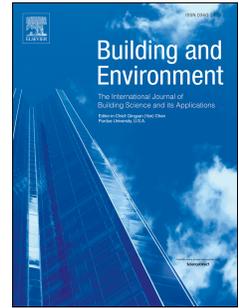


# Journal Pre-proof

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

Marcel Schweiker<sup>1</sup>), Eleni Ampatzi<sup>2</sup>), Maedot S. Andargie<sup>3</sup>), Rune Korsholm Andersen<sup>4</sup>), Elie Azar<sup>5</sup>), Verena M. Barthelmes<sup>6</sup>), Christiane Berger<sup>7</sup>), Leonidas Bourikas<sup>8</sup>), Salvatore Carlucci<sup>9</sup>), <sup>10</sup>), Giorgia Chinazzo<sup>11</sup>), Lakshmi Prabha Edappilly<sup>12</sup>), <sup>1</sup>), Matteo Favero<sup>10</sup>), Stephanie Gauthier<sup>13</sup>), Anja Jamrozik<sup>14</sup>), Michael Kane<sup>15</sup>), Ardeshir Mahdavi<sup>7</sup>), Cristina Piselli<sup>16</sup>), Anna Laura Pisello<sup>16</sup>), Astrid Roetzel<sup>17</sup>), Adam Rysanek<sup>18</sup>), Kunind Sharma<sup>15</sup>), Shengbo Zhang<sup>19</sup>)

1) Building Science Group, Karlsruhe Institute of Technology, Karlsruhe, Germany;

2) Welsh School of Architecture, Cardiff University, Cardiff, UK;

3) Department of Civil and Mineral Engineering, University of Toronto, Toronto, Canada;

4) International Centre for Indoor Environment and Energy, Technical University of Denmark, Kgs. Lyngby, Denmark;

5) Department of Industrial and Systems Engineering, Khalifa University, Abu Dhabi, UAE;

6) Thermal Engineering for the Built Environment Laboratory, École polytechnique fédérale de Lausanne, Lausanne, Switzerland;

7) Department of Building Physics and Building Ecology, TU Wien, Vienna, Austria;

8) Lancaster Institute for the Contemporary Arts, Lancaster University, UK;

9) Energy, Environment, and Water Research Center, The Cyprus Institute, Nicosia, Cyprus;

10) Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, Norway;

11) Department of Civil and Environmental Engineering, Northwestern University, Evanston, USA;

12) Department of Civil Engineering, Building Technology and Construction Management, Indian Institute of Technology Madras, India;

13) Faculty of Engineering & Physical Sciences, University of Southampton, Southampton, UK;

14) Breather Products Inc., Montreal, Canada;

15) Department of Civil and Environmental Engineering, Northeastern University, Boston, MA, USA;

16) Department of Engineering, University of Perugia, Perugia, Italy;

17) School of Architecture and Built Environment, Deakin University, Geelong, Australia;

18) School of Architecture and Landscape Architecture, the University of British Columbia, Vancouver, BC, Canada;

19) Department of Mechanical and Industrial Engineering, University of Toronto, Toronto, ON, Canada

## 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

1 an overview of the state of the art, but also contributes to the identification of existing  
2 knowledge gaps in this area and the corresponding need for future research. In particular,  
3 many studies use “convenience” variables and samples, there is often a lack of theoretical  
4 foundation to studies, and there is little research linking perception to action.

## 5 **Key words**

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

## 8 **1. Introduction**

### 9 **1.1. Background and state-of-the-art**

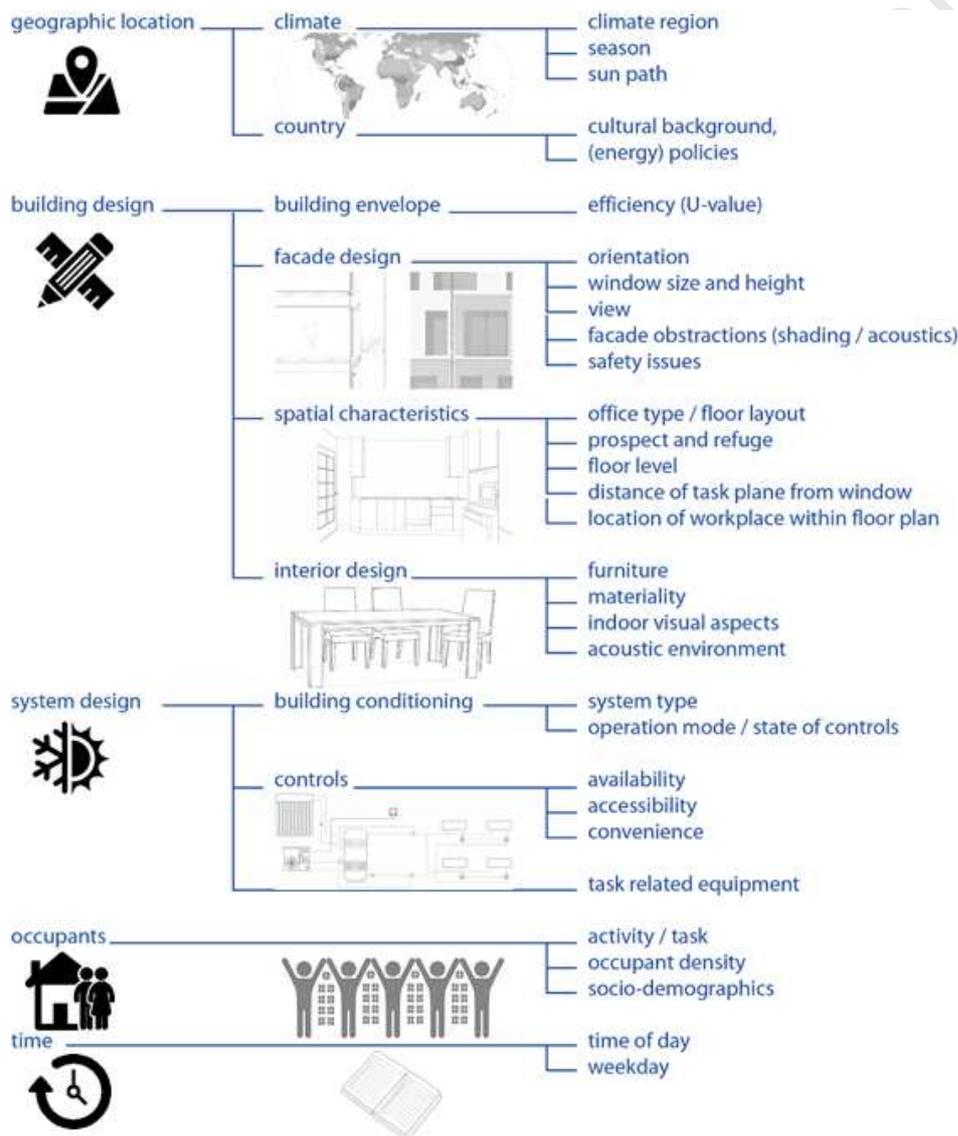
10 Inhabitants of industrialized areas spend most of their time (85-96%) inside buildings [1;  
11 2]. Meanwhile, the human sensory system receives information regarding multiple indoor  
12 environmental exposures. Building energy consumption is significantly influenced by  
13 occupant perception and behaviour; that is, occupants’ evaluation of thermal, visual,  
14 acoustic, and air quality stimuli and their reactions to any resulting discomfort [3]. As such,  
15 these four principal categories of environmental stimuli are integral to building design  
16 standards [4]. Not all interactions of occupants with their built environment result from  
17 dissatisfaction, but a close link between perception and behaviour exists [5].

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

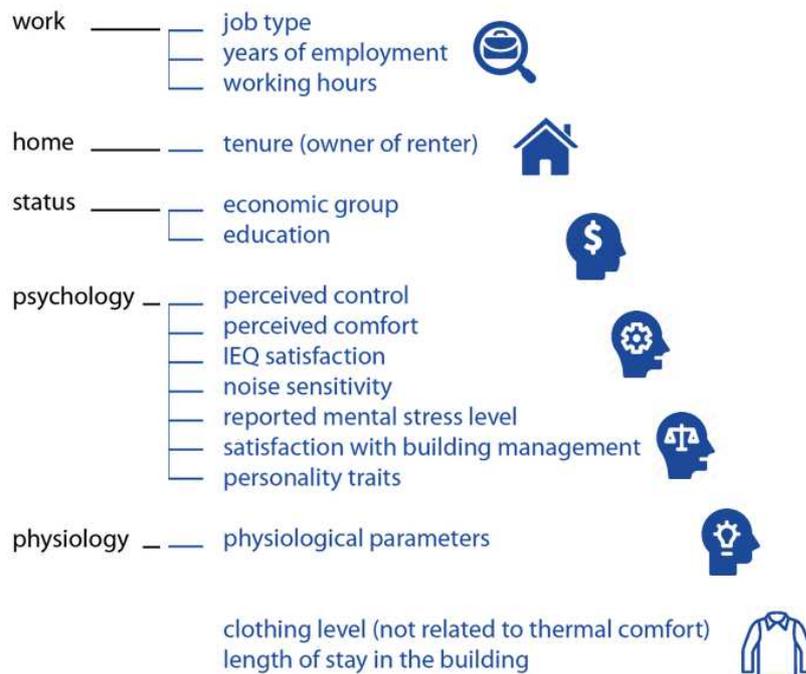
30 Literature reviews on multi-domain approaches are less numerous. Recently, Torresin et  
31 al. [20] identified 45 laboratory studies published after 1990 dealing with the effects of two  
32 or more environmental domains on perception and performance. Earlier reviews were  
33 based on smaller numbers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

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

11



12  
 13 *Fig. 1. Contextual variables and their categorization.*



1  
2 *Fig. 2. Personal variables and their categorization.*

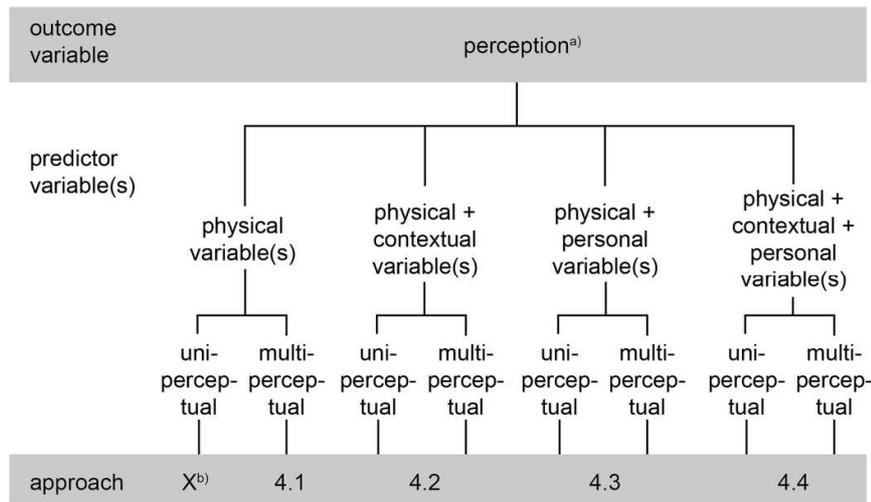
3 This brief overview reveals a lack of reviews that considered multi-domain influences on  
4 occupants' perception and behaviour. The current review aims to fill this gap as described  
5 in the following.

## 6 **1.2 Objective, research questions, and scope**

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

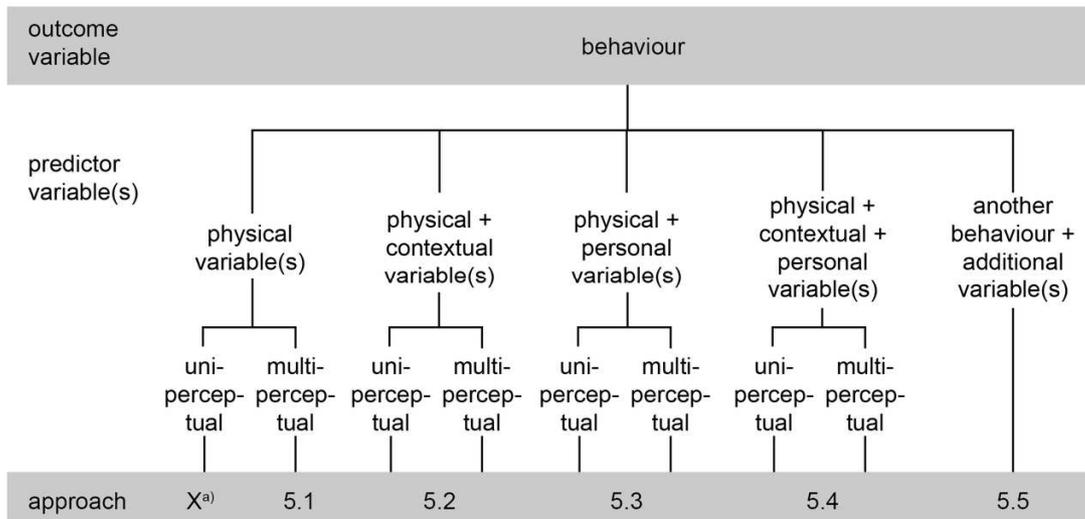
12 The main research questions were (1) Why did researchers choose the domains and  
13 questions they considered?, (2) How did they approach multi-domain investigations?, (3)  
14 What were the key results?, and (4) What are limitations and gaps of their approaches?

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



<sup>a)</sup> overall perception and/or domain specific perception  
<sup>b)</sup> not considered as multi-variable approach and not included in this review

1  
 2 *Fig. 3. Schema of multi-variable approaches with perception as the outcome variable.*



<sup>a)</sup> not considered as multi-variable approach and not included in this review

3  
 4 *Fig. 4. Schema of multi-variable approaches with behaviour as outcome variable. Note that*  
 5 *the approach numbers at the bottom of this figure refer to the corresponding subsection*  
 6 *numbers within this review.*

7 Physical-perceptual independent variables cover measurable physical properties of the  
 8 indoor and outdoor environment, e.g. indoor and outdoor air temperature for the thermal  
 9 environment. All the physical properties of the thermal, visual, acoustic, and air quality  
 10 environment are considered. *Physical multi-perceptual* approaches are defined as those

1 covering variables from more than one domain of perception (e.g., thermal and visual  
2 perception). Studies dealing with multiple variables covering one domain only (e.g., solely  
3 air temperature and relative humidity, which are both from the thermal domain, on thermal  
4 perception) are not considered unless they included either contextual or personal variables.  
5 All *contextual and personal variables* shown in Figure 1 and 2 are considered, except  
6 personal variables related to demographic factors (e.g. age, sex), or clothing if dealing with  
7 thermal perception.

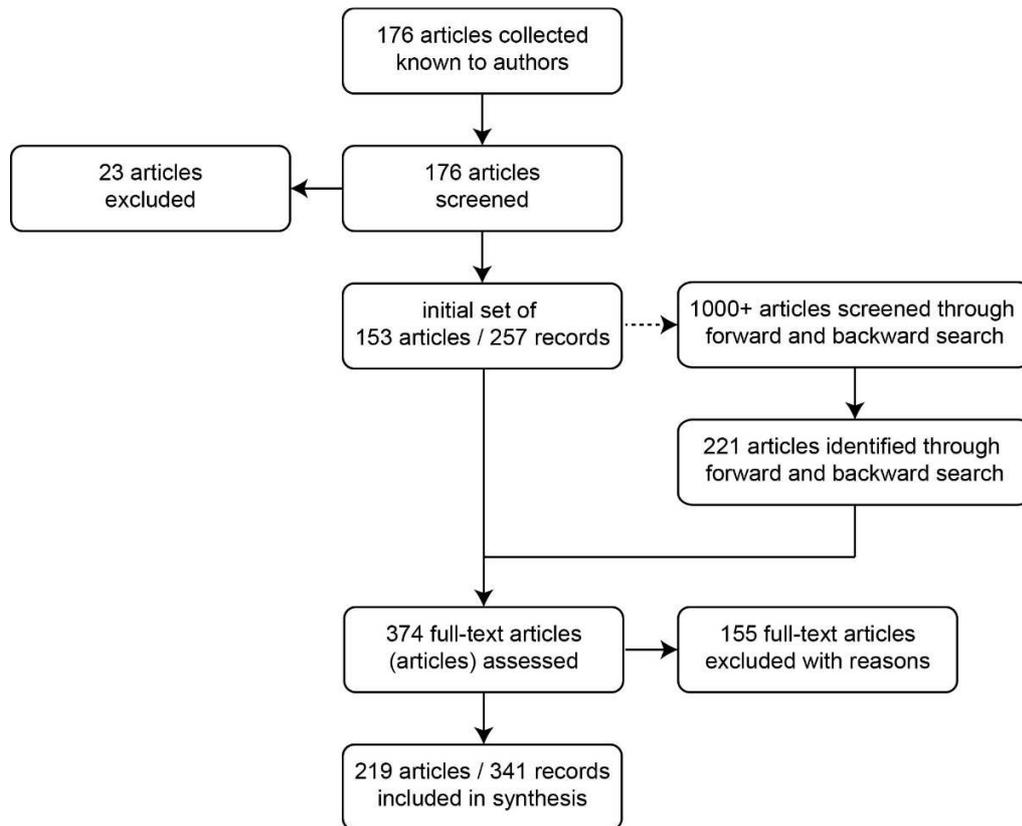
8 *Other behaviour and additional variables* are included to cover studies that consider the  
9 status of one behaviour in the analysis of another behaviour. For example, window opening  
10 behaviour as dependent and the status of the heating system as independent variable.

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

## 16 **2. Methods**

17 This review's approach is visualized in Figure 5. The visualization is based on the "Preferred  
18 Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) schema [25].  
19 However, in contrast to a systematic review, first, we collected and reviewed known  
20 research, which returned 153 articles. This initial step included searches in author's  
21 individual reference databases as well as in bibliographic search engines (Table 1). Second,  
22 the more than 1,000 articles citing these 153 articles or being cited by this initial collection  
23 were assessed. Together with their evaluation, we categorize our work as critical review  
24 [26].

25



1  
2 *Fig. 5. Schema of the review process.*

3 *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"

4

## 5 **2.1 Selection process**

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

10 The exclusion criteria were: (1) out of scope; (2) other than English language; (3) full text  
11 unavailable, and (4) not peer-reviewed. In addition, (5) duplicates such as conference and

1 journal articles presenting the same research were considered once; and (6) review papers  
2 without additional analyses such as meta-analysis were not considered.

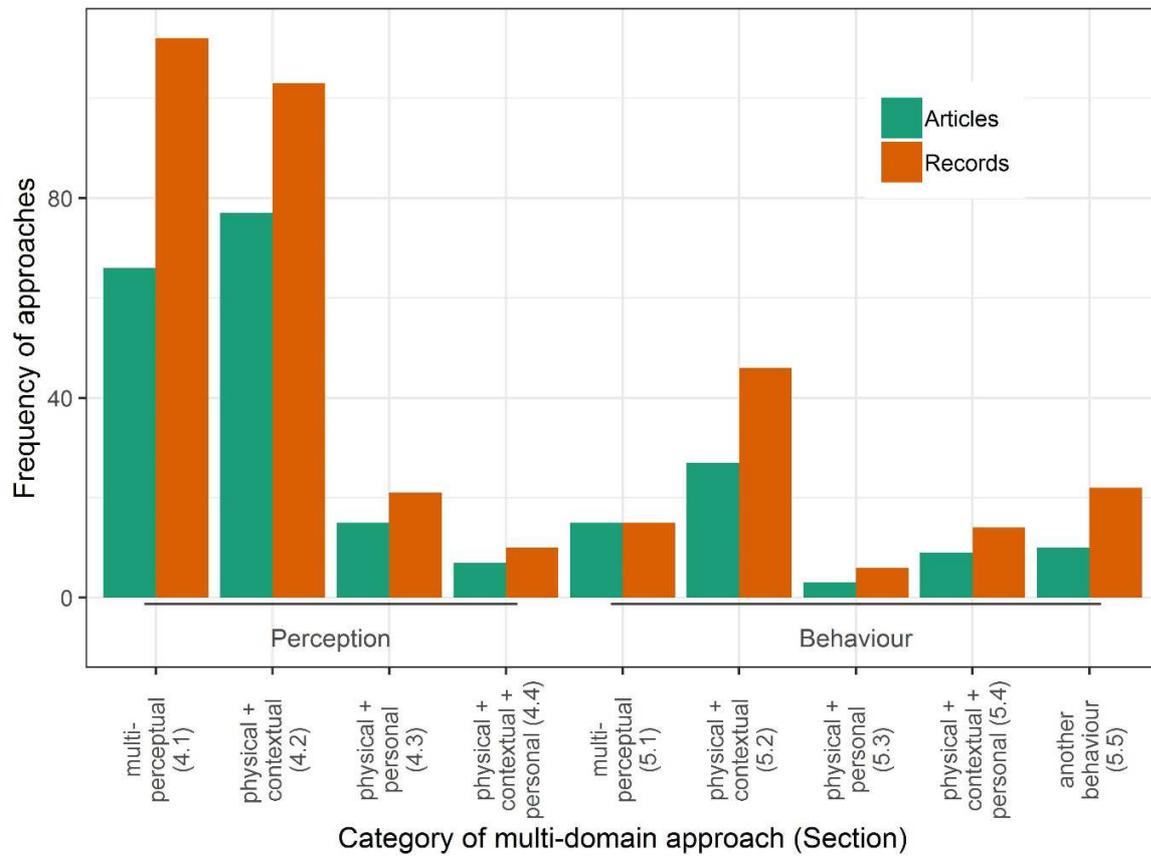
### 3 **2.2 Records' structure**

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

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

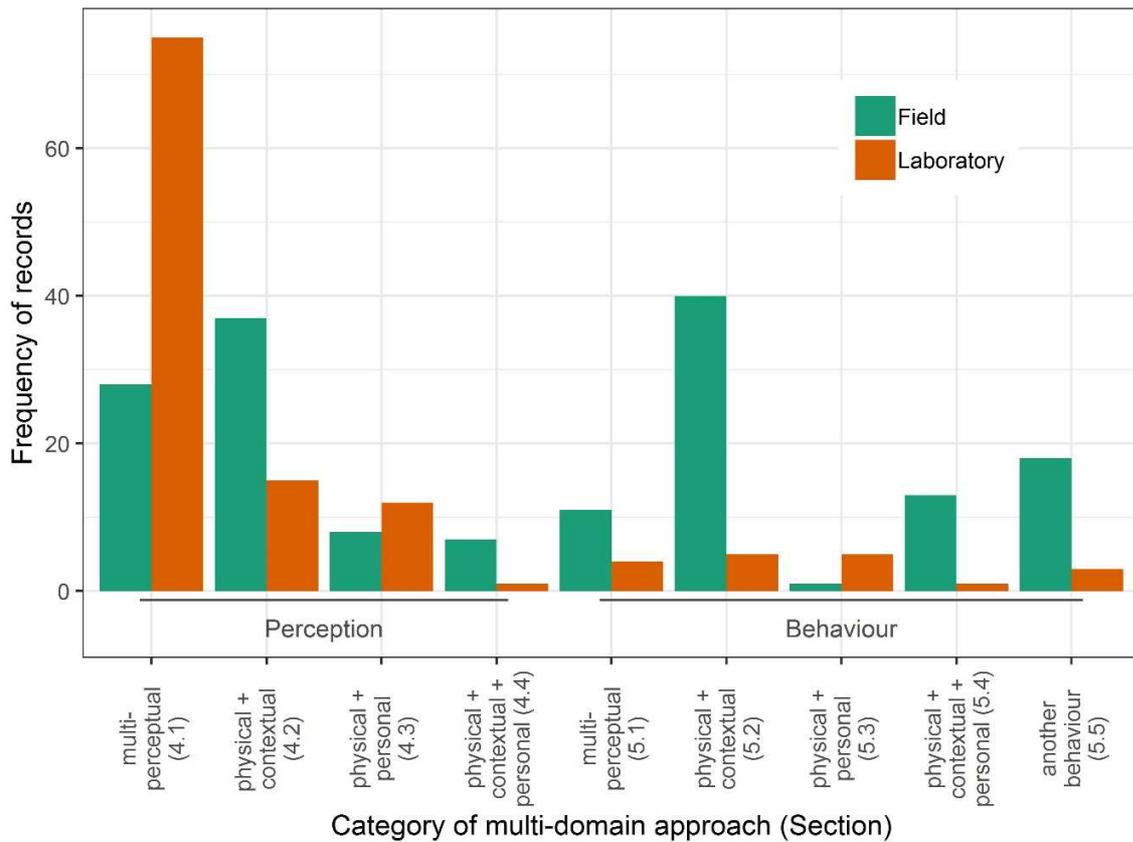
### 12 **3. Comparison between perceptual and behavioural multi-domain** 13 **approaches**

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



1  
2 *Fig. 6. Frequency of studies reviewed per approach.*

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



1  
2 *Fig. 7. Frequency of records separated by type of study.*

3 The sample size varies according to the type of sample analysed, i.e. whether authors  
4 reported buildings, rooms, or participants (Table 2). The number of participants in  
5 laboratory studies ranged from 5 to 199 with nearly half of the studies with less than 30  
6 (mean 45.6, SD 42.2, median 30). In field studies, the largest number of participants (N=  
7 52,980 and N = 29,632) were observed in two studies combining physical and contextual  
8 variables (subsection 4.2) using existing databases of online surveys [27; 28] (mean of all  
9 field studies 824.1, SD 3178, median 138). Sample sizes below 10 participants were  
10 observed in several subsections. Arguments were for example an integral research  
11 approach triangulating between four qualitative and quantitative methods [29] or in-depth  
12 insights by gathering detailed information through interviews and discussions [30]. The  
13 number of buildings varies from 1 [31] to 351 [27].

14 *Table 2. Number of participants, offices, or buildings by category. N = number of records, Min =*  
15 *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

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

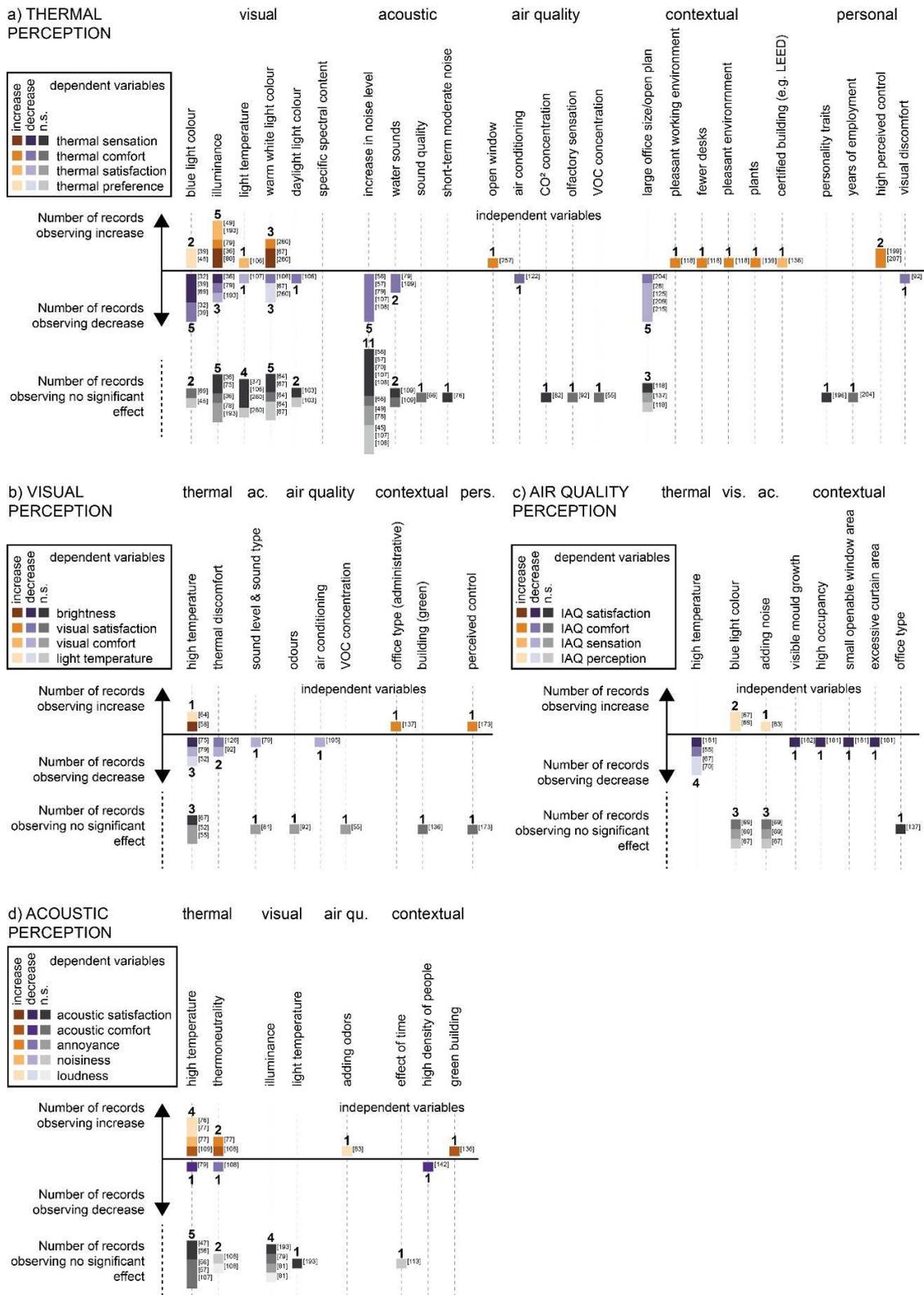
3 *Table 3. Geographic distribution of records*

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 4. Perceptual studies

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

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



1  
2 *Fig. 8. Overview of crossed main effects related to thermal, visual, air quality and acoustic*  
3 *perception based on studies including significance tests.*

## 1 **4.1. Physical multi-perceptual approaches**

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

### 7 **4.1.1 Motivational background**

8 The majority of the studies cite the need for better understanding of exposure situations  
9 involving multiple indoor environmental variables. Other studies observed effects of  
10 multiple environmental variables without a specific intent to examine their  
11 interactions [53; 62]. Studies considered different combinations of environmental variables,  
12 most frequently thermal and visual [34; 37-39; 52; 67; 102-104]. A few studies investigated  
13 other combinations of variables, such as visual and acoustic [45], thermal and acoustic [56;  
14 57; 66], visual and IAQ [59], acoustic and IAQ [83], visual, thermal, and acoustic [48; 49; 62;  
15 70], as well as IAQ, thermal, and acoustic [35; 41]. Researchers were mostly interested in  
16 the effect on dependent variables such as occupants' comfort, sensation, and  
17 preference [34; 39; 48; 52; 66; 102-104]; and satisfaction [59; 68].

### 18 **4.1.2 Approaches**

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

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

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

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

38 As expected, data analysis involve various well-established formats and techniques from  
39 descriptive and inferential statistics. The collection of statistical methods commonly  
40 referred to as ANOVA (Analysis of Variance) is frequently deployed for processing and

1 interpretation of measurement results [40; 45; 52; 66; 68; 70], as are mixed-effects  
2 models [37; 39; 49; 67; 104].

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

6 Environmental physical conditions were monitored and participants were asked to rate  
7 their perceptions through questionnaires on comfort, sensation and satisfaction (e.g., [53;  
8 105]). Measurements of environmental conditions were associated with participants'  
9 subjective ratings, and the subjective ratings with each other, using measures such as  
10 correlation [105] or ANOVA [106]. Field studies enabled the variation of environmental  
11 conditions for large samples of subjects (e.g., 331 students in 7 varied classrooms [105]).

### 12 **4.1.3 Findings**

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

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

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

11 Many studies observed no interactions between environmental factors tested (e.g., [37;  
12 38]), or were not designed in a way to investigate these interactions (field studies).

#### 13 **4.1.4 Identified gaps and future directions**

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

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

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

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

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

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

## 7 **4.2. Physical + contextual variables**

8 This subsection examines studies investigating the combined effects of physical and  
9 contextual variables on environmental perception. These studies examined how context  
10 may interplay with single- or multi-sensory domain perceptions by imposing unknown or  
11 indirect influences on the physical properties of the environment or by shaping the users'  
12 perceptions and expectations in line with social or cultural experiences [27-29; 42; 112-  
13 192].

### 14 **4.2.1 Motivational background**

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

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

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

### 30 **4.2.2 Approaches**

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

35 Subjective evaluation through surveys is a common approach for data collection of comfort  
36 or satisfaction based on the self-reporting of participants [27; 28; 174]. Several studies  
37 involve measurements of indoor environmental quality metrics related to thermal, acoustic,  
38 and visual properties alongside with occupants' subjective votes [42; 74; 124; 129; 136;  
39 137; 142; 144; 145; 169; 170; 175-177].

1 The most frequent building typologies were office buildings (e.g. [115; 119; 126; 134; 140;  
2 143; 147; 178-180]) and educational buildings (e.g. [116; 120; 123; 181-183]), followed by  
3 residential buildings [122; 153; 175], hostels and student residences [42; 121], restaurants  
4 and cafés [132; 142], factories [118; 184], a healthcare facility [150], a shopping mall [141]  
5 and airport terminal [47].

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

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

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

#### 22 **4.2.3 Findings**

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

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

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

39 One of the most important components of the building envelope is the window [190]. Poor  
40 thermal comfort (e.g., cold or warm window) [175; 191], daylight glare [191], and poor  
41 acoustic comfort [191] are reported by participants in large-windowed residential or office

1 buildings. Additionally, the design of solar control devices and solar control techniques can  
2 affect occupant comfort, especially thermal and visual. For instance, Karlsen et al. [192]  
3 demonstrate that occupants prefer venetian blinds with adjustable slat angles to those with  
4 only on-off position. These handful of studies are among the few that made conclusions  
5 from surveys, while the majority of other studies use simulation approaches beyond the  
6 scope of this review.

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

16 NV and passively cooled buildings that allow occupants to control aspects of the indoor  
17 environment, excited positive thermal comfort perceptions outside the fixed temperature  
18 limits set in standards [120; 130; 148; 180]. Moreover, controllability strongly increases  
19 occupants' satisfaction with thermal indoor conditions in winter and summer [28; 120;  
20 130; 148].

#### 21 **4.2.4 Identified gaps and future directions**

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

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

36 In most studies, the context was represented by one or a few variables. However, context is  
37 a complex system of multiple dynamically interacting variables. For example, visual  
38 perception varies with the location of a workplace within a floor plan [169], but the  
39 occupants' perception is further influenced by other spatial parameters such as orientation  
40 and fenestration of the façade [175], climate related parameters such as season, sun  
41 path/latitude [126], and indoor surface materials [114]. Our review identified no study,  
42 which investigated the complexity and interplay of multiple contextual variables, which is

1 likely due to methodological challenges with required data types and the needed quantity of  
2 data. New methodological approaches might be needed for future studies to describe and  
3 understand the complexity and interplay of contextual variables.

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

#### 10 **4.3. Physical + personal variables**

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

##### 14 **4.3.1 Motivational background**

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

##### 22 **4.3.2 Approaches**

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

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

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

35 The applied statistical analysis methods largely vary among the studies, ranging from  
36 ANOVA and MANOVA [197; 198; 203] to regression [196], correlation analysis [52; 168;  
37 193; 194], and non-parametric analysis [195].

### 1 **4.3.3 Findings**

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

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

### 22 **4.3.4 Identified gaps and future directions**

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

### 37 **4.4. Physical + contextual + personal variables**

38 While some of the studies discussed in the previous subsections explored physical,  
39 contextual, and personal predictors of perceptions, none aimed to understand the  
40 interactions of these independent variables. The current subsection covers eleven research

1 efforts that addressed this gap by simultaneously examining at least one predictor variable  
2 from each category [30; 72; 125; 204-211].

### 3 **4.4.1 Motivational background**

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

### 14 **4.4.2 Approaches**

15 Ten of the reviewed articles are field studies conducted in non-controlled building  
16 environments, while one [206] took place in a laboratory controlled office setting. The  
17 studied environments were office [125; 204-208], residential [30; 72; 209; 210], and retail  
18 buildings [211]. Dependent variables considered included domain-specific comfort metrics  
19 such as thermal comfort [30; 204; 209], neutral temperature [206], visual comfort [211;  
20 205], and acoustic comfort [210]. Two studies [72; 125] considered domain-specific  
21 comfort metrics and overall perceived comfort levels of the respondents.

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

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

### 33 **4.4.3 Findings**

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

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

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

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

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

#### 24 **4.4.4 Identified gaps and future directions**

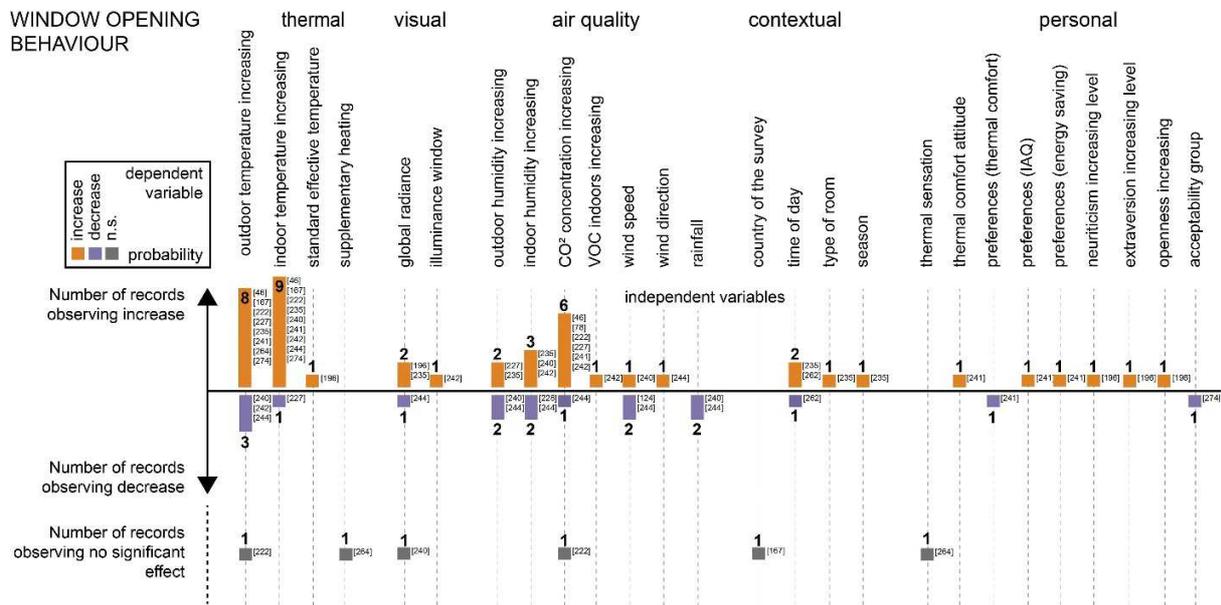
25 The findings presented above do not provide a clear understanding of the interactions nor  
26 fundamentals of the combined effect of physical, contextual, and personal predictors of  
27 perception. The findings cannot be generalized given the small sample of studies that met  
28 the criterion used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

## 38 **5. Behaviour**

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

1 Figures 9 to 12 show the crossed main effects of multiple independent variables on different  
 2 types of behaviour, which will be discussed in the following subsections.

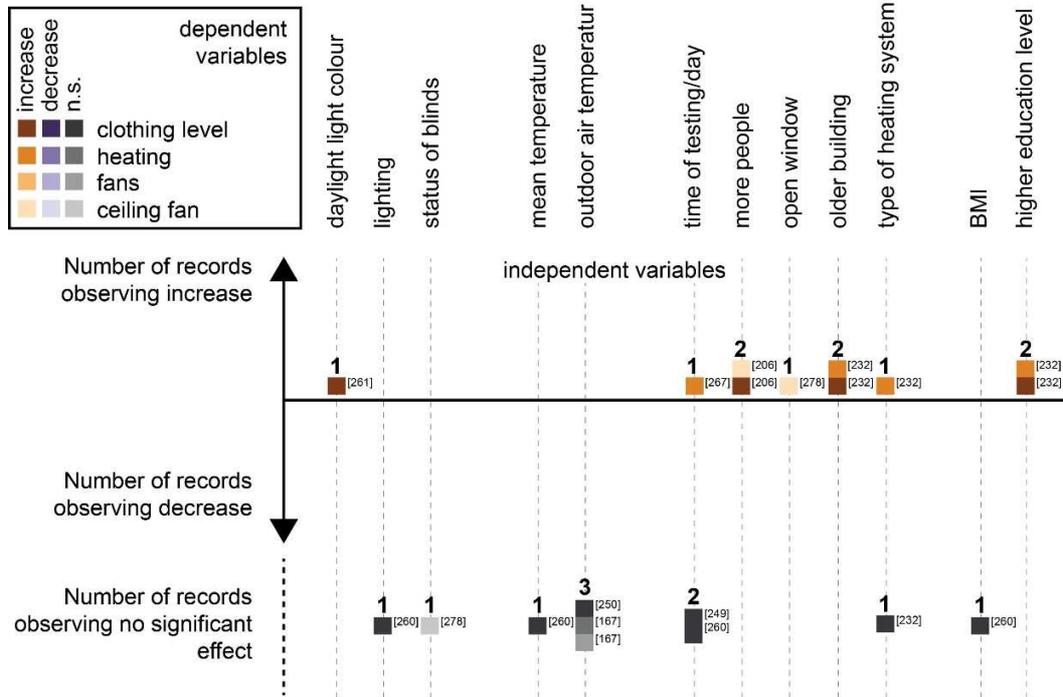
3



4  
 5

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

THERMAL BEHAVIOUR



1  
2 Fig. 10. Effects of physical, contextual and personal variables on different types of thermal  
3 behaviours.

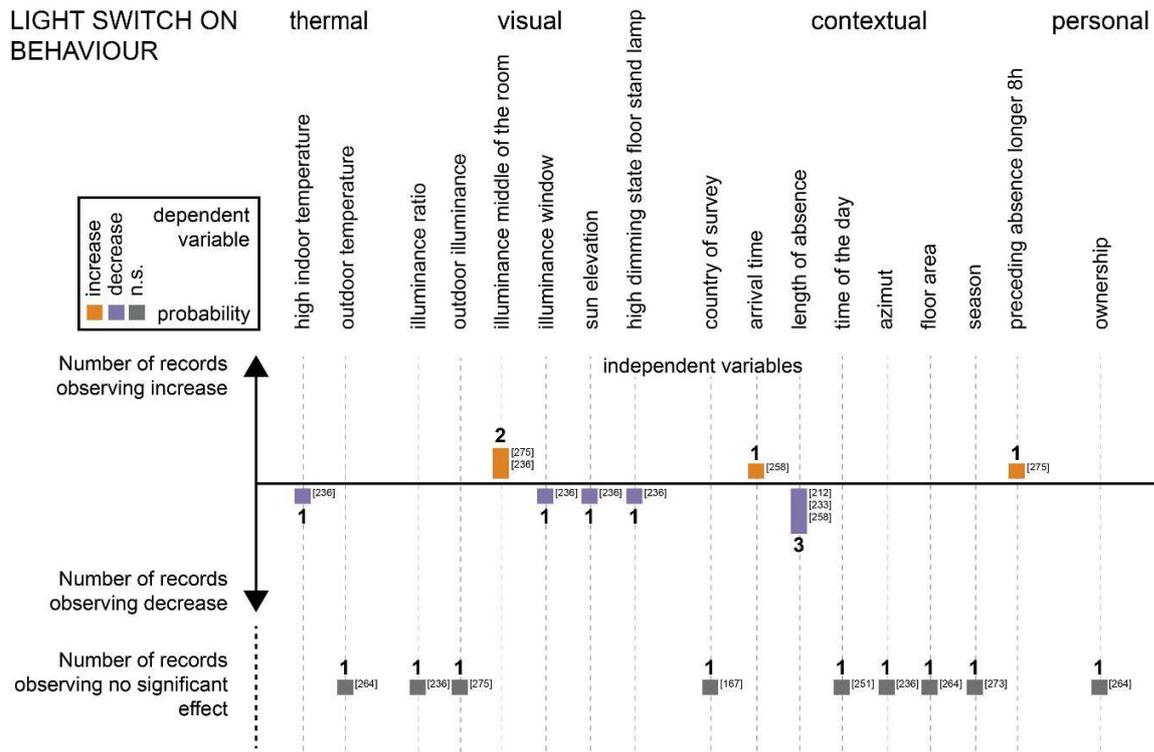


Fig. 11. Effects of physical, contextual and personal variables on light switch on behaviour.

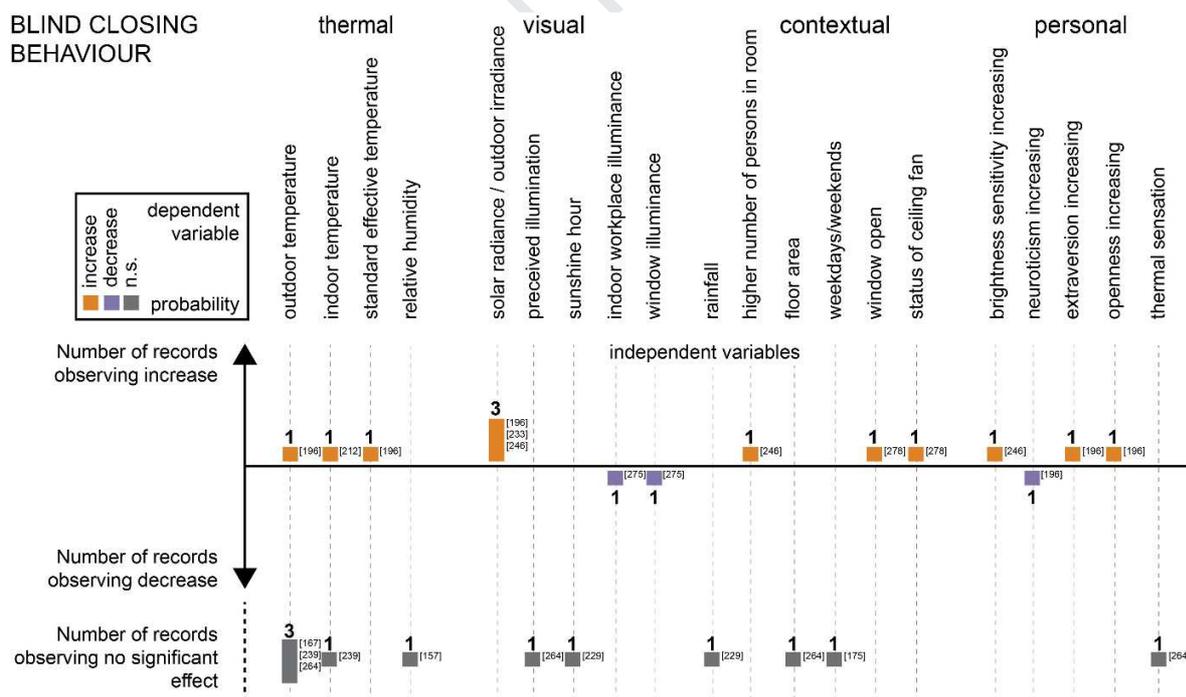


Fig. 12. Effects of physical, contextual and personal variables on blind closing behaviour.

## 1 **5.1. Physical multi-perceptual approaches**

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

### 4 **5.1.1 Motivational background**

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

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

### 18 **5.1.2 Approaches**

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

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

28 The duration of behavioural studies followed one of three trends: they undertook either a  
29 short duration of measurements in a manner of days [214; 219], a medium-term  
30 measurement across a single climate season [212; 221; 227], or a much longer-term study  
31 across several seasons up to an entire year or more [46; 213; 215; 216; 222; 224-226; 228;  
32 229]. The shortest measurements had the controlled laboratory studies. A notable example  
33 is Daum et al. [213], who collected over 6,800 individual survey responses over a period of  
34 3 years.

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

1 multiple linear regression, univariate and multivariate logistic regression, were used by all  
2 studies.

### 3 **5.1.3 Findings**

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

7 The findings from these papers defended widely understood principles of thermal and  
8 visual comfort in the built environment, as opposed to revolutionising them or putting them  
9 into question. For example, the studies which evaluated the extent to which window  
10 open/close behaviour would be driven by outdoor climatic conditions, IAQ, or other  
11 parameters, broadly concluded that indoor and outdoor air temperature, coupled with IAQ  
12 and/or solar radiation, are the primary drivers of window control by occupants [46; 216;  
13 217; 221; 222; 226; 228]. Outdoor air quality was identified as a moderate parameter of  
14 influence, particularly when it is considerably poor [226]. While solar radiation should be  
15 deemed a quasi-thermal parameter with a direct effect on indoor and outdoor air  
16 temperature and indoor heat gains, IAQ is related to a different domain, so that window  
17 open/close behaviour can be understood as a multi-domain problem.

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

### 25 **5.1.4 Identified gaps and future directions**

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

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

39 Despite prior evidence that circadian lighting affects occupants' perception, only the  
40 experimental studies evaluated the association of circadian lighting conditions on occupant

1 behaviour. The study of circadian lighting, both natural and artificial, and its effect on  
2 human physiology and psychology warrants further attention by field studies. None of the  
3 evaluated field studies explored whether light colours, or other indicators of circadian  
4 lighting, affected occupant behaviour. We also observed that noise levels were not  
5 frequently measured across studies that evaluated window open/close behaviour, even  
6 though the relationship between noise and window operation is not trivial [230].

## 7 **5.2. Physical + contextual variables**

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

### 11 **5.2.1 Motivational background**

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

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

### 27 **5.2.2 Approaches**

28 The majority of papers addressed window control (N=16), next to window blinds control  
29 (7), thermal adjustments (e.g. thermostat adjustment, switching on space heating and/or  
30 cooling systems)(7), lighting control (7), and adjustment of fan speed (2). Multi-domain  
31 independent variables were related to the thermal environment (36), the visual  
32 environment (17), and IAQ (13). Only one record included information on acoustic  
33 variables [248]. Amongst these independent variables, the most common for window  
34 control behaviour models were related to indoor and outdoor temperatures [18; 167; 203;  
35 206; 231; 233; 235-238; 240; 241; 244; 248; 252] and IAQ [18; 231; 235-237; 241; 244;  
36 248; 252]. Blinds behaviour models mostly included thermal variables [167; 175; 206; 229;  
37 233; 239; 253]; and visual variables [206; 229; 233; 239; 253]. The papers investigating  
38 thermal adjustments only included thermal environmental variables in combination with  
39 contextual variables [167; 206; 232; 238; 245; 249; 250].

1 The contextual factors included the time of day or arriving/leaving times [31; 203; 231;  
2 233; 236; 237; 239; 240; 242; 246], the previous control state [203], geographical  
3 location [238; 167], ventilation type [203; 238; 140], building system and envelope  
4 characteristics (e.g. installed technologies, building envelope efficiency, window opening  
5 size) [244; 245], facade orientation [251; 175], dress code [249], season or cloud  
6 cover [175], socio-economics [232], and occupancy levels [206].

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

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

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

### 20 **5.2.3 Findings**

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

32 In line with section 5.1.3, studies including physical and contextual variables found  
33 correlations between window operation and IAQ indicators (e.g. CO<sub>2</sub> and VOC  
34 concentrations) [31; 231; 235; 236; 252]. Stazi et al.'s review [18] found that window  
35 opening was mostly linked to CO<sub>2</sub> concentration in residential buildings. According to Fabi  
36 et al. [255], all papers that measured IAQ indicators found correlations with window  
37 operation.

38 Several studies found a strong relationship between window blind control operation and  
39 the time of day [233; 239; 246], while others did not [251]. Another important contextual  
40 factor influencing window blinds operation is the facade orientation [233; 246; 251]. Time

1 of day and/or arrival/leaving times play an important role also for light switch  
2 behaviour [233; 242].

### 3 **5.2.4 Identified gaps and future directions**

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

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

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

### 22 **5.3. Physical + personal variables**

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

#### 27 **5.3.1 Motivational background**

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

#### 30 **5.3.2 Approaches**

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

36 Research exploring physical and personal variables as predictors to behaviour analysed  
37 these two predictors independently or jointly. Indraganti et al. [256] applied descriptive  
38 and inferential analysis to explore the relationships between occupant's behaviours (14

1 control actions) and personal variables (dress habits); in parallel, the relationship between  
2 occupant's behaviours (air-conditioning and fan usage) and physical variable (outdoor daily  
3 mean temperature) was explored through logistic regression. Schweiker et al. [196] applied  
4 mixed effect regression analysis to explore the effect of physical (thermal and visual) and  
5 personal (personality traits) variables on occupant's behaviours (clothing adjustments,  
6 window opening, blind closing, and ceiling fan usage). Gunay et al. [258] applied discrete-  
7 time Markov logistic regression to explore the effect of physical (ceiling illuminance) and  
8 personal (occupant's presence) variables on occupant's behaviours (light switching and  
9 window blind actions).

### 10 **5.3.3 Findings**

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

### 19 **5.3.4 Identified gaps and future directions**

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

## 27 **5.4. Physical + contextual + personal variables**

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

### 31 **5.4.1 Motivational background**

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

### 36 **5.4.2 Approaches**

37 The majority of the publications were field studies, often based on or involving  
38 questionnaire surveys [256; 257; 262; 264]. Almost all the studies used logistic regressions

1 to evaluate the cross-main effects of environmental and non-environmental factors on the  
2 occupants' behaviour. The analysis of the interactions between different predictors has not  
3 been established yet, but there is a growing body of literature with results that point out its  
4 importance [267; 268].

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

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

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

### 16 **5.4.3 Findings**

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

24 In an office building in the hot and humid climate region of India, window use was mostly  
25 defined by contextual factors such as the time of day; meanwhile, the occupants did not  
26 interact with other building controls [256]. A study in China [266] concluded that the  
27 window used in the studied offices was a combination of physical and contextual factors  
28 such as the sunshine hours. Wei et al. [265] revealed a seasonal effect and a significant  
29 influence of the location of the window (ground floor or not) and personal preference  
30 (habitual or not) on the "end-of-day" window state. Absence in subsequent days and  
31 contextual factors such as daylight saving time and façade orientation did not have a  
32 significant effect. Seasonal effects were also evident in a South Korean study [268]. In  
33 spring, window use was affected by the CO<sub>2</sub>-concentration, whereas in summer the indoor  
34 temperature was a significant driver. In winter, indoor temperature and CO<sub>2</sub>-concentration  
35 did not have a statistically significant effect. Yun et al. [257] showed a significant  
36 relationship between comfort and perceived control over temperature in NV buildings and  
37 highlighted that a change of the windows' state is more likely with high compared to low  
38 perceived control [257].

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

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

#### 6 **5.4.4 Identified gaps and future directions**

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

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

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

### 25 **5.5. Physical + multi-behavioural approaches**

26 The focus of the 13 studies in this subsection is on the interrelations between the indoor  
27 environmental conditions with a combination of different behavioural responses [212; 225;  
28 254; 258; 270-278].

#### 29 **5.5.1 Motivational background**

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

#### 34 **5.5.2 Approaches**

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

37 In contrast to the previous subsection, the research in this field is focused on office  
38 buildings. Window use remains the most prominent behaviour and is studied in

1 combination with personal adaptation behaviours (e.g. physiological responses [278],  
2 clothing adjustments, and interactions with the heating and cooling systems [274]).  
3 Responses to changes in visual conditions are discussed in light of interactions with shades  
4 and electric lighting [212].

5 The physical variables commonly considered were the indoor and outdoor air temperature,  
6 relative humidity, wind speed, illuminance, and the level of CO<sub>2</sub>-concentration as an  
7 indicator of IAQ. The non-physical variables differed again with the building characteristics  
8 and the researchers' objectives and included season, period of day, type of room and  
9 current state of controls. However, the analysis of the significance and impact of different  
10 variables followed mostly again a cross-main effects approach.

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

### 13 **5.5.3 Findings**

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

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

### 34 **5.5.4 Identified gaps and future directions**

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

## 1 **6. Discussion and conclusion**

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

### 5 **6.1 Motivational background**

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

### 10 **6.2. Approaches**

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

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

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

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

37 Contextual influences and occupant behaviour are more difficult to study in an artificial  
38 setting of a laboratory environment. The low frequency of interactions (i.e., 1 to 4 actions  
39 per day) would require very long and expensive study periods uncommon in laboratory

1 settings. Still, more attempts would be beneficial to reveal true causalities, because field  
2 studies also have drawbacks. The lack of experimental control over environmental  
3 conditions means that the conditions cannot be causally related to human outcomes, and  
4 that environmental conditions are likely to naturally co-occur in predictable ways (e.g., a  
5 position near a window in the summer is likely warmer and brighter than one on the  
6 interior of a room).

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

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

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

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

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

### 14 **6.3 Findings**

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

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

1 explanations to what extent interactions can be additive, antagonistic, or synergetic. For  
2 example, Talsma et al. [283] propose a framework that shows the interaction between  
3 multi-physical perception and attention.

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

#### 21 **6.4 Future directions**

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

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

38 Second, researchers should clarify whether their research is intended to explore new  
39 influences, i.e. supporting the development of new theories or the extension of existing  
40 ones, or test an existing theory. In addition, researchers should clearly state the limitations  
41 of their studies, especially when dealing with small samples, discuss the applicability and  
42 comparability of results in the context of existing knowledge, and be careful with false  
43 causalities arising from unobserved confounding factors. Thereby, generalization is

1 relevant to find common patterns. However, addressing individual differences and  
2 revealing factors leading to such differences, even for single cases, is of high importance in  
3 order to consider outliers as valuable points of information. The latter assertion is valid  
4 either because these points are true outliers and explanations available (see e.g. O'Brien et  
5 al. [287] for a qualitative approach to explain outliers). Or, because they point to  
6 methodological issues (e.g., the question asked is prone to misinterpretation under specific  
7 circumstances).

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

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

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

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

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

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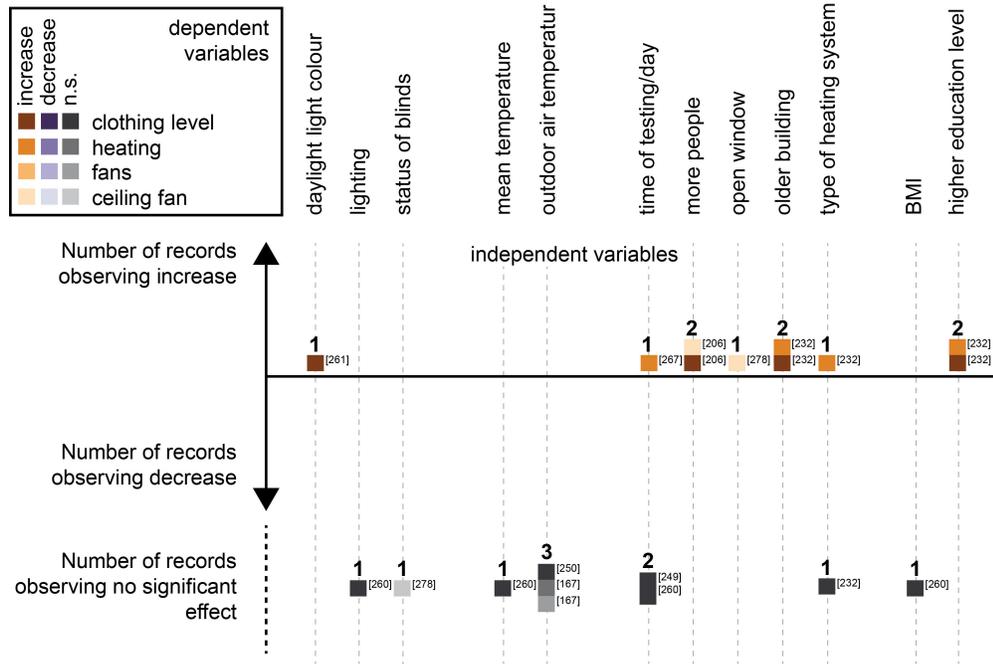
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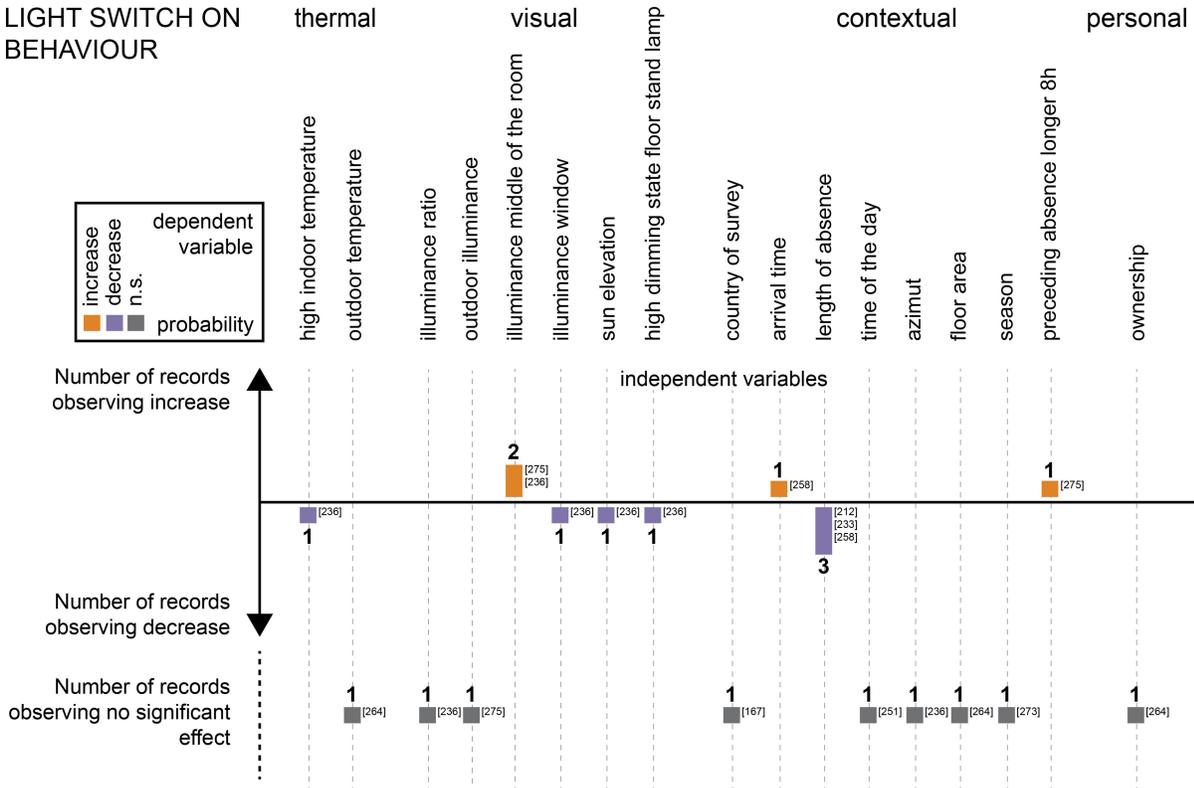
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THERMAL BEHAVIOUR

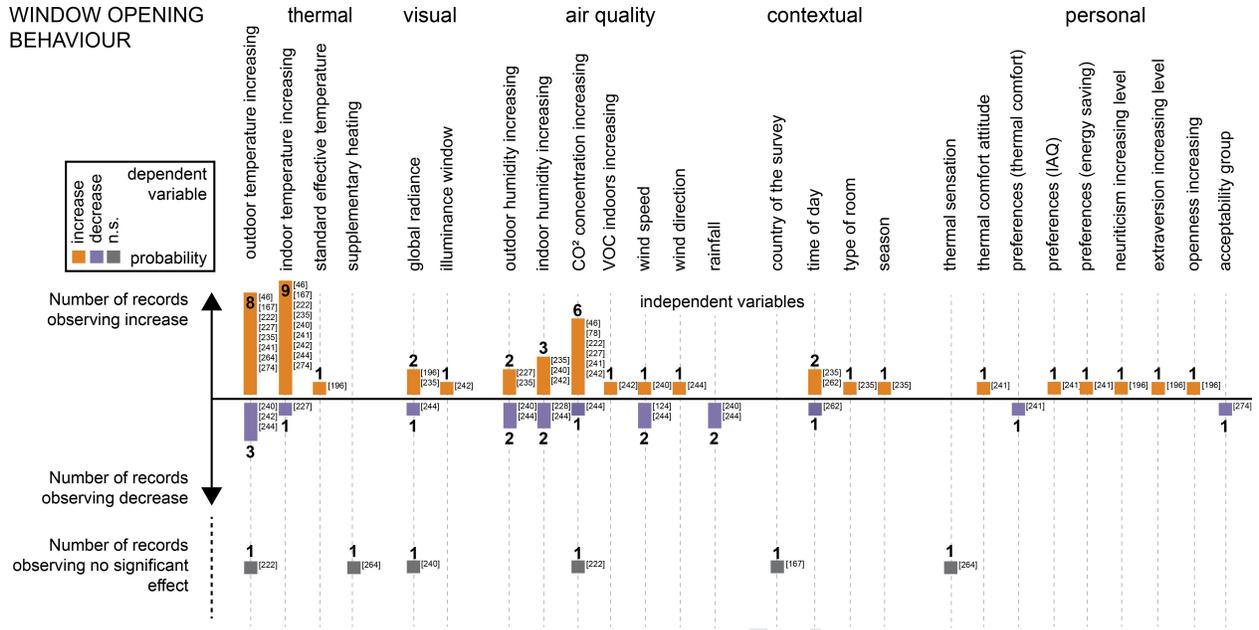


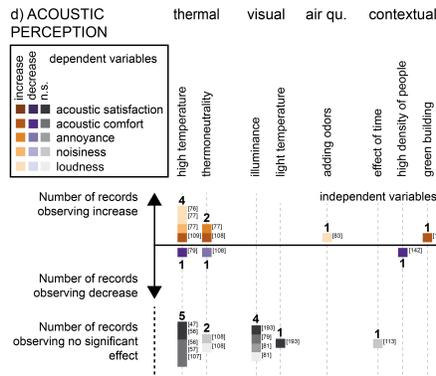
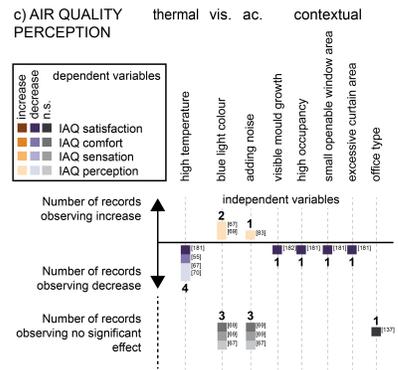
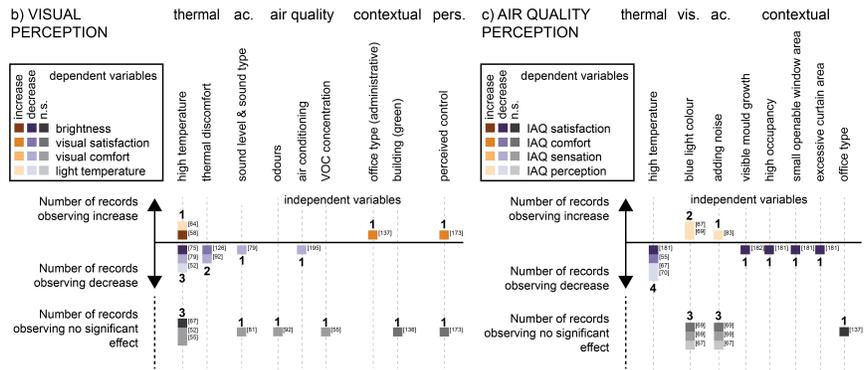
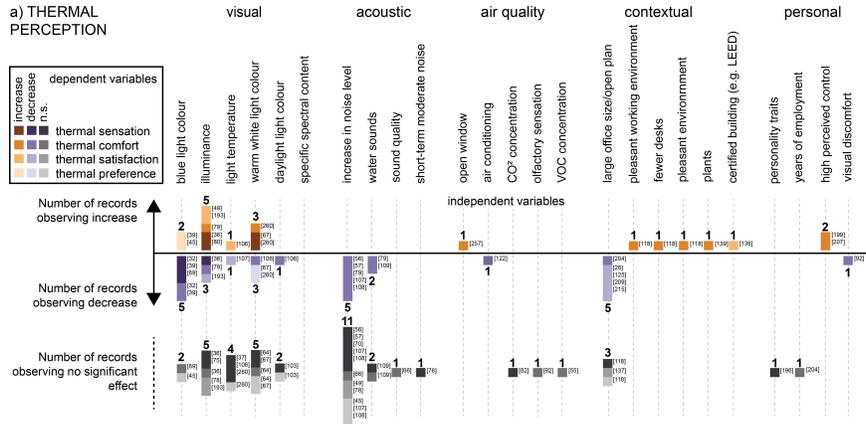
LIGHT SWITCH ON BEHAVIOUR

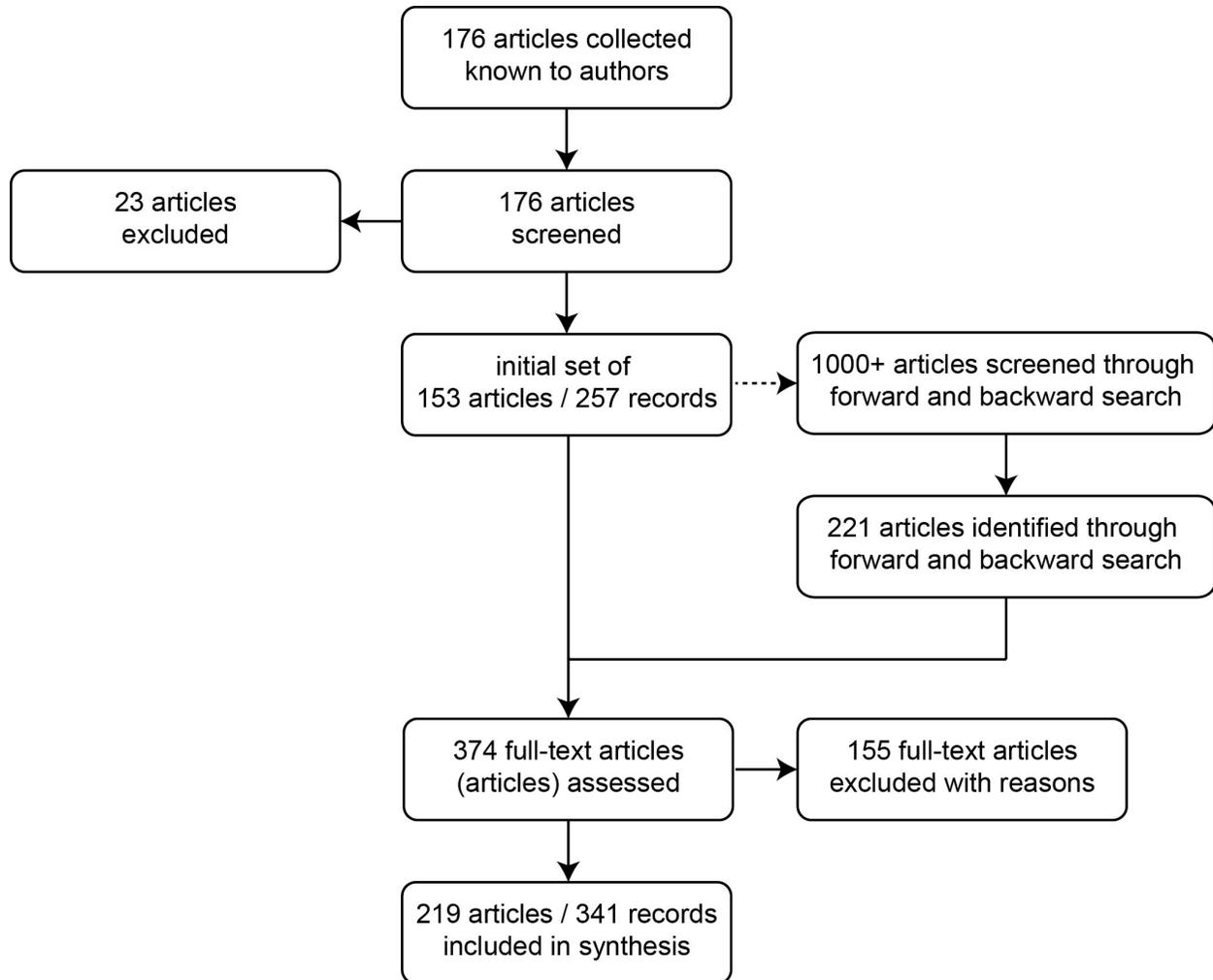


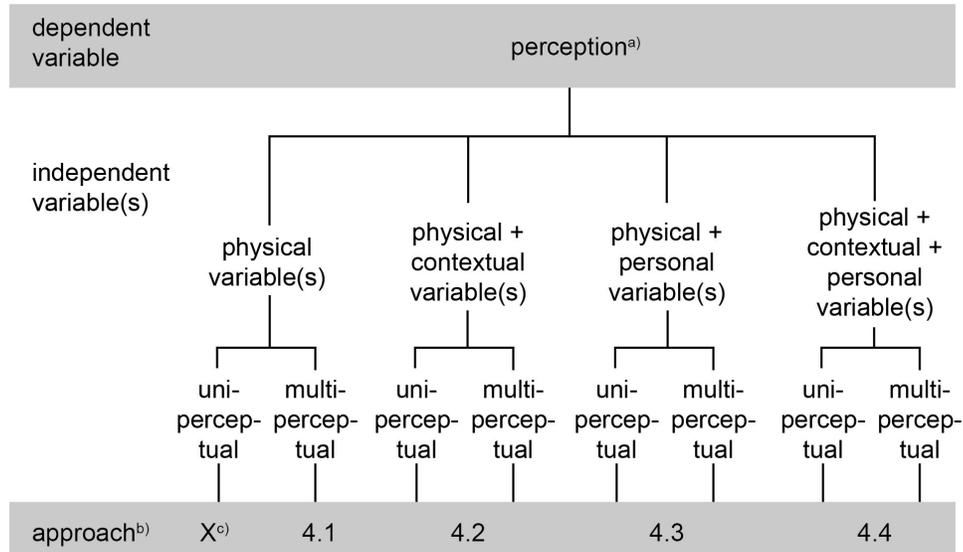
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WINDOW OPENING BEHAVIOUR





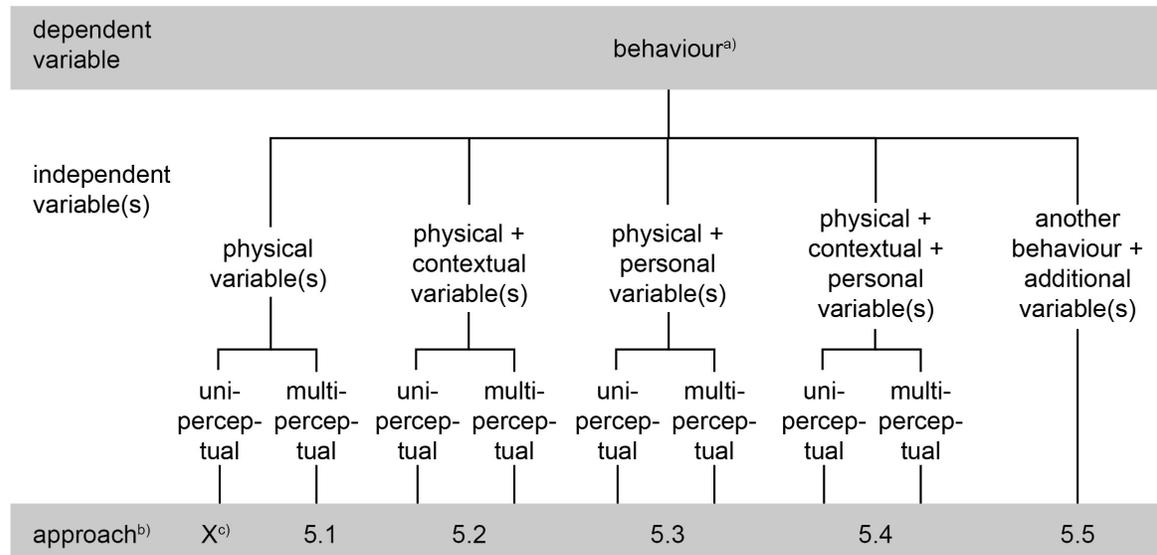




<sup>a)</sup> Perceptual dependent variables (e.g. comfort, sensation, and satisfaction) relate to individual domains, including thermal, visual, acoustic, indoor air quality (IAQ), or overall perception of the indoor environment

<sup>b)</sup> Approach numbers refer to the subsection numbers within this review

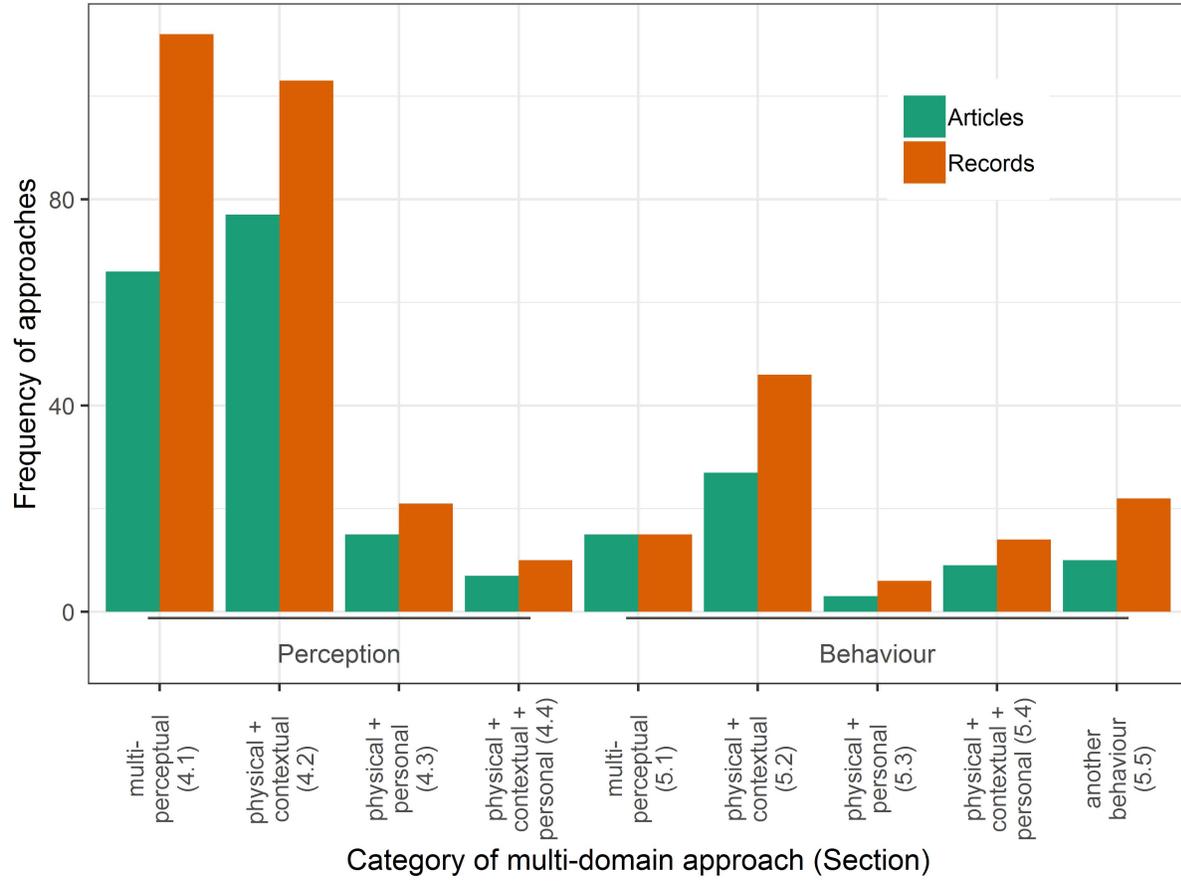
<sup>c)</sup> Not considered as multi-variable approach and not included in this review

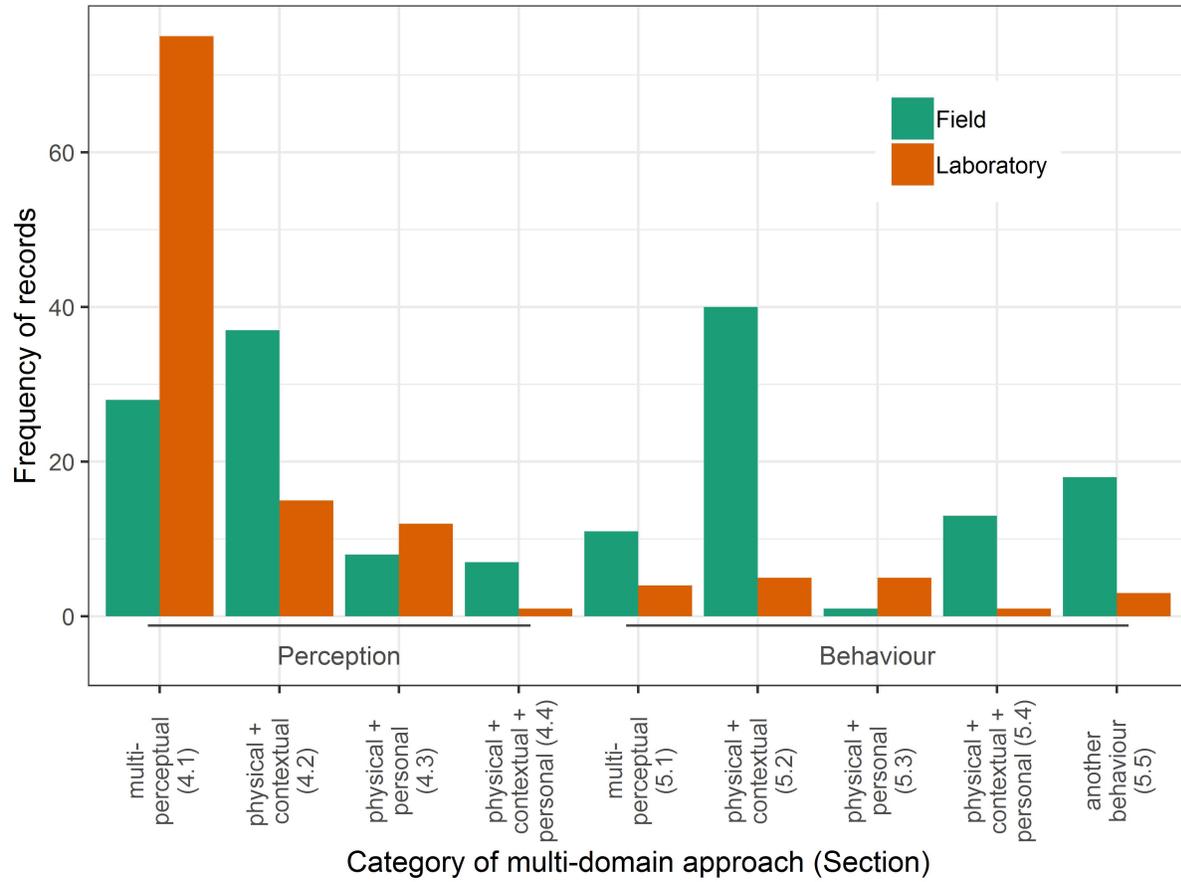


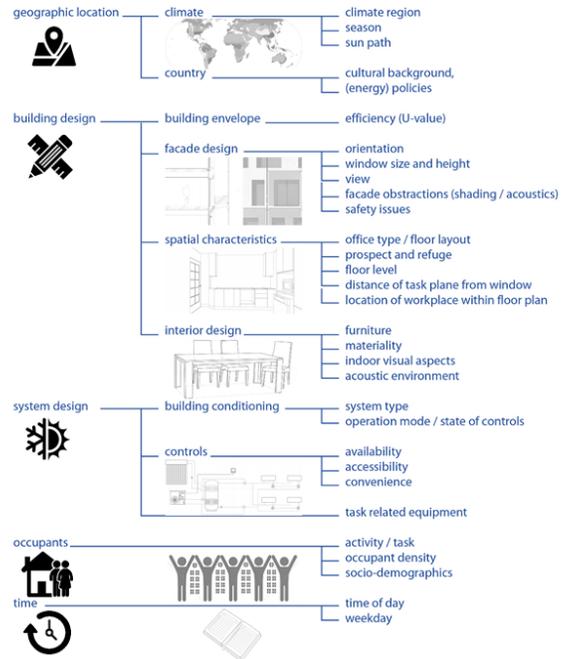
<sup>a)</sup> Behavioural dependent variables are actions on windows, blinds, and other elements leading to thermal, visual, acoustic or IAQ adjustments.

<sup>b)</sup> Approach numbers refer to the subsection numbers within this review

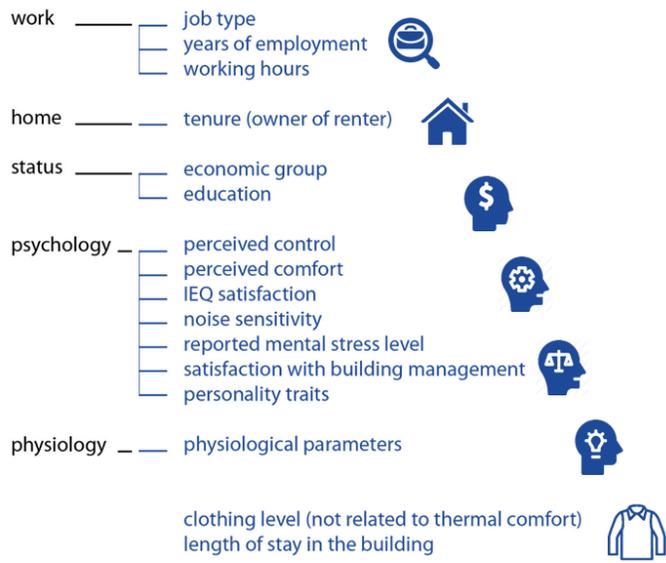
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Building occupants are continuously exposed to multiple indoor environmental stimuli.

Personal and contextual aspects are additional domains influencing occupants' perception and behaviour.

Scientific literature in this area typically deals with these multiple stimuli in isolation.

The present contribution reviews 219 multi-domain papers on occupants' indoor environmental perception and behaviour.

In conclusion, 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.

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## Declaration of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We further confirm that any aspect of the work covered in this manuscript that has involved either experimental animals or human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

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Signed on behalf of all authors