art, but also contributes to the identification of existing knowledge gaps in this area and the corresponding need for future research. In particular, many studies use “convenience” variables and samples, there is often a lack of theoretical foundation to studies, and there is little research linking perception to action.

Key words

Human perception; comfort; occupant behaviour; multi-physical; multi-perceptual; contextual; personal; multi-domain

1. Introduction

1.1. Background and state-of-the-art

Inhabitants of industrialized areas spend most of their time (85-96%) inside buildings [1; 2]. Meanwhile, the human sensory system receives information regarding multiple indoor environmental exposures. Building energy consumption is significantly influenced by occupant perception and behaviour; that is, occupants’ evaluation of thermal, visual, acoustic, and air quality stimuli and their reactions to any resulting discomfort [3]. As such, these four principal categories of environmental stimuli are integral to building design standards [4]. Not all interactions of occupants with their built environment result from dissatisfaction, but a close link between perception and behaviour exists [5].

While environmental stimuli occur simultaneously, the majority of scientific literature considers environmental influences on human perception and occupant behaviour in isolation. Literature reviews related to single-domain perceptions cover thermal [6-8], visual [9-12], indoor air quality (IAQ) [13], or acoustic [14-16] perception, as well as single-domain influences on occupants’ actions [5; 17-19]. An understanding of multi-domain environmental effects is lacking. ASHRAE [4] states “*current knowledge on interactions between and among factors that most affect occupants of indoor environments is limited*”. Addressing this knowledge gap, Torresin et al. [20] proposed a multi-domain research framework that identifies interactions and crossed effects between domains. Interactions are combined effects of two or more distinct domains (e.g., thermal and visual), on a third domain (e.g., overall environmental satisfaction). In contrast, crossed effects involve a main effect of one domain (e.g., thermal stimuli) on another domain (e.g., visual perception).

Literature reviews on multi-domain approaches are less numerous. Recently, Torresin et al. [20] identified 45 laboratory studies published after 1990 dealing with the effects of two or more environmental domains on perception and performance. Earlier reviews were based on smaller numbers of studies [21-23]. Frontczak et al. [23] reviewed nine studies focusing on the influence of individual domains on overall satisfaction. Candas et al. [21] discussed neurophysiological and behavioural findings on multisensory influences on thermal perception based on 25 publications. Centnerová et al. [22] reviewed eight papers with the same topic. The authors of this review could not identify earlier reviews addressing multi-domain approaches related to occupant behaviour.

In addition to the four principal indoor environmental domains, contextual and personal variables influence occupants' perception and behaviour and are summarized in Figure 1 and 2. Schweiker et al. [5] reviewed drivers of occupant behaviour, including contextual and personal factors. However, they did not examine interactions between these factors. Frontczak et al. [23] reviewed personal and contextual influences on overall satisfaction with the indoor environment. Schweiker et al. [8] included personal (psychological) and contextual factors in their review on individual differences in thermal perception. O'Brien et al. [24] concluded that most approaches analysed aggregated average models and diversity is captured through statistical approaches, without extracting personal or contextual factors.

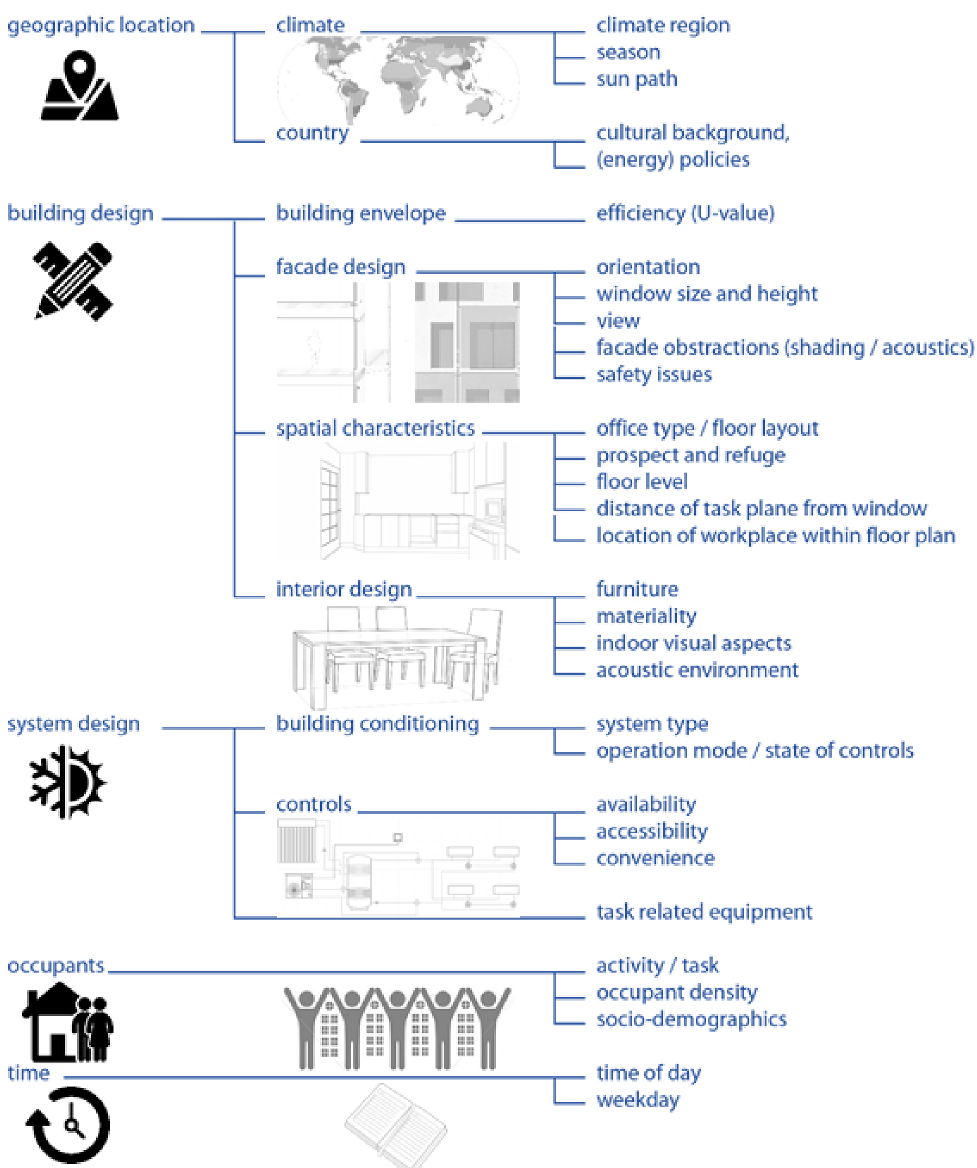

Fig. 1. Contextual variables and their categorization.

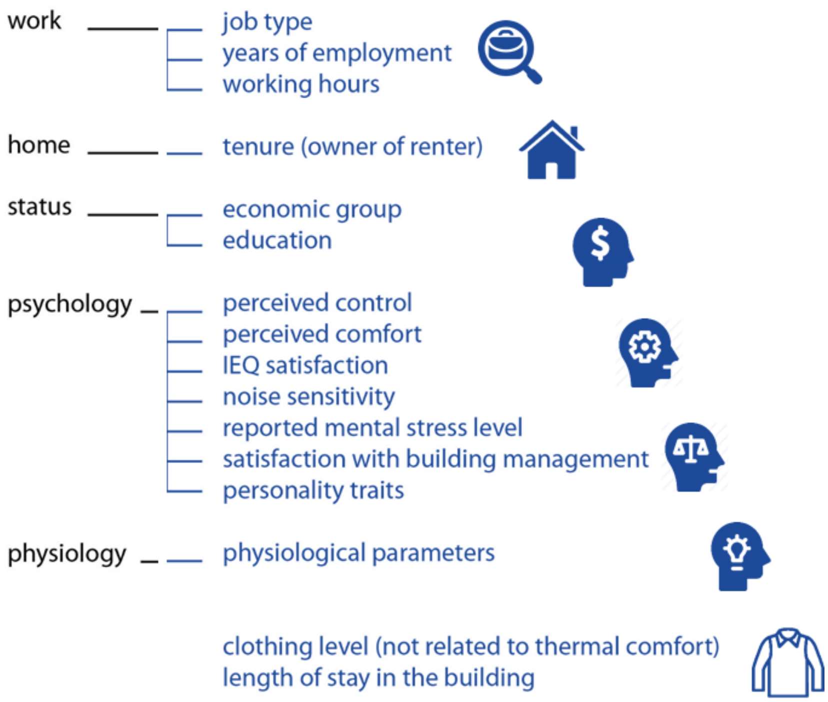

Fig. 2. Personal variables and their categorization.

This brief overview reveals a lack of reviews that considered multi-domain influences on occupants' perception and behaviour. The current review aims to fill this gap as described in the following.

1.2 Objective, research questions, and scope

The primary objective is to examine multi-domain approaches with a much broader scope compared to previous reviews in order to enter into a new phase of conceptual developments in the field. This review aimed to identify motivations, key methods, findings, and gaps in the field of multi-domain approaches to human perception and behaviour in indoor environments.

The main research questions were (1) Why did researchers choose the domains and questions they considered?, (2) How did they approach multi-domain investigations?, (3) What were the key results?, and (4) What are limitations and gaps of their approaches?

The scope of this review covers studies applying a *multi-domain* approach to people's perception of the indoor environment and their resulting behavioural outcomes. The first categorization level made is between "perception" and "behaviour", as shown in Figures 3 and 4, respectively. Studies without any physical predictors or with performance or health-related outcomes are beyond the scope.

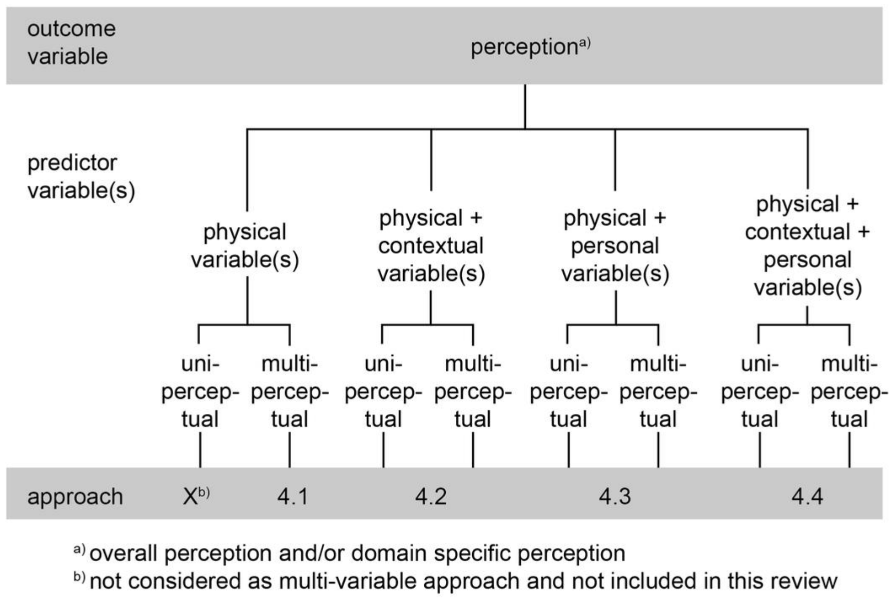

Fig. 3. Schema of multi-variable approaches with perception as the outcome variable.

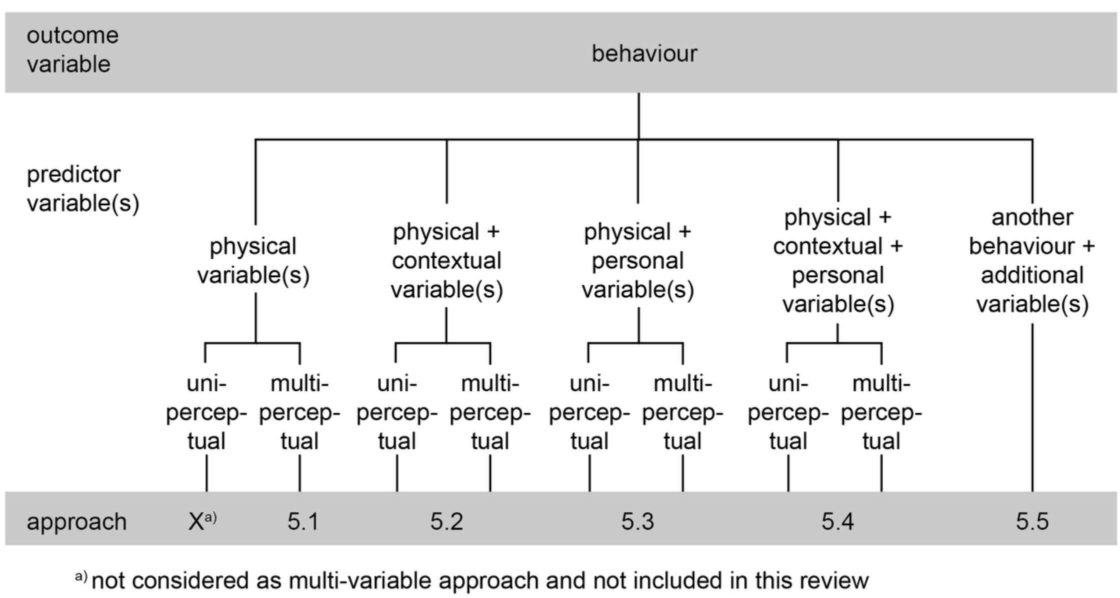

Fig. 4. Schema of multi-variable approaches with behaviour as outcome variable. Note that the approach numbers at the bottom of this figure refer to the corresponding subsection numbers within this review.

Physical-perceptual independent variables cover measurable physical properties of the indoor and outdoor environment, e.g. indoor and outdoor air temperature for the thermal environment. All the physical properties of the thermal, visual, acoustic, and air quality environment are considered. *Physical multi-perceptual* approaches are defined as those covering variables from more than one domain of perception (e.g., thermal and visual perception). Studies dealing with multiple variables covering one domain only (e.g., solely air temperature and relative humidity, which are both from the thermal domain, on thermal perception) are not considered unless they included either contextual or personal variables. All *contextual and personal variables* shown in Figure 1 and 2 are considered, except personal variables related to demographic factors (e.g. age, sex), or clothing if dealing with thermal perception.

Other behaviour and additional variables are included to cover studies that consider the status of one behaviour in the analysis of another behaviour. For example, window opening behaviour as dependent and the status of the heating system as independent variable.

This review covers laboratory studies, field studies, and questionnaire surveys. Studies related to perception or behaviour within the outdoor environment, virtual reality studies, or research based on simulations are out of scope. As such, this review provides a comprehensive overview of multi-domain approaches to understanding human perception and occupant behaviour indoors.

2. Methods

This review's approach is visualized in Figure 5. The visualization is based on the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) schema [25]. However, in contrast to a systematic review, first, we collected and reviewed known research, which returned 153 articles. This initial step included searches in author's individual reference databases as well as in bibliographic search engines (Table 1). Second, the more than 1,000 articles citing these 153 articles or being cited by this initial collection were assessed. Together with their evaluation, we categorize our work as critical review [26].

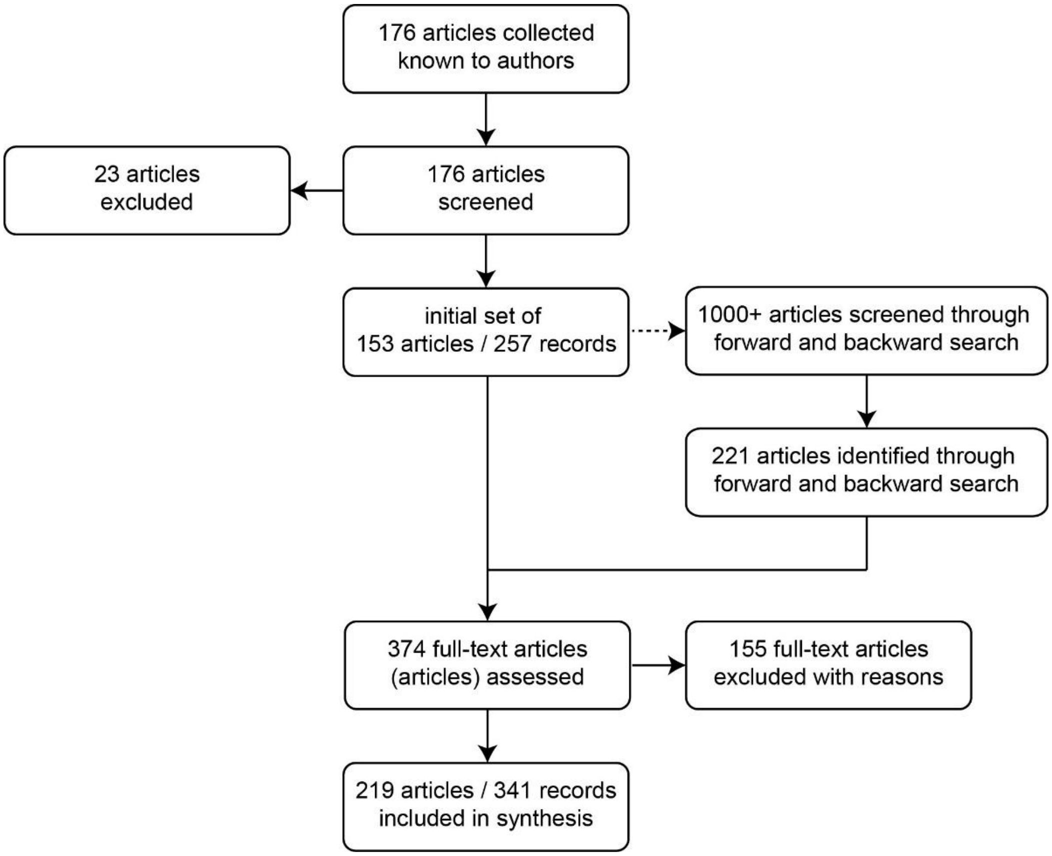

Fig. 5. Schema of the review process.

Table 1. Literature searches performed during the first phase of this review.

Database/search engine	Search terms (combinations of)
Web of Science	"thermal", "visual", "acoustic", "comfort", "satisfaction", "perception", "behaviour"
Scopus	"thermal", "visual", "acoustic", "personal", "contextual", "multi-domain", "comfort"
Science Direct	"occupant behaviour", "multi-domain", "model", "combined effects"
Google Scholar	"thermal", "visual", "acoustic", "comfort", "satisfaction", "perception", "behaviour"
Google Scholar	"indoor factors", "interaction", "combination"
Google Scholar	"Occupant", "thermal", "comfort", "satisfaction", "visual", "behaviour"
Google scholar	"occupant behaviour", "multi-domain", "model", "combined effects"
Deakin University library (linked to several databases)	"thermal comfort", "visual comfort", "acoustics"

2.1 Selection process

The units of analysis were the articles and their records. A record is defined as a dependent variable analysed within an article. As such, one article presenting analysis for two or more dependent variables (e.g. analyses of thermal and visual perception as dependent variable) has an equivalent number of records.

The exclusion criteria were: (1) out of scope; (2) other than English language; (3) full text unavailable, and (4) not peer-reviewed. In addition, (5) duplicates such as conference and journal articles presenting the same research were considered once; and (6) review papers without additional analyses such as meta-analysis were not considered.

2.2 Records' structure

The following data were extracted: dependent and independent variables; number (N) of participants, offices, and/or buildings; sex and age distributions; number of votes obtained or length of study; type of study (e.g. field or laboratory); type of building (e.g. residential or office); type of conditioning (e.g. naturally-ventilated (NV) or air-conditioned (AC)); region in which the study was conducted; data collected; statistical approach applied, and key findings.

In addition, introduction and discussion sections were scanned for the study's motivation and gaps/future research needs mentioned.

3. Comparison between perceptual and behavioural multi-domain approaches

Multi-domain approaches with perception as a dependent variable (244 records/163 articles) are three times more frequent than behavioural multi-domain studies (97 records/64 articles). Note that eight articles report results from perceptual and behavioural dependent variables (see the complete review table: https://osf.io/gnvp2/?view_only=00b08233881f471795d1d8dee79e9828). The most frequent approach in perceptual and behavioural studies was a combination of one or more physical factors with contextual variables (Figure 6).

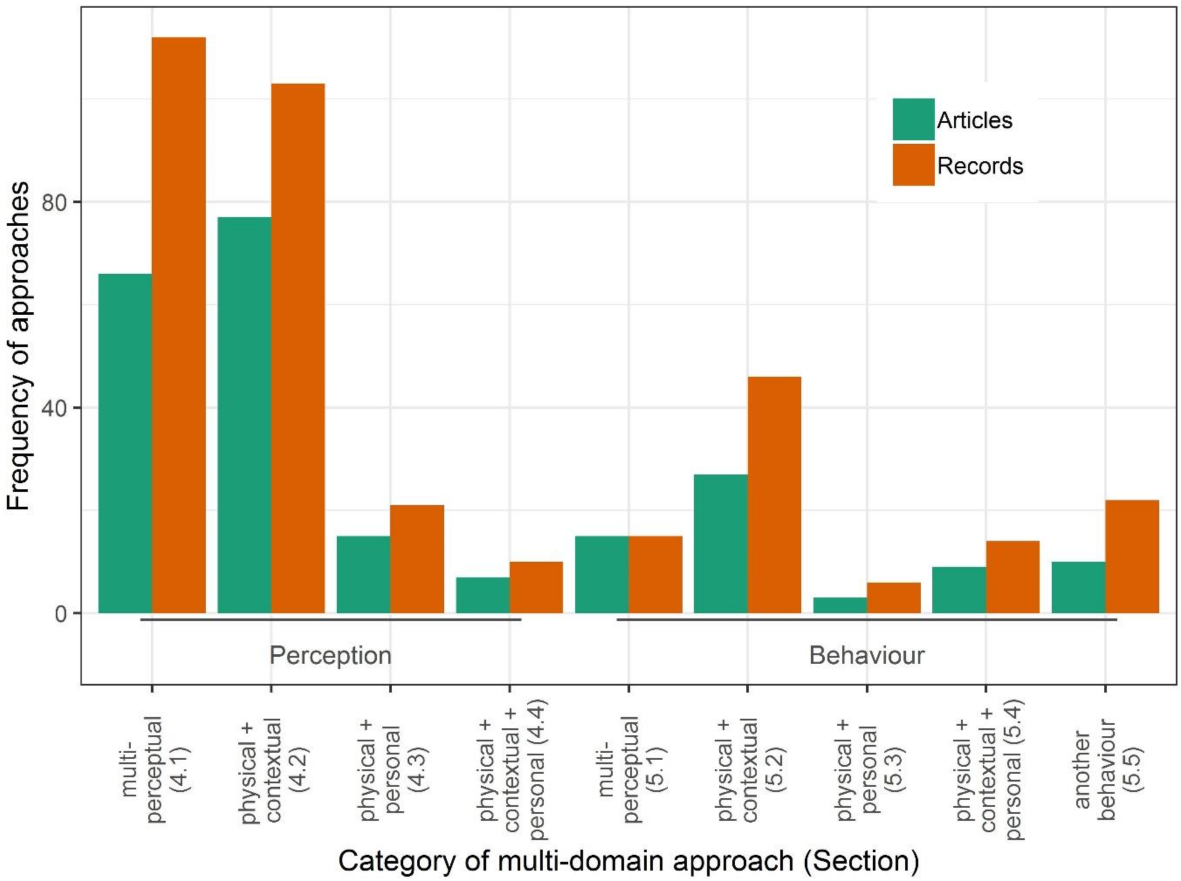

Fig. 6. Frequency of studies reviewed per approach.

In both research areas, perception and behaviour, field studies are the most frequent methods used (Figure 7). Laboratory studies only dominate in studies, which examined multi-perceptual effects without contextual or personal variables.

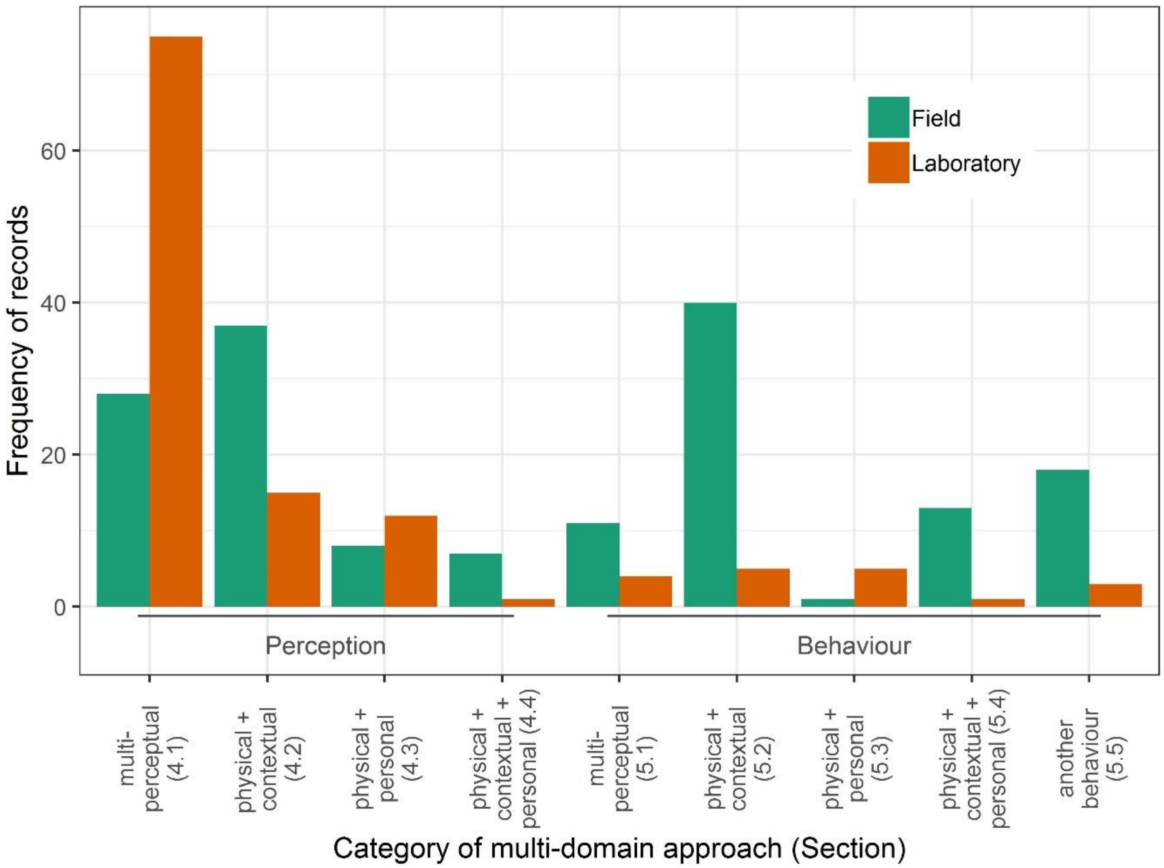

Fig. 7. Frequency of records separated by type of study.

The sample size varies according to the type of sample analysed, i.e. whether authors reported buildings, rooms, or participants (Table 2). The number of participants in laboratory studies ranged from 5 to 199 with nearly half of the studies with less than 30 (mean 45.6, SD 42.2, median 30). In field studies, the largest number of participants (N= 52,980 and N = 29,632) were observed in two studies combining physical and contextual variables (subsection 4.2) using existing databases of online surveys [27; 28] (mean of all field studies 824.1, SD 3178, median 138). Sample sizes below 10 participants were observed in several subsections. Arguments were for example an integral research approach triangulating between four qualitative and quantitative methods [29] or in-depth insights by gathering detailed information through interviews and discussions [30]. The number of buildings varies from 1 [31] to 351 [27].

Table 2. Number of participants, offices, or buildings by category. N = number of records, Min = minimum, SD = standard deviation, Med = median, Max = maximum.

Section	Participants						Rooms/offices						Buildings/households					
	N	Min	Mean	SD	Med	Max	N	Min	Mean	SD	Med	Max	N	Min	Mean	SD	Med	Max
4 Perception																		
4.1 Physical multi-perceptual	109	6	99.3	186.6	35	990	0						3	1	2	1	2	3
4.2 Physical + contextual	82	7	1525.9	6674.6	168	52980	10	1	6.3	5.3	4	18	34	2	38.6	84.2	14.5	351
4.3 Physical + personal	16	20	557.9	1852.4	93	7500	8	6	56.5	51.9	46	120	6	2	4.3	3.8	2	11
4.4 Phys. + cont. + pers.	9	35	295.4	206.3	400	482	0						1	8	8		8	8

5 Behaviour																		
5.1 Physical multi-perceptual	9	5	42.2	44.8	20	128	4	1	3.5	3.1	2.5	8	4	9	17.8	6.1	19.5	23
5.2 Physical + contextual	11	17	504.9	891.3	36	2787	18	3	83.6	159.2	14	555	20	1	30.5	28.9	16.5	70
5.3 Physical + personal	4	65	65	0	65	65	2	6	63	80.6	63	120	1	2	2		2	2
5.4 Physical + cont. + pers.	6	32	1091.8	905.3	933	2787	2	4	4.5	0.7	4.5	5	4	13	35	14.7	42	43
5.5 Physical + multi-behavioural	11	8	18.5	9.3	21	40	6	3	8.5	3.6	8	14	4	1	1	0	1	1

The geographic distribution is presented in Table 3. Studies were predominantly conducted in Central Europe, North America, and Eastern Asia.

Table 3. Geographic distribution of records

Section	Africa	Asia	Europe	North-America	Oceania	South-America
4 Perception						
4.1 Physical multi-perceptual	1	44	38	9	0	0
4.2 Physical + contextual variables	0	22	34	28	2	1
4.3 Physical + personal variables	0	3	10	6	0	0
4.4 Physical + contextual + personal variables	0	2	2	0	1	0
5 Behaviour						
5.1 Physical multi-perceptual	0	8	1	2	0	0
5.2 Physical + contextual	0	3	13	3	0	0
5.3 Physical + personal	0	0	5	1	0	0
5.4 Physical + contextual + personal	0	3	2	0	2	0
5.5 Physical + multi-behavioural	0	0	16	2	1	0

4. Perceptual studies

This section is divided into four subsections: physical; physical and contextual; physical and personal; and physical, personal, and contextual. In each subsection, we reflect on the motivational background, the methods employed for data collection and analysis, and some of the key findings. We conclude each subsection with thoughts on the current state of the art, prevailing knowledge gaps, and future research needs.

Figure 8 summarises the findings on crossed main effects on thermal, visual, IAQ, and acoustic perception referred to in the following.

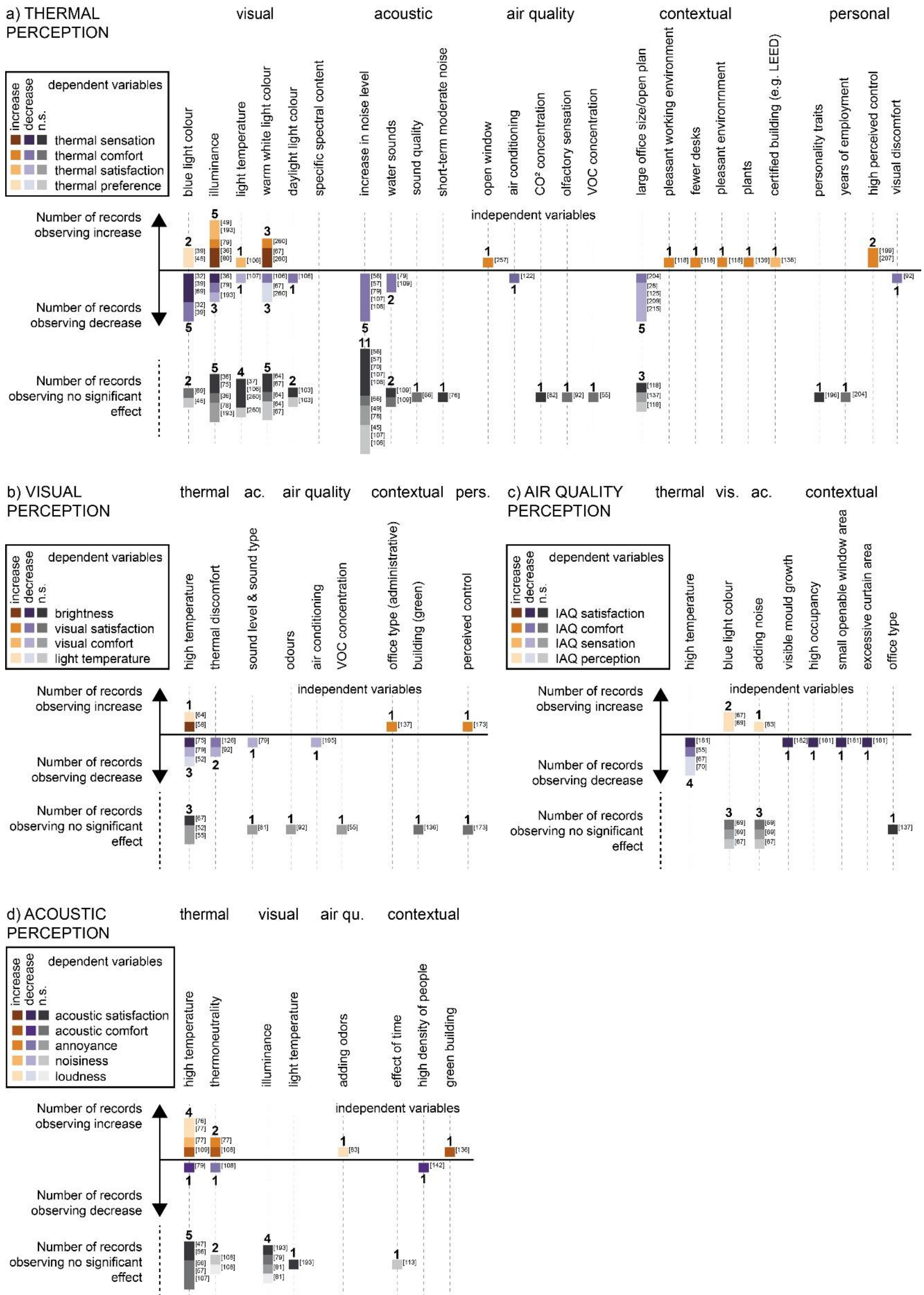

Fig. 8. Overview of crossed main effects related to thermal, visual, air quality and acoustic perception based on studies including significance tests.

4.1. Physical multi-perceptual approaches

A considerable number of studies addressed the effects of multiple environmental factors on occupant perception. While not all these studies specifically address the combined effects of multiple indoor environmental variables, most acknowledge at least their concurrent presence [32-109]. In the following, we focus on a number of these papers and their contributions, directly relevant to the topic of multi-domain exposures.

4.1.1 Motivational background

The majority of the studies cite the need for better understanding of exposure situations involving multiple indoor environmental variables. Other studies observed effects of multiple environmental variables without a specific intent to examine their interactions [53; 62]. Studies considered different combinations of environmental variables, most frequently thermal and visual [34; 37-39; 52; 67; 102-104]. A few studies investigated other combinations of variables, such as visual and acoustic [45], thermal and acoustic [56; 57; 66], visual and IAQ [59], acoustic and IAQ [83], visual, thermal, and acoustic [48; 49; 62; 70], as well as IAQ, thermal, and acoustic [35; 41]. Researchers were mostly interested in the effect on dependent variables such as occupants' comfort, sensation, and preference [34; 39; 48; 52; 66; 102-104]; and satisfaction [59; 68].

4.1.2 Approaches

The majority of papers involved short-term laboratory studies in office settings. Only in a few studies, participants were given the opportunity to adjust certain factors of their immediate surroundings [45; 59] or exercise a choice upon experiencing different settings [40].

Experimental settings typically involved different properties of the physical environments such as air temperature (thermal environment), sound type and level (acoustic environment), illumination level, glare intensity, light colour (visual environment), and airflow rates (thermal and air quality environment). Laboratory studies typically lasted a few hours or up to a day. Typically, experiments tested one or more levels of a physical variable crossed with one or more levels of another physical variable (e.g., three levels of temperature crossed with two levels of illumination, as in Kulve et al. [104]), while holding other indoor environmental variables constant.

The majority of experiments had within-subject designs, that is, all participants experienced all experimental conditions, typically counterbalanced by randomising the order of conditions. Within-subject experiments are more sensitive to the manipulation of independent variables, which is important for studies with smaller sample sizes.

The occupancy-related implications of environmental factors were queried using techniques such as surveys and questionnaires (e.g., [48]), comfort and sensation scales (e.g., [66]), and visual observations (e.g., [70]).

As expected, data analysis involve various well-established formats and techniques from descriptive and inferential statistics. The collection of statistical methods commonly referred to as ANOVA (Analysis of Variance) is frequently deployed for processing and interpretation of measurement results [40; 45; 52; 66; 68; 70], as are mixed-effects models [37; 39; 49; 67; 104].

In the majority of the less frequent field studies, the setting was a university classroom and participants were students. However, field studies were also conducted in office, hospital (e.g., [34]), and residential settings [50]. Field studies typically lasted several months.

Environmental physical conditions were monitored and participants were asked to rate their perceptions through questionnaires on comfort, sensation and satisfaction (e.g., [53; 105]). Measurements of environmental conditions were associated with participants' subjective ratings, and the subjective ratings with each other, using measures such as correlation [105] or ANOVA [106]. Field studies enabled the variation of environmental conditions for large samples of subjects (e.g., 331 students in 7 varied classrooms [105]).

4.1.3 Findings

Studies described in the reviewed papers entail a host of valuable findings (Figure 8). Tiller et al. [66] reported a slight effect of acoustical conditions on subjective ratings of thermal comfort, but no reverse effect. Nagano and Horikoshi [56] concluded that operative temperature has a slight effect on auditory comfort sensation votes and thus that the thermal environment must be taken into consideration in acoustical studies. On the other hand, they did not observe any effect of noise on reported thermal sensation. On the contrary, Pellerin et al. [107] indicated a noise effect on thermal comfort in warm conditions, but not of temperature on acoustic sensation, comfort, and preference. Yang et al. [108; 109] reported that thermal comfort decreased with increased noise level, and with the noise of a fan as compared to that of babble, and that water sounds increased cold sensation and decreased thermal comfort. The authors also observed the influence of the thermal environment on acoustic comfort and sensation, but with contrasting findings, as they report a decrease of annoyance and an increase of acoustic comfort at thermoneutrality [108] as well as an increase in acoustic perception and annoyance at thermoneutrality [77; 109].

Nakamura et al. [58] reported that higher colour temperature is preferred in summer and vice versa in winter. Fanger et al. [45] observed slight lighting effects on thermal comfort: people preferred a slightly lower temperature under red light than under blue light. Similar results were reported by Albers et al. [32] and by Winzen et al. [69], with electric light colour affecting thermal sensation, comfort and temperature estimation. Chinazzo et al. [39] suggested that participants' thermal sensation reports were influenced by the colour of the daylight. For instance, as compared to orange daylight exposure, a colder thermal sensation was reported in the case of blue daylight, even though the measured temperature remained the same. Daylight quantity was also reported to affect thermal perception, with increased thermal comfort under dim daylight conditions in a warm environment and under bright daylight conditions in a cold environment [103]. However, the authors indicate no effect of daylight illuminance levels on thermal sensation [103], similarly to what was reported by an earlier study with electric lighting [75]. Meanwhile, Azmoon et al. [34] observed improved thermal comfort responses because of increased light intensity.

Unexpected effects were sometimes found on variables that were not the focus of the experimental study. For example, people reported IAQ differences across temperature settings [67], or across combinations of acoustic, lighting, and temperature settings [49]. In some cases, papers noted significant effects only under restricted conditions. For example, Geng et al. [47] observed that people were less satisfied with IAQ and lighting under certain temperature settings, but not others. In some cases, papers noted statistically non-significant interactions between environmental conditions. For example, Pan et al. [83] observed that adding noise to odour mitigated the effect of odour on air-quality-related measures. However, with a sample sizes of N = 9, small interaction effects are unlikely detected.

Many studies observed no interactions between environmental factors tested (e.g., [37; 38]), or were not designed in a way to investigate these interactions (field studies).

4.1.4 Identified gaps and future directions

The review of multi-physical perceptual research shows the extent of valuable knowledge generated over the past five decades. However, the yield is less extensive and less conclusive if we specifically query for frequent, clear, and consistent instances of cross-modal influence. The results are in many instances inconclusive, and in certain cases even contradictory. It is thus of paramount importance to reflect upon some of the key shortcomings and limitations of past research, which correspond more or less directly to requirements for future research efforts.

Given the difficulties of conducting research including real occupants in realistic settings (involving, amongst others practical, ethical, and economic issues), it is not surprising that most studies are short-term. Moreover, the participants, often young students, are not necessarily representative of pertinent populations, for instance, of office workers. Most studies were conducted in offices, yet other building typologies such as residential buildings are practically ignored by the literature.

Researchers frequently try to establish some measure of realism in the experimental settings, but this is rarely effectual given the difficulty in concealing the inherent artificiality of the available testing facilities. As such, the reviewed studies do not truly succeed in addressing the implications of the Hawthorne effect, even though, scholars argue about its nature and suitable methods to account for it in research [110; 111].

Studies often start with some reference to previous research (frequently to authors' own previous publications), but there is very little evidence of actual carryover of past studies' findings. As such, the majority of the studies appear to practically start from scratch. Perhaps consequently, different studies do not deploy standard research designs, data collection strategies, metrics, and statistical analysis techniques, making attempts toward conducting meta-analyses factually futile.

There is arguably a paucity of collaborative, multi-institutional, international, and interdisciplinary experimental studies. Specifically, few studies seem to have truly recognized the critical importance of conceptual and methodological integration of engineering and human science methods.

One fundamental problem with most research efforts is the absence of foundational theories that would facilitate the processes of hypothesis formulation and testing. This may be of course in part due to the inherent complexity of the subject. However, the chances of obtaining scalable and generalizable results remain slim if research designs do not at least make an attempt to start from a provisional general theory of the nature of the perceptual and behavioural processes involved in multi-domain exposure situations.

4.2. Physical + contextual variables

This subsection examines studies investigating the combined effects of physical and contextual variables on environmental perception. These studies examined how context may interplay with single- or multi-sensory domain perceptions by imposing unknown or indirect influences on the physical properties of the environment or by shaping the users' perceptions and expectations in line with social or cultural experiences [27-29; 42; 112-192].

4.2.1 Motivational background

The drive for research varies greatly between the studies identified. Some researchers challenge the absence of an established single index for holistic comfort [124; 129; 167]. In other studies, the combined effects of physical and contextual variables were merely incidental rather than an intended outcome [124].

In four of the identified studies, the inclusion of contextual factors was thought to enrich environmental evaluation by factoring subjectivity into assessments typically based on only physical criteria [112; 114; 132; 149]. Similarly, some research aimed to improve post-occupancy evaluation techniques, from how data is collected or analysed [72; 168], to examine the combined influence of suspected co-contributors to satisfaction in a single-sensory domain [169].

We identified three distinct research themes focusing on specific building attributes. One addressed the concurrent influence of environmental and spatial factors present in open-plan office space configurations [42; 113; 137; 142; 170], a second examined limitations of green building design and rating systems [125; 127; 136; 171], and a third concerned the impact of the presence of control opportunities [115; 116; 172; 173].

4.2.2 Approaches

In contrast to the studies reviewed in section 4.1, the interest seems to be more in real settings, shown by the majority of studies applying field study approaches. Here, the influences of the contextual factors can be examined with limited cost and reduced difficulty in the experimental set-up.

Subjective evaluation through surveys is a common approach for data collection of comfort or satisfaction based on the self-reporting of participants [27; 28; 174]. Several studies involve measurements of indoor environmental quality metrics related to thermal, acoustic, and visual properties alongside with occupants' subjective votes [42; 74; 124; 129; 136; 137; 142; 144; 145; 169; 170; 175-177].

The most frequent building typologies were office buildings (e.g. [115; 119; 126; 134; 140; 143; 147; 178-180]) and educational buildings (e.g. [116; 120; 123; 181-183]), followed by residential buildings [122; 153; 175], hostels and student residences [42; 121], restaurants and cafés [132; 142], factories [118; 184], a healthcare facility [150], a shopping mall [141] and airport terminal [47].

The length of data collection differed depending on the methodology and the research focus. Longitudinal studies ranged from months to years [171; 185]. Studies employing structured or semi-structured interviews may span over several seasons [141; 186; 187]. Short survey or interview studies last usually no more than two months [148; 150; 153], but can be as short as a few days [124; 125; 140; 143; 174; 181; 188].

The most common approach used in almost all studies are summary statistics, including mean and variance. In addition, several types of correlational analysis, parametric and non-parametric tests are common approaches.

Overall perception was the most frequently researched dependent variable, followed closely by thermal perception and then by visual perception, acoustics, and IAQ. Metrics for overall perception ranged from mainstream choices such as overall satisfaction, acceptability or comfort (and even 'uncomfortableness') to measures of 'psychic well-being", preference for space and affective quality of space. The metrics used for thermal, visual, acoustic, and IAQ perceptions were more conventional, with higher variance for the visual domain, including satisfaction with lighting, glare perception, eye discomfort and appearance of the environment.

4.2.3 Findings

The influence of geographic location is not conclusive. With similar climate conditions, occupant responses to warm and cold weather tend not to differ greatly across countries [28]. Similarly, Sakellaris et al. [157] found minimal differences in multiple types of perception between two locations. In contrast, thermal and IAQ perception differed between occupants of the same country, especially for those countries with a large north-south spread [98].

The interior design and furniture in office and school settings correlated strongly with comfort [135; 133; 143; 151; 157]. Perception of illuminance level strongly depended on office layout and furniture type [123; 183; 189]. Furthermore, since daylight levels exhibit strong spatial dependence, visual comfort at workplaces varied greatly with proximity to the window [27; 151].

The perceptual aspects of visibility in classrooms [183; 189], privacy in offices [27; 151], and available space in offices [27] are additional factors associated with room layout and furniture selection, which correlated with visual and overall comfort levels. Few studies recommend optimal office layout or furniture selection for comfort. This is likely due to the subjective and non-quantifiable nature of these properties.

One of the most important components of the building envelope is the window [190]. Poor thermal comfort (e.g., cold or warm window) [175; 191], daylight glare [191], and poor acoustic comfort [191] are reported by participants in large-windowed residential or office buildings. Additionally, the design of solar control devices and solar control techniques can affect occupant comfort, especially thermal and visual. For instance, Karlsen et al. [192] demonstrate that occupants prefer venetian blinds with adjustable slat angles to those with only on-off position. These handful of studies are among the few that made conclusions from surveys, while the majority of other studies use simulation approaches beyond the scope of this review.

Perception and comfort in green buildings vs. conventional buildings varied greatly among studies. Two studies demonstrated that occupants' overall comfort is higher for green buildings [127; 144]. In contrast, Gou et al. [128] observed no significant difference in overall comfort between these building types. The contrasting results may be due to two reasons. First, the overall comfort can be influenced by occupants' attitude towards the "green" identity of the building [171]. Second, the term "green" building is not universally defined, and used for buildings that are certified by different standards (e.g. LEED [144], LEED and GBL [128], BREEAM [171]). These standards differ significantly in their assessment criteria. Consequently, the building performance can vary largely.

NV and passively cooled buildings that allow occupants to control aspects of the indoor environment, excited positive thermal comfort perceptions outside the fixed temperature limits set in standards [120; 130; 148; 180]. Moreover, controllability strongly increases occupants' satisfaction with thermal indoor conditions in winter and summer [28; 120; 130; 148].

4.2.4 Identified gaps and future directions

The contextual variables discussed in this paper are those mentioned in the literature. Further research would be needed to evaluate whether the most researched dependent and independent variables are the most influential.

Among the building related parameters, façade design and interior design are crucial. Few studies use a surveying approach to evaluate façade design options. Thus, further field surveys are needed to associate occupant multi-domain perception with design decisions. Simulations alone cannot substantiate the claims, as they may not truly reflect the actual indoor environment. Spatial information is merely described in the text. For future studies, publishing this information in a visual format is desirable, e.g., with photos and architectural drawings such as floor plans, sections, or elevations, which can convey the spatial situation better. Examples of appropriately published spatial architectural information exist [29; 125; 142]. In general, further research on spatial characteristics would be desirable, because spatial characteristics and typologies also depend on building types and the number of studies considering each building type is currently small.

In most studies, the context was represented by one or a few variables. However, context is a complex system of multiple dynamically interacting variables. For example, visual perception varies with the location of a workplace within a floor plan [169], but the occupants' perception is further influenced by other spatial parameters such as orientation and fenestration of the façade [175], climate related parameters such as season, sun path/latitude [126], and indoor surface materials [114]. Our review identified no study, which investigated the complexity and interplay of multiple contextual variables, which is likely due to methodological challenges with required data types and the needed quantity of data. New methodological approaches might be needed for future studies to describe and understand the complexity and interplay of contextual variables.

Most papers used statistics for data analysis, and these methodologies tend to require large sample sizes for higher validity. If context is evaluated at a high level of resolution, i.e. with in-depth analysis of the spatial geometric or architectural design characteristics, it is unlikely that large sample sizes exposed to identical characteristics can be obtained for all building types. Therefore, a broader variety of approaches and methodologies could expand the investigated contexts.

4.3. Physical + personal variables

This subsection concerns thirteen studies that combine the impact and mutual influence of measured indoor environmental conditions and personal variables on occupants' perception [52; 168; 193-203].

4.3.1 Motivational background

In some studies, the analysis of personal variables is tangential and brief, while in other studies, the main purpose and motivation is to understand how personal variables influence occupants' perception. The analysis of personal variables is important to understand the differences in perception observed among individuals or groups in similar environmental conditions [196]. Nevertheless, all experimental studies aimed to evaluate the possible correlation between personal variables and the different domains of environmental perception.

4.3.2 Approaches

Studies include one or more dependent variables related to thermal, visual, acoustic, IAQ, or overall perception. Other studies considered productivity as a dependent variable together with comfort perception [202], which is out of the scope here.

Almost all studies were conducted in office or educational buildings or in controlled chambers that simulate a working environment. Only one study was found concerning a non-office commercial building, a shopping centre [193].

Field studies including physical measurements and questionnaires dominate in this subsection. For a higher control and a broader collection of the physical variables, some studies used laboratories that reproduce commercial [193], educational [52; 197], or office environments [194; 196; 198]. One study is based on questionnaires [168]. Yun [199], instead, applied a mixed methodology to evaluate the energy implications of personal variables, specifically of perceived control.

The applied statistical analysis methods largely vary among the studies, ranging from ANOVA and MANOVA [197; 198; 203] to regression [196], correlation analysis [52; 168; 193; 194], and non-parametric analysis [195].

4.3.3 Findings

Overall, findings showed that personal variables significantly influence multi-domain comfort perception positively or negatively.

Occupants' perceived control and satisfaction with building management are among the key analysed personal variables significantly interacting with the overall perception. Robertson et al. [195] highlighted that workers' visual comfort and personal wellbeing are influenced by perceived control over lighting, especially in non-naturally ventilated buildings. Additionally, occupants' reduced perceived control over the indoor environment has a significant negative effect on their thermal comfort [199] and general perception of a building [168]. On the contrary, the availability of choice over lighting control were demonstrated to decrease occupants' perceived importance of lighting in offices [198] and their performance [197]. Focusing on the interaction of thermal, acoustic, and visual domains, Dang et al. [193] showed that, although thermal and acoustic personal satisfaction are not directly correlated with lighting parameters, they interact with personal lighting satisfaction. On the other hand, a significant effect of thermal variables and clothing level on visual perception was obtained only in artificially illuminated buildings, since in daylight the influence of other parameters, e.g. acoustics, becomes relevant [52]. Finally, Schweiker at al. [196] demonstrated that personality traits, i.e. neuroticism, extraversion, openness to new experiences, are moderating thermal perception. Focusing on physiological parameters, Pigliautile et al. [194] highlighted that a multi-domain approach is required to understand human comfort thoroughly.

4.3.4 Identified gaps and future directions

Generally, very few studies were identified that deal with the interaction of multi-domain perception and personal variables beyond demographics. Moreover, many of these studies concern the impact of perceived control on environmental conditions and less focus is given to other personal variables. In addition, many studies simply report the differences observed among occupants with different personal variables without attempting to understand its motivation, which limits their contribution to the factual understanding of the influence of personal variables. Another important gap is the small sample size and the lack of diversity of the samples. Although gender balance is generally fulfilled, many of the studies selected university students for their experiments. Finally, none of the reviewed papers include a study focused on residential environments. While certain personal variables, such as perceived control and privacy, might be less significant in residential spaces compared to office buildings, other variables, such as the expectation of building performance and energy/money saving might be significant, and thus worthy of exploration.

4.4. Physical + contextual + personal variables

While some of the studies discussed in the previous subsections explored physical, contextual, and personal predictors of perceptions, none aimed to understand the interactions of these independent variables. The current subsection covers eleven research efforts that addressed this gap by simultaneously examining at least one predictor variable from each category [30; 72; 125; 204-211].

4.4.1 Motivational background

All studies promote a multi-domain approach to perceptual evaluation. For instance, Jin et al. [211] highlight the need to study physical (i.e., objective) and non-physical (i.e., subjective) drivers of occupants' perceptions with their indoor environment. Pivac et al. [204] state the importance of physiological and social factors in the evaluation of perceptions. Indraganti et al. [209] focus on the role of occupants' demographic and personal characteristics while assessing thermal comfort. Hitchings et al. [30] highlight the need to study cultural, geographic, and seasonal adaptation effects. Other studies aimed to understand overall environmental satisfaction levels [72; 125]. Overall, a unified and explicit goal of proving that physical, contextual, and personal variables combine to explain perceptions is lacking.

4.4.2 Approaches

Ten of the reviewed articles are field studies conducted in non-controlled building environments, while one [206] took place in a laboratory controlled office setting. The studied environments were office [125; 204-208], residential [30; 72; 209; 210], and retail buildings [211].Dependent variables considered included domain-specific comfort metrics such as thermal comfort [30; 204; 209], neutral temperature [206], visual comfort [211; 205], and acoustic comfort [210]. Two studies [72; 125] considered domain-specific comfort metrics and overall perceived comfort levels of the respondents.

Data collection was carried out through environmental sensing devices, questionnaires, walkthroughs, inspections, interviews, and diaries. The data collection duration varies from one-time surveys (e.g., [210]) to data collected over an extended period of time (e.g., 40 days in Sadeghi et al. [205]).

The data analysis approaches include qualitative and quantitative assessments. Starting with the former, Hitchings et al. [30] used a qualitative analysis of the collected data. The other studies mostly applied statistical analysis methods to derive relationships between, on the one hand, the environmental, contextual, and personal data that were collected, and on the other, the respondents' perceptions of comfort. The statistical methods include ANOVA [125; 210], X^2-tests [72], Mann-Whitney U-test and the Kruskal-Wallis test [204], correlations [72; 205; 210; 211], and linear regression [205; 206; 209-211; 125].

4.4.3 Findings

While this subsection covers a broader scope of predictor categories than previous sections, the results are not more diverse. The results do not explicitly confirm that physical, contextual, and personal predictors collectively drive the reported perceptions. The findings of the articles are mostly identifying single or dual types of interacting perception drivers, which is in line with the observations of previous subsections.

Starting with thermal perception, Pivac et al. [204] found that environmental metrics, office type, and job type have a significant influence on the perceived thermal comfort. Indraganti and Rao [209] observed a strong correlation between the respondents' economic group and their reported comfort levels, and weaker relationship with the other considered variables such as season and tenure. Schweiker and Wagner [206], on the other hand, highlight a significant influence of perceived control on neutral temperature, while office type affected perceived control.

Related to visual perception, Jin et al. [211] found that the measured illuminance level is the dominant driver of visual comfort, while the existence of daylighting plays an essential role in subjective satisfaction. Sadeghi et al. [205] found a strong relationship between the occupants' perception of control and their acceptability of a broader range of visual conditions.

In Park et al. [210], the authors studied potential drivers of subjective responses to floor impact noise in residential buildings. They highlight a significant impact of noise sensitivity and floor slab thickness on the reported acoustic comfort levels.

The main observation by Xue et al. [72] and Freihoefer et al. [125] is a significant difference in the reported overall comfort levels between workspace types (open and closed). Xue et al. [72] found that the combined effect of thermal comfort and IAQ significantly influences visual comfort, while the abundance of daylight hours and illuminance levels showed strong positive correlations with reported visual perceptions. More interestingly, the authors confirm strong dependencies between pairs of variables such as IAQ/thermal comfort and room orientation, adaptive behaviours of shading/lighting and visual comfort, and finally, mental stress and acoustic comfort.

4.4.4 Identified gaps and future directions

The findings presented above do not provide a clear understanding of the interactions nor fundamentals of the combined effect of physical, contextual, and personal predictors of perception. The findings cannot be generalized given the small sample of studies that met the criterion used for inclusion in this subsection. Furthermore, the data analysis methods applied were mostly constraint to studying relationships between a limited number of variables (in many cases two variables), falling short of providing a comprehensive understanding of the influence of multi-variable predictors and their interactions. More extensive diversity of predictors and complexity of analysis tools (e.g., Principal Component Analysis and Artificial Neural Networks) can be considered in future research to draw more diverse and comprehensive conclusions on the drivers of occupant perceptions. Finally, except for Schweiker and Wagner [206], none of the studies were conducted in controlled environments, which is another potential avenue for exploring multi-domain predictors of perception.

5. Behaviour

This section summarizes studies considering the relationship between measurable conditions of indoor environmental quality and occupant behaviour.

Figures 9 to12 show the crossed main effects of multiple independent variables on different types of behaviour, which will be discussed in the following subsections.

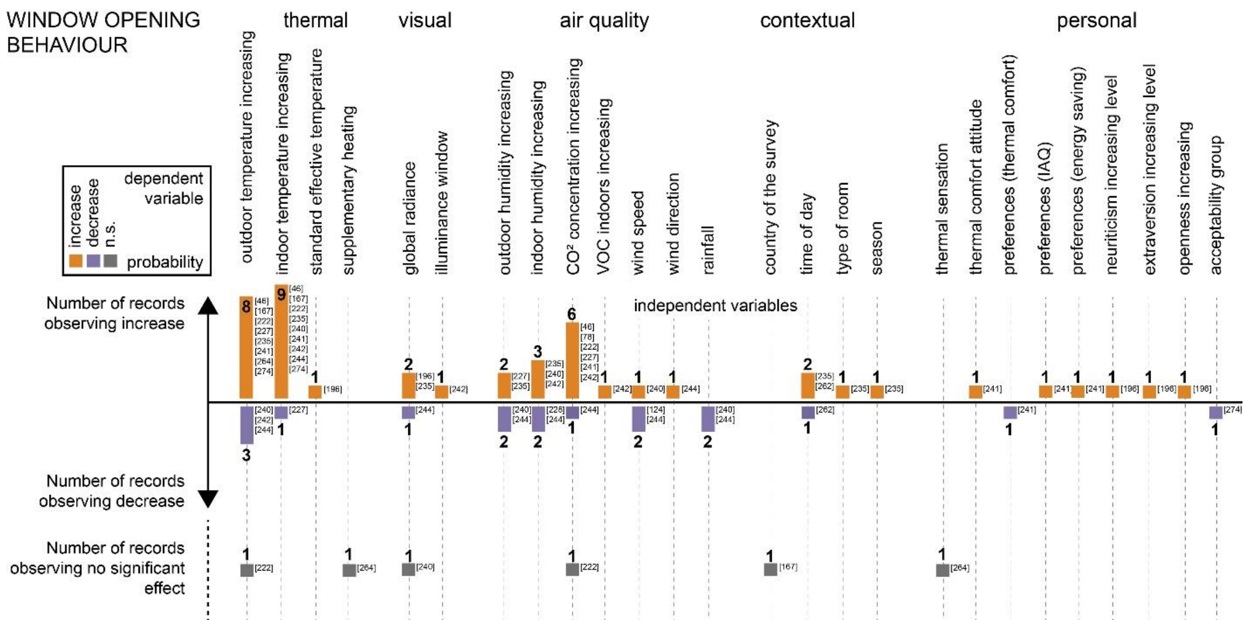

Fig. 9. Effects of physical, contextual and personal variables on window opening behaviour

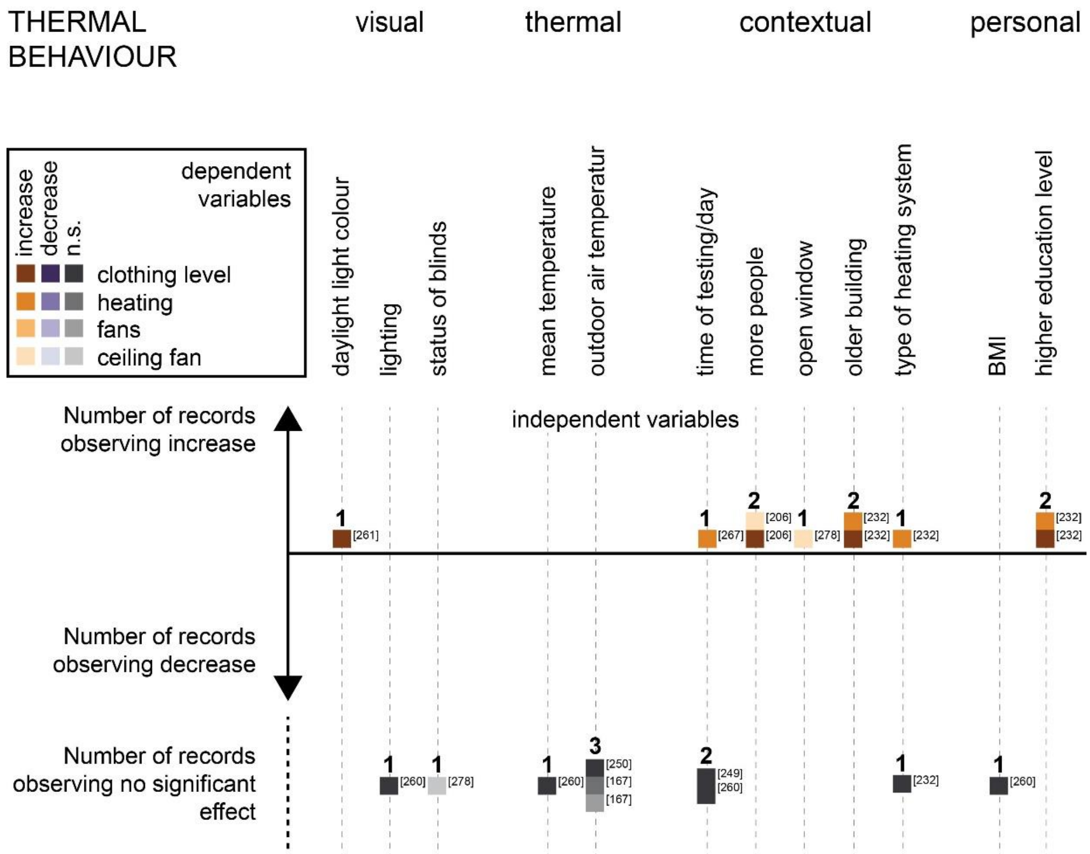

Fig. 10. Effects of physical, contextual and personal variables on different types of thermal behaviours.

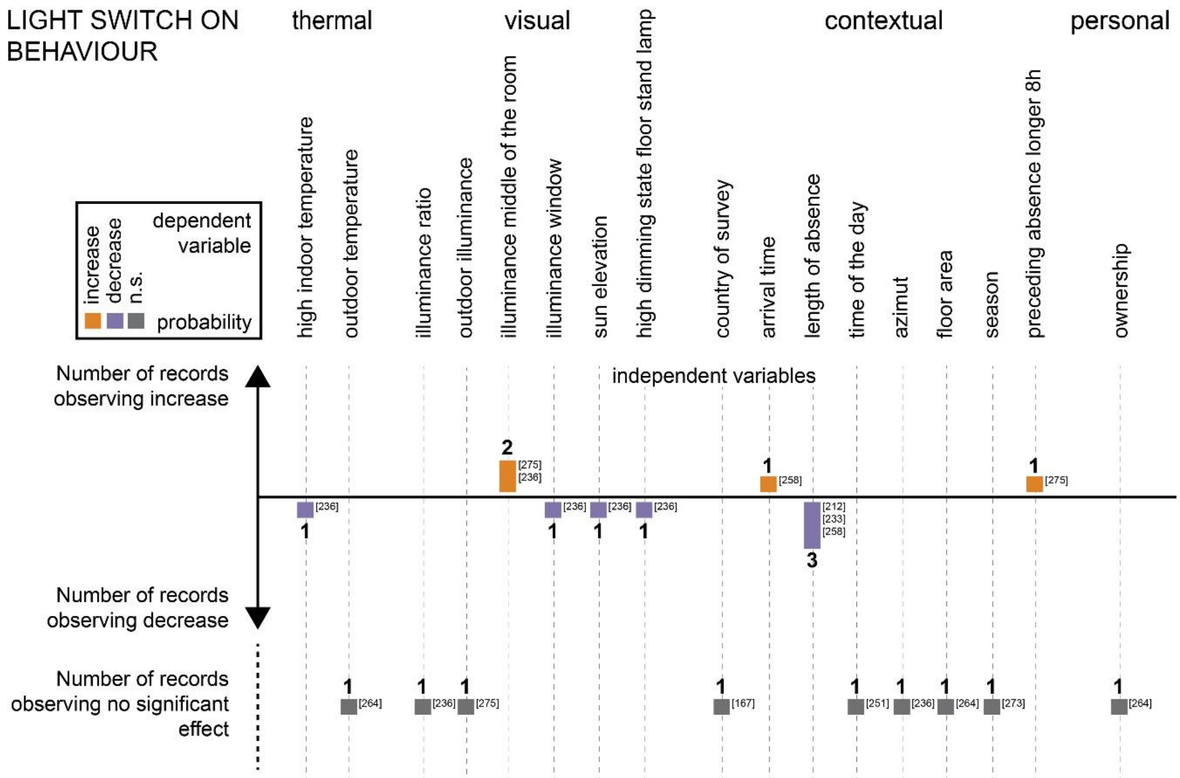

Fig. 11. Effects of physical, contextual and personal variables on light switch on behaviour.

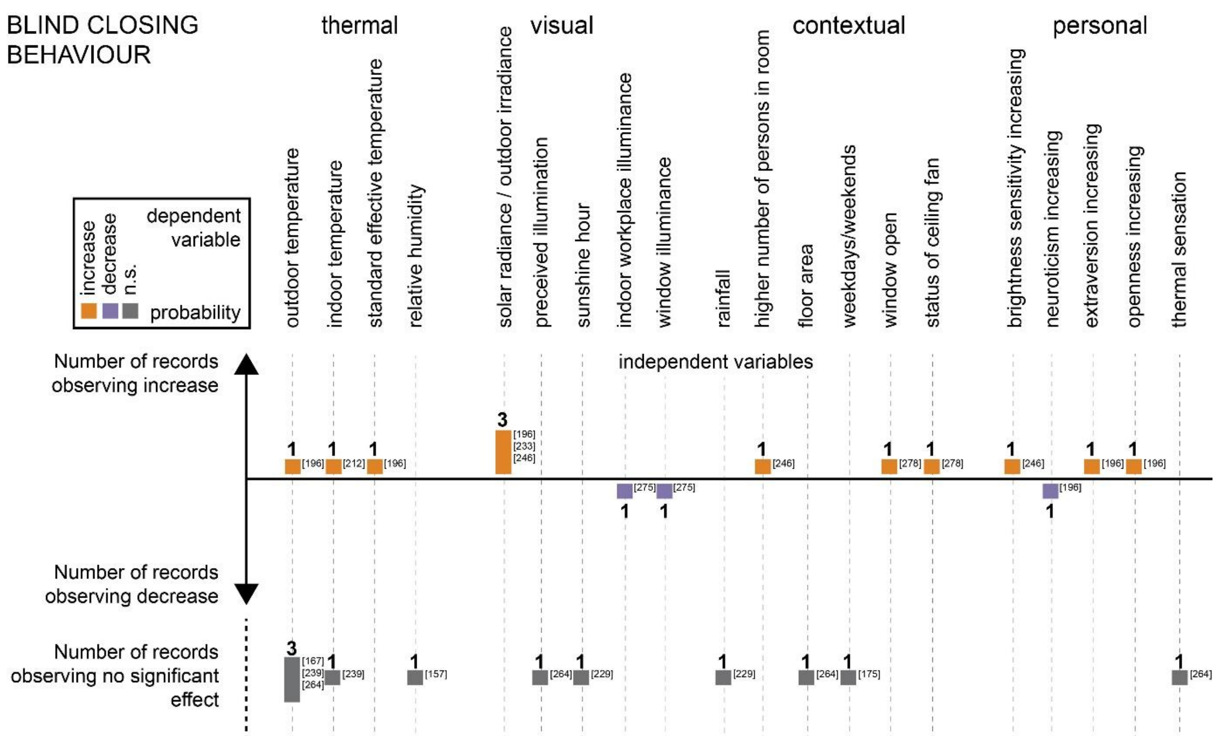

Fig. 12. Effects of physical, contextual and personal variables on blind closing behaviour.

5.1. Physical multi-perceptual approaches

The nineteen studies analysed in this subsection attempt to relate occupant behaviour to multi-perceptual physical environmental conditions [46; 212-229].

5.1.1 Motivational background

The motivation behind the majority of these studies was to evaluate the drivers of occupant behaviour in the context of multiple domains of occupant comfort. In general, all of the studies aimed at a better forecasting and simulation of occupant behaviour under multiple indoor environmental performance criteria. Specifically, all but few studies were concerned with the effect of indoor and outdoor climatic conditions on occupant control of windows, blinds, and/or lighting, as well as the derivative effect of such control on perceived thermal comfort, lighting comfort, and/or building energy use.

The underlying objective was the characterization of the relationship between measurable physical parameters, and occupant behaviour. Specific objectives include the evaluation of the effect of solar insolation on perceived thermal comfort, lighting comfort, and occupant controls of window blinds [215] and the development of a data-driven personalized thermal comfort model and minimum daylight requirement model to be used for model-predictive control of window blinds [213].

5.1.2 Approaches

All reviewed papers relied to some extent on physical monitoring of indoor environmental conditions and direct monitoring or measurement of occupant control decisions (e.g., window opening behaviour). Most studies undertook some form of occupant comfort evaluations via questionnaires, and several papers undertook monitoring of outdoor climatic conditions (e.g., outdoor air temperature, and air pollution concentrations).

All but few papers described *field* studies of offices or dwellings. The exceptions were *laboratory* studies [214; 218; 219]. All field studies took place in regions where there are discernible heating and cooling seasons, and no studies were undertaken in climatic regions such as the Tropics or Sub-Tropics.

The duration of behavioural studies followed one of three trends: they undertook either a short duration of measurements in a manner of days [214; 219], a medium-term measurement across a single climate season [212; 221; 227], or a much longer-term study across several seasons up to an entire year or more [46; 213; 215; 216; 222; 224-226; 228; 229]. The shortest measurements had the controlled laboratory studies. A notable example is Daum et al. [213], who collected over 6,800 individual survey responses over a period of 3 years.

The studies' methods of data analysis were, for example, correlations between the probability of an action and environmental variables. For example, Inkarojit [215] evaluated the correlation of the probability of occupants' opening or closing windows against received solar radiation on window surfaces. Similarly, Daum et al. [213] used their analysis to correlate the probability of window blinds opening/closing actions against indoor air temperature. Various forms of regression methods, such as linear regression, multiple linear regression, univariate and multivariate logistic regression, were used by all studies.

5.1.3 Findings

Given an underlying, often implied understanding across all studies that occupant behaviour is inherently stochastic, the main format of illustrated findings were probability density functions of occupant behaviour against one or more parameters.

The findings from these papers defended widely understood principles of thermal and visual comfort in the built environment, as opposed to revolutionising them or putting them into question. For example, the studies which evaluated the extent to which window open/close behaviour would be driven by outdoor climatic conditions, IAQ, or other parameters, broadly concluded that indoor and outdoor air temperature, coupled with IAQ and/or solar radiation, are the primary drivers of window control by occupants [46; 216; 217; 221; 222; 226; 228]. Outdoor air quality was identified as a moderate parameter of influence, particularly when it is considerably poor [226]. While solar radiation should be deemed a quasi-thermal parameter with a direct effect on indoor and outdoor air temperature and indoor heat gains, IAQ is related to a different domain, so that window open/close behaviour can be understood as a multi-domain problem.

All studies that evaluated the physical drivers and indicators of window blind and lighting operation [212; 213; 215; 225; 229] observed the effect of multiple environmental conditions on blind and lighting controls, but still found parameters of solar insolation to be the primary driving force of control decisions. While window blinds are a form of solar and thermal control, and electric lighting is needed in the absence of daylight, it is surprising, that all studies suggested that blind and lighting control are univariate problems determined by solar insolation alone.

5.1.4 Identified gaps and future directions

Overall, meteorological conditions were not usually measured adjacent to the buildings or sites under analysis, or at least were not indicated to have been done so. Differences in microclimatic conditions, from what is experienced directly outside a building envelope to what is measured from a central weather station, is non-negligible and is a potential limitation of correlations made between weather and human behaviour [226].

Of the studies examining window opening/closing behaviour, works such as Jeong et al. [216] indicate that caution must be taken when data from only one or two seasons are used. In other words, drivers of behaviour in winter may not apply in summer conditions, and studies in either season may not apply to conditions under Autumn and Spring. The effort to observe occupant behaviour across multiple seasons was, if not a norm across the long-term works, an identified research gap across several of the medium-term studies. As observed by Naspi et al. [222], this view may be the main research gap of studies in this subsection.

Despite prior evidence that circadian lighting affects occupants' perception, only the experimental studies evaluated the association of circadian lighting conditions on occupant behaviour. The study of circadian lighting, both natural and artificial, and its effect on human physiology and psychology warrants further attention by field studies. None of the evaluated field studies explored whether light colours, or other indicators of circadian lighting, affected occupant behaviour. We also observed that noise levels were not frequently measured across studies that evaluated window open/close behaviour, even though the relationship between noise and window operation is not trivial [230].

5.2. Physical + contextual variables

This section provides insights into thirty-one studies aimed at predicting or explaining behaviours that include at least one type of physical and one type of contextual predictor variable.

5.2.1 Motivational background

Similar to the studies identified in subsection 5.1, one of the key objectives behind the majority of papers is to account for behaviour-related uncertainty in building energy simulation and to develop models, which are hence developed to help bridge the gap between measured and predicted energy consumption [31; 167; 203; 229; 231-243]. Some of the studies stated that their contribution was based on the need to develop models for specific geographic contexts or building types (e.g., hospital wards) [244]. Linked to this objective is the investigation of cause-effect relationships between the operation of the building by occupants and different technologies installed [245].

Other studies investigated control interaction for providing enhanced input for building automation control [246] or the optimization of peak electricity loads [175]. Furthermore, researchers stated that the key objectives were to gain better insights into occupants' choices of adaptive opportunities for thermal comfort enhancement in specific climatic contexts [140; 247-250], or into the effect of occupancy on perceived control and behavioural patterns [206]. Other papers modelled occupant interaction with certain controls to gain a better understanding on other environmental factors [251].

5.2.2 Approaches

The majority of papers addressed window control (N=16), next to window blinds control (7), thermal adjustments (e.g. thermostat adjustment, switching on space heating and/or cooling systems)(7), lighting control (7), and adjustment of fan speed (2). Multi-domain independent variables were related to the thermal environment (36), the visual environment (17), and IAQ (13). Only one record included information on acoustic variables [248]. Amongst these independent variables, the most common for window control behaviour models were related to indoor and outdoor temperatures [18; 167; 203; 206; 231; 233; 235-238; 240; 241; 244; 248; 252] and IAQ [18; 231; 235-237; 241; 244; 248; 252]. Blinds behaviour models mostly included thermal variables [167; 175; 206; 229; 233; 239; 253]; and visual variables [206; 229; 233; 239; 253]. The papers investigating thermal adjustments only included thermal environmental variables in combination with contextual variables [167; 206; 232; 238; 245; 249; 250].

The contextual factors included the time of day or arriving/leaving times [31; 203; 231; 233; 236; 237; 239; 240; 242; 246], the previous control state [203], geographical location [238; 167], ventilation type [203; 238; 140], building system and envelope characteristics (e.g., installed technologies, building envelope efficiency, window opening size) [244; 245], facade orientation [251; 175], dress code [249], season or cloud cover [175], socio-economics [232], and occupancy levels [206].

Most of the 26 field studies used physical measurements (24) and 11 of them also surveys. Two studies used a combination of measurements, surveys, and observations, and one field study used only observations. The duration of the data collection varied from a few days (laboratory studies such as [206]) up to several years [239].

Some of the studies combined field measurements with a questionnaire-based investigation [140; 246; 167], or used questionnaires [232] or interview techniques [245] independently. Most records refer to office environments (22), next to residential buildings (9), and hospital environments (1).

The statistical methods used were logistic regression [236; 237; 240; 242; 244], probit analysis [203; 238; 167], neural networks [231], Markov processes [239], data mining approaches [237], and Bayesian networks [31; 241]. Other statistical analysis included Generalized Estimation Equations [246], ANOVA analysis [115], weighted and linear trend lines [140].

5.2.3 Findings

A wide range of studies found a strong dependency between the time of day and window control patterns in offices [236; 237; 203] and residential buildings [31; 235; 240; 252]. Hansen et al. [232] found that window operation in Danish households was correlated with building characteristics, such as technical installations and energy efficiency of the building envelope, while it was not correlated with the building age. Shi et al. [244] found that windows with large adjustable opening sizes are more likely in ajar state and the interaction frequency is much higher. Based on questionnaires, the indoor temperature at which a substantial proportion of occupants start to open windows for ventilation was observed similar in all climates, but window use was more common in Europe than in Pakistan [167; 238]. Rainfall was also found to have a significant effect on opening a window, along with the location of the office (and its relation to safety) [254].

In line with section 5.1.3, studies including physical and contextual variables found correlations between window operation and IAQ indicators (e.g. CO_2 and VOC concentrations) [31; 231; 235; 236; 252]. Stazi et al.'s review [18] found that window opening was mostly linked to CO_2 concentration in residential buildings. According to Fabi et al. [255], all papers that measured IAQ indicators found correlations with window operation.

Several studies found a strong relationship between window blind control operation and the time of day [233; 239; 246], while others did not [251]. Another important contextual factor influencing window blinds operation is the facade orientation [233; 246; 251]. Time of day and/or arrival/leaving times play an important role also for light switch behaviour [233; 242].

5.2.4 Identified gaps and future directions

Although all studies included at least one contextual variable, further work needs to create a comprehensive approach including a more extensive set of contextual and potentially personal factors.

Regarding contextual physical environmental factors, further attention should be paid to the ease and convenience of using building system interfaces, the state of other devices (or controls) and the influence of building automation routines on behavioural patterns. Furthermore, contextual factors such as interior design and furniture layout, or the relation between the indoor and outdoor environments (e.g., view to the outside) need to be further investigated. Even various social factors, such as social constraints, group interactions, the presence of multiple occupants on occupant behaviour in open space versus private office [206], and control behaviour due to safety reasons need to be further investigated. Although some studies compared a few different geographical locations, a more comprehensive approach is needed to understand the variability of occupant behaviour in different climatic zones and/or cultural backgrounds.

Related to the research method, relationships between indoor variables and window transitions, based purely on survey responses (e.g. [238; 167]), must be treated with caution. Since the window state affects indoor variables [235; 255], conditions just prior to an event are needed.

5.3. Physical + personal variables

This subsection reviewed six studies looking at physical and personal predictors, which could explain some of the differences amongst adaptive behaviours. The personal predictors include clothing habits, socio-cultural expectations, personality traits, and occupancy preferences.

5.3.1 Motivational background

Most studies investigating physical and personal variables concurrently aimed to develop occupants' behaviour models to control building systems.

5.3.2 Approaches

The studies consider thermal systems [256; 257], lighting systems [198; 258], or thermal and lighting systems [196]. These systems were generally operating in non-stressful conditions (i.e. acceptable environmental conditions). One common dimension considered in study designs is their longitudinal aspect, with studies lasting from a day to many months.

Research exploring physical and personal variables as predictors to behaviour analysed these two predictors independently or jointly. Indraganti et al. [256] applied descriptive and inferential analysis to explore the relationships between occupant's behaviours (14 control actions) and personal variables (dress habits); in parallel, the relationship between occupant's behaviours (air-conditioning and fan usage) and physical variable (outdoor daily mean temperature) was explored through logistic regression. Schweiker et al. [196] applied mixed effect regression analysis to explore the effect of physical (thermal and visual) and personal (personality traits) variables on occupant's behaviours (clothing adjustments, window opening, blind closing, and ceiling fan usage). Gunay et al. [258] applied discrete-time Markov logistic regression to explore the effect of physical (ceiling illuminance) and personal (occupant's presence) variables on occupant's behaviours (light switching and window blind actions).

5.3.3 Findings

Most studies highlight that occupants respond to environmental discomfort, but fail to revert the state once discomfort disappears. Gunay et al. [258] observed that occupants closed blinds upon glare and switched-on lights upon low daylight; but they often failed to open the blinds and to switch-off the lights. Occupants' locus of control is not a concern in non-stressful/acceptably good conditions [198]. Furthermore, occupants' interactions with building environmental systems may be linked to daily routine and habits [257] and differences in behavioural patterns between sub-populations based on personality traits are considerable high [196].

5.3.4 Identified gaps and future directions

Most studies highlighted a lack of the contextual dimension, including climate, seasonal effects, building types, building orientations, complexity of controls, interior layout, single/shared spaces, and organisational policies [198; 196; 257; 258]. In addition, multi-domain physical predictors are missing except for one study including IAQ [196]. Finally, studies should consider the Hawthorne effect already discussed in section 4.1.4 and by Schweiker et al. [196]. In general, very few studies have systematically assessed the effect of personal variables other than age and gender on behaviour.

5.4. Physical + contextual + personal variables

This subsection summarizes eleven studies looking at the influence of physical environmental conditions and their interactions with contextual and personal factors on occupant behaviour [256; 259-268].

5.4.1 Motivational background

As in previous subsections, modelling of occupants' behaviour for use in building performance simulations for office buildings is the main motivation common in studies across the world. Thereby, the main research focus is on window control behaviour, and its impact on the energy consumption.

5.4.2 Approaches

The majority of the publications were field studies, often based on or involving questionnaire surveys [256; 257; 262; 264]. Almost all the studies used logistic regressions to evaluate the cross-main effects of environmental and non-environmental factors on the occupants' behaviour. The analysis of the interactions between different predictors has not been established yet, but there is a growing body of literature with results that point out its importance [267; 268].

The four commonly studied behaviours are interactions with windows, use of heating controls, electric lighting use, and interaction with shades.

The physical variables were the internal and outdoor air temperature, globe temperature and air velocity. Some studies collected additional measurements of carbon dioxide concentration, particulate matter [266], and solar radiation [267]. Contextual factors included building features and maintenance, the orientation of windows, floor level (security), the type of office, and socio-cultural aspects such as habits and dress code. Personal factors included perceived control.

The number of residential and office building studies was similar, but residential longitudinal studies usually have a longer duration. Office studies benefit mainly from a large number of respondents albeit often being cross-sectional surveys for shorter periods.

5.4.3 Findings

While all studies observed physical, contextual, and personal variables, window use was mainly analysed as a function of outdoor temperature [256; 264], indoor temperature, and IAQ [268]. Often, the probability of an opened window is positively correlated with outdoor temperature, but Kim et al. [262] showed a bell-shaped relationship were above a certain ambient temperature this positive correlation is reversed and the number of closed windows increases again. This effect was observed in previous single-domain studies [269] and shows the importance of local context in the interpretation of the observed behaviours.

In an office building in the hot and humid climate region of India, window use was mostly defined by contextual factors such as the time of day; meanwhile, the occupants did not interact with other building controls [256]. A study in China [266] concluded that the window used in the studied offices was a combination of physical and contextual factors such as the sunshine hours. Wei et al. [265] revealed a seasonal effect and a significant influence of the location of the window (ground floor or not) and personal preference (habitual or not) on the "end-of-day" window state. Absence in subsequent days and contextual factors such as daylight saving time and façade orientation did not have a significant effect. Seasonal effects were also evident in a South Korean study [268]. In spring, window use was affected by the CO_2-concentration, whereas in summer the indoor temperature was a significant driver. In winter, indoor temperature and CO_2-concentration did not have a statistically significant effect. Yun et al. [257] showed a significant relationship between comfort and perceived control over temperature in NV buildings and highlighted that a change of the windows' state is more likely with high compared to low perceived control [257].

The lighting behaviour in households was found to be influenced by the solar radiation, perceived illumination, outdoor temperature, thermal sensation and IAQ [264] showing the complexity of the interrelationships between multiple physical and personal variables.

The interaction of household occupants with the radiator thermostat set-points showed that the occupants could be classified into different behaviour categories according to the number of interactions with the heating controls [267]. The set-point changes were significantly influenced by the indoor relative humidity, outdoor ambient temperature, solar radiation, wind speed and time of day.

5.4.4 Identified gaps and future directions

Above findings show the importance of contextual factors and how these non-physical factors affect occupants' perception and behaviour. They emphasize the need for systematic analysis of the contextual factors and study their interactions with the physical and personal variables. However, there is a lack of research into the relationships and interactions amongst multi-perceptual, contextual, and personal factors and their combined influence on occupant behaviours. While there seems to be a consensus on the physical variables measured, there are still differences in the selection of contextual and personal variables and their reporting. The type of building system varied with the particularities of the location (e.g. climate, prevailing architecture and construction typologies) and seemed biased by what the sites permitted and the studies' aims. The main reason could be that these parameters are often "fixed", defined by the building and location and not directly controlled by the researchers.

Contextual factors are mainly referred to in generic context without systematically assessing their interactions and impact on other predictors. Missing relationships, for example, are different climatic and cultural background factors on window use behaviour [257].

In relation to lighting studies, research is required to assess the effect of light on psychological factors and investigate the duration of the effects on comfort [260].

5.5. Physical + multi-behavioural approaches

The focus of the 13 studies in this subsection is on the interrelations between the indoor environmental conditions with a combination of different behavioural responses [212; 225; 254; 258; 270-278].

5.5.1 Motivational background

The aim of these studies is related again to energy savings through more realistic modelling of occupancy behaviour in simulations. The underlying objective was to characterise the relationship between physical environmental parameters and occupant behaviour including the assessment of the interactions and combined effect of multiple behaviours.

5.5.2 Approaches

Similarly to the previous subsection, the behaviours investigated were interactions with windows, heating and lighting controls including electric lights and shading.

In contrast to the previous subsection, the research in this field is focused on office buildings. Window use remains the most prominent behaviour and is studied in combination with personal adaptation behaviours (e.g. physiological responses [278], clothing adjustments, and interactions with the heating and cooling systems [274]). Responses to changes in visual conditions are discussed in light of interactions with shades and electric lighting [212].

The physical variables commonly considered were the indoor and outdoor air temperature, relative humidity, wind speed, illuminance, and the level of CO_2-concentration as an indicator of IAQ. The non-physical variables differed again with the building characteristics and the researchers' objectives and included season, period of day, type of room and current state of controls. However, the analysis of the significance and impact of different variables followed mostly again a cross-main effects approach.

Data collection occurred through surveys with concurrent field measurements, except for one study in a controlled office-like environment [278].

5.5.3 Findings

Despite the influence of indoor and outdoor physical variables confirming observations of previous subsections, the occupancy state (arrival/departure) was the most often studied other behaviours. Langevin et al. [274] found a significant influence of indoor/outdoor temperature and arrival time on clothing, fan, heater, and window use behaviours. While the occupancy state interacted with window opening [236], the previous or next absence for more than 8 hours did not have a significant effect on the opening behaviour during departure or the closing behaviour upon arrival [275]. In contrast, the closing behaviour during departure and the opening behaviour during arrival were influenced by the absence duration. Fabi's review of the physical predictors that influence light switching behaviour identified the key drivers absence duration and daylight [273]. Season, light sensor control, and time spent with the light off were not significant. Similarly, lighting use is a function of the daylight availability and the duration of absence before switching the lights on or after switching the lights off [212]. In the intermediate period, the only significant variable is the worktop daylight illuminance level. The same study concluded that the majority of shade adjustments take place during the first arrival or last departure of the day.

Schweiker et al.'s analysis of the interactions between behaviours indicates a significant impact of the fan operation and clothing level on the window behaviour but no significant effect of sun shading [278]. In addition, the window state affects significantly fan and sun shading use. Sanati et al. [271] found no significant effect between sunlight availability, window occlusion, and electric light usage in a single university building.

5.5.4 Identified gaps and future directions

The low number of studies in this subsection showed that the influence amongst the studied behaviours themselves is seldom thoroughly assessed. Fabi et al. [236] suggested that there is a need to investigate the correlation of behaviour responses to multiple, instantaneous factors.

6. Discussion and conclusion

Overall, this review reveals the diversity of approaches and findings of multi-domain analysis. This section compares and discusses the findings and identified gaps from individual subsections above.

6.1 Motivational background

In perceptual studies, the main motivation is a better understanding of the phenomena involved. In behavioural studies, the aim is mostly model development for predictive purposes. This does not mean that perceptual studies do not involve any aspects of prediction, but, the authors stated to focus on understanding, rather than modelling.

6.2. Approaches

A variety of methodological approaches for research design and assessment are presented in the literature. Whereas laboratory studies are the most frequent type of perceptual multi-physical studies (subsection 4.1), field studies dominate in all other categories. New approaches using virtual environment (e.g. [272]) published promising results, but still lack sufficient evidence that they permit the reproduction of effects observed in reality.

Geographical contexts are mainly from developed countries (https://www.un.org/en/development/desa/policy/wesp/wesp_current/2014wesp_country_classification.pdf), which likely represents the availability of research funding, rather than the contextual diversity or the population size in a particular context. Therefore, the findings presented are not necessarily representative of buildings, lifestyles, climate zones or cultural regions in developing countries.

Context is more likely considered in studies on human behaviour than perception. This may be due to the advantages of laboratory studies to control multi-physical influences on perception without contextual considerations. For example, the experimental design by Kulve et al. [104] enabled to avoid natural correlations among environmental variables and to causally test the effect of variables on outcomes of interest. In addition, it allowed testing if cross-modal effects occurred at a specific level of one variable (e.g., only in comfortable thermal conditions) or were independent of the level of the other variable (i.e. the same cross-modal effect occurred at all the levels of the other variable).

Few studies considered personal variables beyond demographics despite their inclusion by means of questionnaires being an easy extension in laboratory studies. Participants in laboratory studies are not otherwise distracted from their work or leisure activities as it would be the case in field studies. Still, the application of findings relating to personal factors in the building design process with generally unknown user profiles is less clear, but potentially beneficial for specific buildings (e.g. retirement homes) or individualized operation strategies.

Contextual influences and occupant behaviour are more difficult to study in an artificial setting of a laboratory environment. The low frequency of interactions (i.e., 1 to 4 actions per day) would require very long and expensive study periods uncommon in laboratory settings. Still, more attempts would be beneficial to reveal true causalities, because field studies also have drawbacks. The lack of experimental control over environmental conditions means that the conditions cannot be causally related to human outcomes, and that environmental conditions are likely to naturally co-occur in predictable ways (e.g., a position near a window in the summer is likely warmer and brighter than one on the interior of a room).

The question of causality is also relevant to several papers addressing contextual factors, such as green vs. conventional buildings or NV vs. AC buildings in field studies with a limited number of buildings. These studies assign observed differences in perception or behavioural patterns to the type of building, while neglecting the multitude of other potential influences (e.g., non-documented contextual or personal differences). Without addressing, discussing, or eliminating potential confounding variables, assigned causalities could be mistaken. For potential meta-analyses and other comparisons, well documented contextual elements of the environment under investigation are crucial. Unfortunately, contextual elements and spatial characteristics such as relative position to control devices are often poorly documented– if at all in the text. Therefore, we recommend using the categories presented in Figure 1 together with aspects mentioned in previously published ontologies [279] to describe the contextual aspects.

The assessment of the dependent variables varies largely. While there are meaningful differences in behavioural studies, the perceptual studies vary in the dimension assessed (e.g., thermal sensation, preference, or acceptability), and the type of scale (e.g., categorical, continuous). There is a tendency to ignore previous approaches and develop one's own instruments, without benchmarking them against existing ones (see also subsection 4.1.4). As discussed earlier [20], this variety impedes comparing results across studies, and understanding whether differences between outcomes of two studies are a result of the instrument or differences in (unreported) contextual or personal aspects.

In addition to the diversity in data collection approaches, the analysis approaches taken are at different levels. Studies, most likely in laboratories, exist, which apply multi-domain approaches from study design to analysis. At the same time, the number of field studies reporting the collection of multi-perceptual data is increasing. However, their potential is poorly utilized, because the datas' multi-perceptual nature is not considered during analysis. The reasons for such omission can be manifold. First, limits in word counts in combination with the complexity of describing multi-physical data and their analysis might lessen the potential to report multi-domain analysis approaches first, but cannot be an argument for missing subsequent publications. Second, multi-domain interaction or cross-over statistical analyses might have been conducted, but not reported due to non-significant results; a common issue leading to scientific bias as reported earlier [5]. Third, a lack of statistical skills might have impeded the integration of interaction terms in statistical analysis.

To overcome these shortcomings, all researchers, reviewers, and editors are encouraged to demand extensive descriptions and analysis methods for multi-domain studies until there is a substantial body of evidence that certain aspects are not relevant for a specific perception or behaviour.

Further research shortcomings in all categories are small sample sizes, low diversity in participants, representativeness of samples, and environment. In contrast to previous reviews' discussions [20], which emphasize the general need for larger sample sizes, we argue that the actual number of cases is not the main problem. Examples exist throughout scientific literature in a variety of disciplines, which show the benefits of studies with small sample sizes that still increase the existing knowledge (see Flyvbjerg [280] for an extended discussion). Small sample sizes are to be criticized when lacking a clear strategy for sample selection and being based on so-called convenience samples, i.e. those at hand of the researcher. In contrast, Flyvbjerg [280] discusses information-oriented sampling strategies including the selection of critical cases or maximum variation cases, which enable the extraction of new knowledge even with small sample sizes. At the same time, he emphasizes that small sample sizes are very suitable for falsification of theories – sometimes a single case is sufficient –, but less for generalizing.

6.3 Findings

Overall, results are often inconclusive and in part contradictory (see Figures 8 to 12). Few observations are repeatedly shown: significant effects of visual properties on thermal perception exist, though they are partially contradictory and a comparable amount of studies found no significant interactions. A general statement seems not possible due to explainable effects, that warm light colours are perceived as satisfactory in cold environments and vice-versa. Thermal properties have been shown to influence acoustic perception, while the number of non-significant findings is again in the same magnitude. Related to occupant behaviour, the largest evidence was observed for thermal and IAQ related variables interacting on the window opening behaviour. Such finding is not surprising given that windows enable to control IAQ and thermal conditions except for reasons of outdoor conditions such as high air pollution. Contradictory results are apparent in all categories of multi-domain studies. While such observation can be assigned to the low number of studies in subsections 4.4 and 5.4 and 5.5, it is more surprising for subsections 4.1, 4.2, 5.1, and 5.2, which are based on a much larger number of items.

Despite the large variety of independent variables assessed, there is a need to clarify whether those variables are the most influential ones explaining variances observed in perception or behaviour, or solely the most accessible ones. This necessity is linked to the next gap in the reviewed literature: missing theoretical foundation. One could assume that many, if not all studies, are based on underlying theories of human physiology and perception. However, very few articles mention theories when describing their study design or discussing their findings. Not all studies need to be designed to falsify an existing theory; case studies, especially very detailed ones looking at individual cases, are also very suitable to develop new theories inductively. Nevertheless, a theoretical foundation is meaningful to link and explain potentially diverse findings and to justify the selection or exclusion of specific physical, contextual, or personal variables. Theories relevant for multi-domain approaches may originate from disciplines like psychology, sociology, but also from neurology or physiology. One of the few research items mentioning theoretical foundations is Candas et al. [21], who mention neurophysiological aspects related to multisensory integration in their introduction. However, they do not relate their review findings to such approaches. The literature on multisensory integration [281-283] outlines first explanations to what extend interactions can be additive, antagonistic, or synergetic. For example, Talsma et al. [283] propose a framework that shows the interaction between multi-physical perception and attention.

There are few studies linking perception and action. In behavioural studies, physical quantities are assessed which relate to perceptual domains. For example, the assessed indoor air temperature can be related to thermal perception. As such, the perception of such physical indoor environmental qualities is an assumed prerequisite for the action. Given the low observed correlations between observed physical variables and behavioural actions (R^2 are frequently below .2), it might be necessary to include additional variables or to consider different approaches to understand occupant behaviour. Thereby, several aspects are to be considered. First, perceptual studies show a large variance between and within individuals in the perception of the same physical stimuli. Second, theories in the field of psychology together with empirical findings suggest a difference between the intention to perform an action and the action itself [284-286]. Not surprisingly, previous research has revealed a multitude of factors influencing occupant behaviour [5], which potentially affect the relationship between intention and action (e.g., the level of perceived control, the distance to means of control, or other work tasks that require full attention). Therefore, we recommend looking further at the relationship between perception and action and evaluating whether those contextual and personal factors affecting behaviour effect perception and vice versa.

6.4 Future directions

Based on the results and discussion presented in this review, we propose the following points to be considered by authors and reviewers of future multi-domain approaches.

The first point is easily applicable and pointing to a limitation of this review: keywords for multi-domain studies. Commonly, an *a priori* defined set of search terms is used for a systematic review. However, an initial review of keywords used by a selection of relevant multi-domain articles revealed that the keywords for the individual domains investigated are used, but no specific keyword to clarify the multi-domain approach. Therefore, a systematic search through a set of keywords would have required searching for all possible combinations of individual domain keywords. Given the number of authors involved and their diverse backgrounds from different domains, we decided to start with the collection of articles known to us in combination with a backward and forward search of cited or citing articles. This strategy might have failed to find all relevant research items. However, articles, which have not been cited or do not cite any of the 200+ articles considered for this review might be of minor relevance and likely not adding much to our general conclusions. Still, we suggest future studies to use a unique keyword such as “multi-domain” or “combined effects” in order to facilitate future review efforts.

Second, researchers should clarify whether their research is intended to explore new influences, i.e. supporting the development of new theories or the extension of existing ones, or test an existing theory. In addition, researchers should clearly state the limitations of their studies, especially when dealing with small samples, discuss the applicability and comparability of results in the context of existing knowledge, and be careful with false causalities arising from unobserved confounding factors. Thereby, generalization is relevant to find common patterns. However, addressing individual differences and revealing factors leading to such differences, even for single cases, is of high importance in order to consider outliers as valuable points of information. The latter assertion is valid either because these points are true outliers and explanations available (see e.g. O'Brien et al. [287] for a qualitative approach to explain outliers). Or, because they point to methodological issues (e.g., the question asked is prone to misinterpretation under specific circumstances).

Third, advanced statistical analysis methods for capturing interactions and their complexity are recommended. Aside from the application of multiple regression including interaction terms, hierarchical modelling or structural equation modelling, which permit understanding of interdependent relationships are appropriate methods for this task. Additionally, analysis methods derived from machine learning approaches may be useful to detect underlying patterns in large and rich datasets. When reporting statistical results, significant levels together with effect sizes are crucial information for later meta-analysis.

Fourth, missing agreement on classification of contextual and personal variables leads to the same terms used for different aspects. Therefore, general classifications (e.g., "green buildings") should be avoided in favour of explicit descriptions (e.g., LEED Platinum certified buildings).

Fifth, interactions are complex by nature. Given the large variety of potential interactions between physical, contextual and personal variables, collective approaches, which build upon the knowledge generated, are necessary. We thus encourage researchers to join or establish collaborative activities such as those developed within international research groups like the IEA EBC Annex 79 "Occupant-Centric Building Design and Operation" (http://annex79.iea-ebc.org/), which is the basis for this review. Moreover, a common framework is necessary, which facilitates meta-analysis efforts in the future and allows aligning one's own research into the line of previous research. As a start, our review table is available as a dynamic open-access document permitting others to add their research related to multi-domain approaches (https://osf.io/gnvp2/?view_only=00b08233881f471795d1d8dee79e9828). We hope that this document will serve as a growing knowledge base to increase collectively our knowledge related to multi-domain influences on perception and behaviour.

Sixth is the balance between benefit and risk of increasing the complexity of perceptual or behavioural models partly addressed in behavioural studies by means of statistical measures such as Akaikes Information Criterion [288]. Future studies need to investigate under which circumstances additional factors are meaningful, given issues such as over-fitting and error propagation. This question is best answered based on a solid theoretical foundation together with a clear description of the potential application of the results.

Combining all these conclusions necessitates designing studies within a framework of occupant perception and behaviour that accounts for the complexity of the physiological-perception-cognition-decision-action-automation-building system. First examples for such frameworks have been proposed [289; 290] and attempts to challenge them by means of field or laboratory studies are highly recommended. In addition, the development of guidelines on this topic is an expected future development of this work.

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