Test rooms to study human comfort in buildings: a review of controlled experiments and facilities

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Abstract

Occupants' comfort perception affects building energy consumptions. To improve the understanding of human comfort, which is crucial to reduce energy demand, laboratory experiments with humans in controlled environments (test rooms) are fundamental, but their potential depends on the characteristic of each research facility. Nowadays, there is no common understanding for definitions, concepts, and procedures related to human comfort studies in test rooms. Identifying common features would allow standardising test procedures, reproducing the same experiments in different contexts, and sharing knowledge and test possibilities. This review identifies 187 existing test rooms worldwide: 396 papers were systematically selected, thoroughly reviewed, and analysed in terms of performed experiments and related test room details. The review highlights a rising interest in the topic during the last years since 46% of related papers has been published between 2016 and 2020. A growing interest in non-thermal sensory domains (such as visual and air quality) and multi-domain studies about occupant whole comfort emerged from the results. These research trends have entailed a change in the way test rooms are designed, equipped and controlled, progressively becoming more realistic inhabitable environments. Nevertheless, some lacks in comfort investigation are highlighted: some continents (like Africa and South America) are found to be underrepresented, while involved subjects are mainly students performing office tasks. This review aspires to guide scientists and professionals toward the improved design or the audit of test room experimental facilities, especially in countries and climate zones where human comfort indoors is under-studied.

Highlights

- Test rooms: environmentally controlled and equipped space to study human comfort
- Systematic review of controlled studies on human comfort (396 papers)
- 187 test rooms analysed in terms of construction and technical details
- Overview of single and multi-domain comfort experiments conducted in test rooms
- Trends in conducted experiments and test room-related design

Keywords

Test room; laboratory; climate chamber; human comfort; human-centric experiments; thermal comfort; visual comfort; acoustic comfort; indoor air quality; multi-domain comfort; energy performance; Indoor Environmental Quality;

Word count: 9995

List of abbreviations

IEQ	Indoor Environmental Quality
WWR	Window-to-wall ratio (expressed in %)
HVAC	Heating, Ventilating and Air Conditioning
ACH	Air Change per Hour
VOCs	Volatile Organic Compounds
SPL	Sound Pressure Level (expressed in dB)
SBS	Sick Building Syndrome
EEG	Electroencephalogram
EDA	Electrodermal activity
ECG	Electrocardiogram
EOG	Electrooculography

1. **Introduction**

People in developed countries spend 85-90 % of their time indoors [1]. Notwithstanding undeniable improvements in the quality of building interiors in the past decades, a range of health risks and discomfort issues associated with exposure to the indoor environment persists. Researchers have demonstrated the strong connection between the indoor environmental quality (IEQ) of a building and occupants' comfort, health, and productivity [2,3]. Moreover, buildings' energy consumption is largely affected by occupants' behaviour [4], triggered by their perception of the surrounding environment [5]. Therefore, decoding human comfort is a crucial issue in building science for enhancing building design and operation from a sustainable perspective and through a human-centric approach [6].

The scientific community approaches human indoor comfort by coupling measurements of the physical environment (e.g., air temperature, sound pressure level, air pollutant concentrations, illuminance) and occupants' feedback collected via surveys, behavioural and/or physiological monitoring. Applied experimental protocols can be broadly categorized into (i) in-field monitoring and (ii) laboratory experiments.

In-field experiments allow researchers to observe subjects in a real environment such as workplaces [7,8], residential [9] or educational [10] buildings, or even semi-open transitional urban spaces [11]. This approach provides essential outcomes, especially for assessing the impact of real-space configurations on occupants' perception [12], the effects of building characteristics on occupants' wellbeing [13], or the impact of occupants' behaviour on buildings' energy consumption [14,15]. However, it does not allow to directly control the environmental parameters of the investigated spaces. Indeed, it is not feasible to isolate the contribution of a single environmental factor or a specific combination of multiple environmental stimuli on subjective responses, for example, overall comfort perception or productivity [16] in in-field research, while this is fundamental to establish a cause-effect relationship related to the comprehension of human comfort and the related occupancy behaviour [17]. These issues can be solved through experiments in controlled environments where desired physical boundaries can be determined and replicated, so different subjects can be exposed to the same stimuli and the influence of subjective factors elucidated [18]. Moreover, laboratory experiments generally allow researchers to perform a more detailed investigation of human subjects and collect physiological signals less commonly monitored in-field.

Many research institutions have built their own environmentally controlled experimental facilities to perform human comfort-related experiments worldwide and throughout the years. Each facility is designed to achieve specific research goals, thus presenting different dimensions, internal layouts, envelope characteristics, energy systems, and monitoring setup. Different equipment types are also included depending on the final aim of an experimental campaign targeting a specific comfort domain. Examples include thermal manikins, commonly simulating human thermal comfort [19] or inhalation exposure [20], or different apparatus for studying the human reaction to specific environmental input such as glare discomfort [21,22]. The test room design influences the experimental design and the accuracy of related modelling. The construction and technological details of the test room decide on the extent and scope of the different stimuli that can be provided as well as the different spatial layouts that can be generated. Being an essential determinant of experimental methodology, a careful design process of these facilities is of primary importance.

Due to the rising interest in better understanding human comfort, many reviews shed light on different perspectives of the topic. Several reviews summarise visual-related studies, reporting both lab and field investigations, as well as simulation studies [24–27]. Others focus on thermal comfort and different modelling approaches [28], main experimental procedures [29,30], or its energy-related implications [31]. Nevertheless, none addresses the diversity of laboratory facilities, which is a key component in the design of human-centred comfort experiments.

The identification of standard tools for advancing knowledge in the field would be helpful for the scientific community. An accepted glossary for identifying such facilities is still missing. Many papers refer to these facilities as test rooms or chambers or test-cells or simply laboratories. Here, "test room" was chosen as the most representative definition, highlighting the differences between facilities designed for human comfort studies and laboratory equipment devoted to material testing. Moreover, we define a "test room" as an enclosed space, environmentally controlled and properly instrumented, in which human-centric comfort studies can be performed through actual occupants' presence and monitoring.

This review aims at describing existing test rooms worldwide and at summarizing experimental studies on human comfort performed in such facilities to outline trends in the field, common components, and define new research perspectives. Precise selection criteria of the papers have been identified and used for the critical review (Section 2), and common technical features and trends in construction have been taken into account (Section 3), while Section 4 focuses on the specific experiments conducted in these facilities to deepen human comfort theory. Each experiment was categorized based on the type of domain(s) of human perception involved (thermal, visual, olfactory, and aural). In this context, a distinction was made between single-domain studies, which describe experiments focusing on thermal, visual, indoor air quality or acoustical stimuli only, and multi-domain studies [18,32], which simultaneously address two or more domains; for instance, the analysis of thermal and acoustic stimuli on overall comfort perception, or the analysis of thermal perception as influenced by lighting or air quality conditions. The key findings and conclusions, including suggestions for future research agenda, are summarised and critically discussed in Sections 5 and 6, respectively.

2. Materials and methods

A systematic bibliographic search was planned and conducted to establish a database as comprehensive as possible, looking at existing test rooms for human comfort experiments according to available scientific literature and not to miss any test rooms that the authors are aware of. The final database is thus the result of two main steps: an automatic search and a supplementary hand search (Figure 1).

The automatic search was systematically conducted through Scopus and Web of Science scientific databases to identify papers concerning human comfort investigation in test rooms, as available up to June 2020. The search was limited to journal papers written in English after 1985 to keep the search consistent between the two scientific databases due to the temporal limitation of Web of Science. To cover the scientific literature on the theme published before 1985, a further search was conducted in Google Scholar. Different typologies of documents such as books, book chapters, reviews, or conference proceedings were thus excluded from the search to improve consistency and avoid repetitions of the same study that may have been presented in different document types. Five queries were designed within these boundaries, corresponding to each aspect of indoor human comfort. The queries were structured in three parts, progressively focusing on the purpose of the review:

(i) on the laboratory facility where human comfort experiments took place,

(ii) on the main aim of the studies, i.e., human comfort, and
(iii) on the specific comfort domain of interest (e.g., thermal, visual, acoustic, air-quality related).

Each part of the query was detailed after a discussion among the authors that are experts in human comfort studies and come from different countries and cultural backgrounds. These cultural differences provide a comprehensive definition of the facilities object of the review. The first two parts of the query were used for all the five queries and consisted of the following keywords: (testroom OR test-room OR chamber OR laborator* OR "test cell") AND comfort. The term "human" was not included for not missing any contributions that may fit the scope but did not explicitly mention humans' involvement. The publications not dealing with human comfort were excluded through the double-screening procedure, as specified in the following. In addition to these keywords, the five queries were distinguished by including the following specific keywords:

1. *Thermal*
2. *Visual OR Lighting*
3. *Acoustic*
4. *Air quality OR Pollution*
5. *Energy*

Each specific query focused on a single comfort aspect addressed from the perspective of the provided physical stimulus, as associated with thermal, visual, aural and olfactory human perception. In contrast, the fifth query focused on the theme of energy that is commonly associated with human comfort studies aimed at improving indoor environmental quality while reducing building energy consumption.

The automatic bibliographic search resulted in 1776 papers. A cleaning procedure of the database was performed by focusing only on experiments both carried out in a controlled environment and addressing human perception and exposure. This procedure accounts for two main steps. The first screening was conducted through a specifically developed script in Python language for automatic abstract screening by excluding papers presenting specific words referred to out-of-scope disciplines such as medicine or veterinary medicine. After this first screening, 598 papers were still included in the review process. and went through the second screening phase: the papers were carefully read and selected according to the primary purpose of the review. Only papers describing experiments performed in the controlled environments (test rooms) whose internal dimensions and conditions were suitable for human experiments were considered for this review.

The hand search was carried out for reducing the automatic search biases and limiting the number of existing test rooms not covered by this review. Additional papers were included according to the previous knowledge of the authors and the selection criteria that is the usage of a controlled environment for conducting experimental research on human perception and exposure. More than half of the additional papers (49 out of the 92) concern the visual comfort domain, meaning that common keywords coming from the other domains were not suitable to catch all the visual comfort studies. The final number of analysed papers was 396.

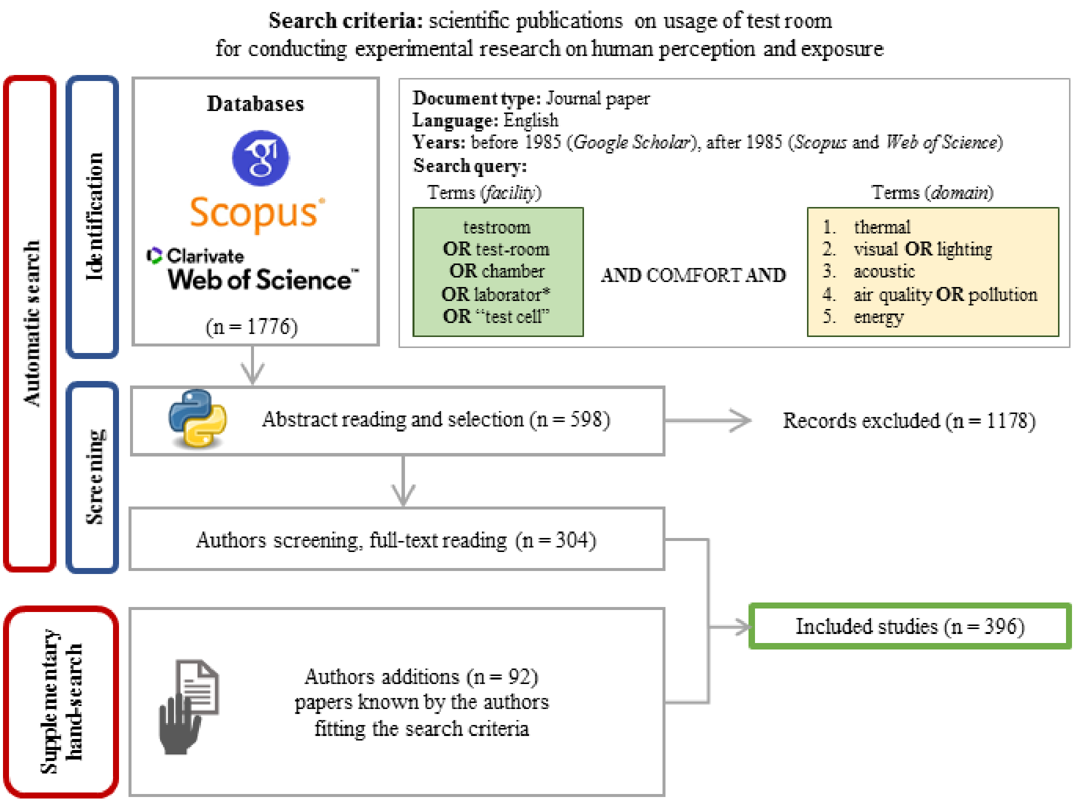


Figure 1. Papers selection workflow.

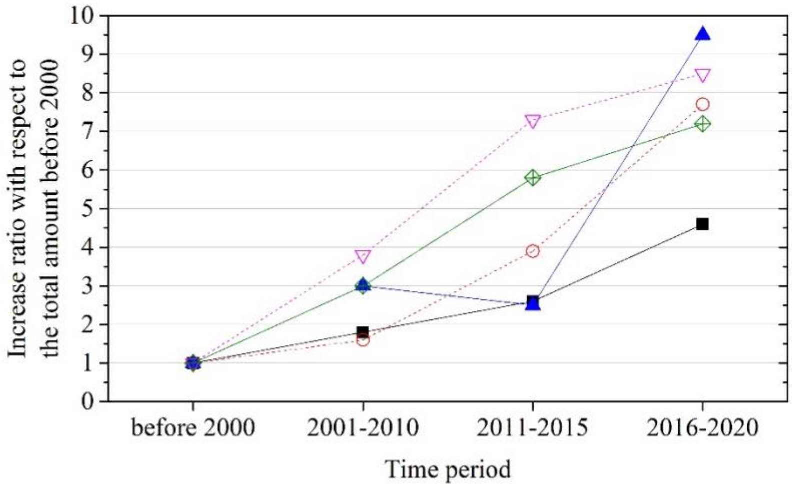
Table 1. Number of journals papers published throughout years (up to June 2020) and concerning each analysed topic.

		Time periods				
	Domain(s)	**≤ 2000**	**2001-10**	**2011-15**	**2016-20[b]**	**Total**
1 domain	Thermal	26	39	50	89	204
	Air quality	3	3	4	8	18
	Acoustic	0	2	2	7	11
	Visual	5	10	23	32	70
2 domains	Thermal + Air quality	0	10	22	19	51
	Thermal + Acoustic	0	3	0	3	6
	Thermal + Visual	1	0	1	17	19
	Air quality + Acoustic	0	1	0	1	2
	Air quality + Visual	0	0	0	0	0
	Acoustic + Visual	0	0	1	1	2
3 domains	Thermal + Air quality + Acoustic	1	0	1	1	3
	Thermal + Air quality + Visual	0	1	1	0	2
	Thermal + Acoustic + Visual	1	0	0	1	2
	Air quality + Acoustic + Visual	0	0	0	0	0
4 domains	Thermal + Air quality + Acoustic + Visual	0	0	1	5	6
	Total	37	69	106	181	396
	energy related[a]	5	15	29	36	85

[a]The energy-related topic is transversal to the others
[b]The count for 2020 considers only those documents indexed until June 2020

Table 1 summarizes the number of analysed papers per topic and year of publication, considering four time periods: (i) up to 2000, (ii) 2001-2010, (iii) 2011-2015, and (iv) 2016-2020. Defined time periods highlight the considerable increase in published papers on controlled test room experiments on human comfort. Indeed, the increase ratio observed during the first decade of the 21st century (1.9) is comparable to the one observed for the first (1.5) and second (1.7) part of the following decade.

The table depicts a predominant interest of the scientific community in thermal comfort investigations (conducted either in isolation or in combination with other factors) followed by energy-related studies (total of 85 papers) and visual comfort assessments. Air quality studies are less common, especially as a single stimulus for the participants involved in test room experiments. Indeed, the total amount of reviewed papers related to air quality assessment is 84. Only 18 of them were found to focus on air quality only as a single stimulus, disabling the olfactory from the thermal perception and all the other spheres of comfort. More detailed presentation of the aims and procedures of the air-quality-only studies is provided in Subsection 4.4.



	Thermal	Visual	Acoustic	Air quality	Energy
Publications before 2000	29	7	2	4	5

Figure 2. Publication increase ratio with respect to the number of published papers before 2000 for each query.

Figure 2 shows trends of publication for each specific domain of comfort, without distinguishing between single and multi-domains experiments, with respect to studies published before 2000. Thermal comfort-related experiments present the slowest increasing ratio from the reference scenario. Air quality-related experiments show the greatest increase in the number of published papers, with a slight decrease in the last five years. A similar trend can be observed for energy-related studies. Visual comfort-related studies are gaining more attention with currently seven times more papers compared to available publications before 2000. Aural comfort is the least investigated domain in controlled environments. Reviewed papers including a focus on acoustic comfort are 32 in total, half of which published in the last five years.

3. The test rooms around the world

From the 396 papers selected according to the systematic review process, 187 different test rooms located in 126 research institutes around the world have been identified based on the descriptions provided in the papers.

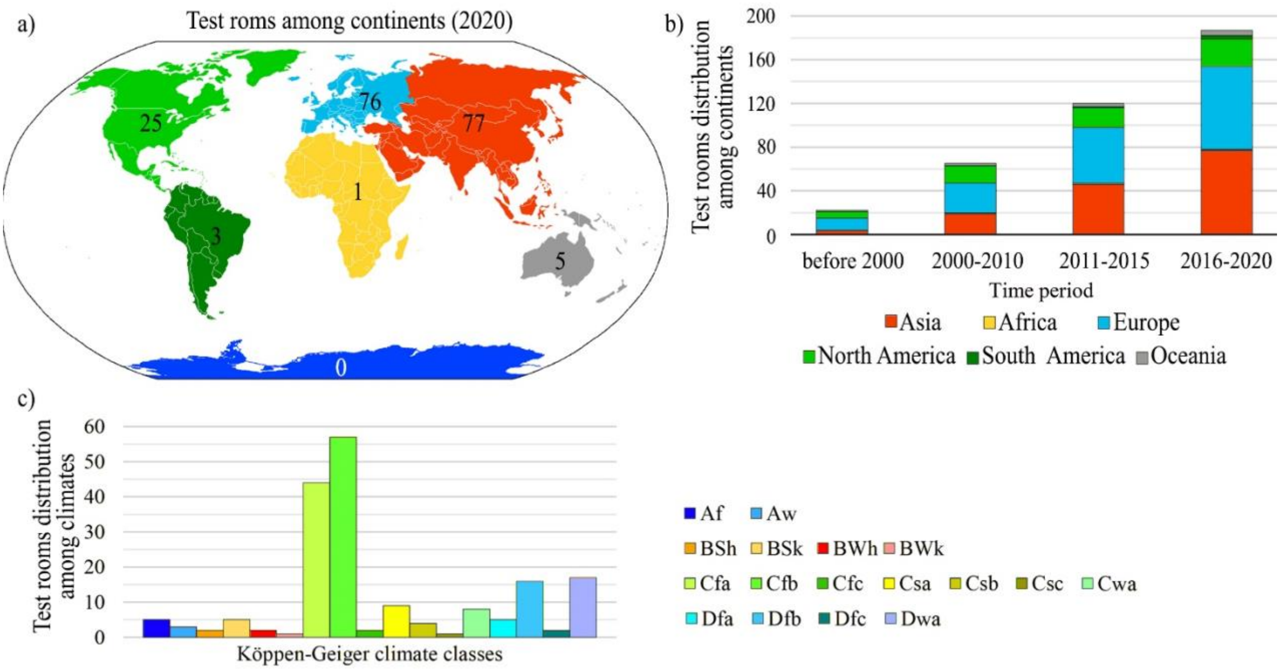


Figure 3. (a) Number of test room facilities located in the seven continents; (b) amount of test rooms located in each continent for each defined time period; (c) frequency distribution of test rooms with respect to Köppen-Geiger climate classes [33].

Figure 3 summarises the test rooms distribution across continents (a,b) and different climate conditions (c), referring to the Köppen-Geiger climate classification [33]. Nowadays, the great majority of test rooms are located in Europe and Asia (82 %), and in a temperate climate, without dry seasons, characterized by hot (Cfa) and warm (Cfb) summer. 29 out of the 44 test rooms located in the Cfa climate zone are in Asia (South and coastal area of Japan and South-Eastern China mainly), while 54 out of the 57 test rooms located in Cfb zones are in Europe (North-Western countries mostly). Figure 3b presents how the worldwide distribution of these facilities varied across time (all the test rooms were dated per the oldest related paper available in the review dataset). European countries have the oldest tradition in human-related experiments conducted in controlled test room settings: 50 % of the facilities already existing before 2000 were located in Europe. The number of facilities in Asia has grown over the last 20 years from 18 to 41 % of the total number worldwide in 2020, overcoming the number of facilities located in North America (13 %).

The following subsections are intended to provide helpful information for researchers evaluating whether to create or buy a test room for human comfort studies. These illustrate the range of test room characteristics that enable the researcher to perform different experiments and investigate specific aspects of human comfort. An overview of construction and technical details is provided in section 3.1 and 3.2, in accordance with the available information from the reviewed papers. Then, sections 3.3 and 3.4 provide insights into the economic investment required to set up these kinds of facilities, either if these are customized or commercially available. Since none of the reviewed papers provides information on test room costs and related economic investment, data provided in sections

3.3 and 3.4 come from an additional search: an online survey was submitted to authors of the identified significant and recent literature, seeking details on key aspects of the needed economic investment (including design, construction, operation and maintenance costs). Finally, commercial test room producers (eight institutions from the U.S. and five institutions from Europe) were directly contacted to provide dedicated insights for the readers, reported in section 3.4.

3.1 Construction details

The construction details were specifically examined to determine how passive elements of the test room, including windows, shades, layout, size, and position within or external to an existing building, may allow or hinder different types of investigations. Unfortunately, comprehensive descriptions of the test rooms construction details are not always available. It was not possible to assess whether the test rooms are located inside a building or are entirely independent buildings for 10 % of the 187 test rooms identified. According to the available information, only 7 % of the facilities are independent buildings, external to any other building [34,35,44–47,36–43]. Five of these independent test rooms are located on a platform that allows the whole structure to rotate [34–37,41]. The great majority are situated inside the related research institute. Among these, it is possible to distinguish between facilities completely detached from the surrounding structure (43 %) and test rooms that are specifically equipped rooms within the hosting building (32 %).

Some test rooms include more than one room. These rooms could be adjacent, but with independent entrances, or connected through an intermediate door. The latter configuration allows researchers to continuously monitor participants’ reactions when exposed to different controlled environmental conditions [48]. Eight of the external facilities have just one room, but the possibility to work with movable internal partitions is mentioned for four of them [38,41,43,44]. The other six outdoor test rooms present two rooms, and four out of the six have movable partitions for changing the interior space layout [34,35,40,45]. For the inside test rooms, single room configurations are most common (79 %), some of which can be modified through movable interior partitions (19 %). More information about the number of rooms embedded in the test rooms and their dimensions are summarised in Table 2.

Table 2. Test rooms composition and dimensions with respect to their position (inside or outside another building).

Test rooms position		**Number of rooms**				**Dimensions [m^3]**				**Total**
		1	**2**	**> 2**	**N/A**	**< 9**	**9-20**	**> 20**	**N/A**	
Inside	Detached[a]	53	8	1	4	5	16	36	9	66
	Integrated[a]	37	8	2	2	0	4	43	2	49
	N/A	32	2	0	6	1	5	20	14	40
Outside		8	6	0	0	0	4	10	0	14
N/A		7	1	0	10	0	1	4	13	18
	Total	137	25	3	22	6	30	113	38	187

[a]with respect to the building structure of the related research centre

It was not possible to define whether the described test rooms present any type of openings for 41 % of the recognized facilities, 25 % of the test rooms located inside have no openings, 18 % have windows facing the outside, 16 % have windows to interior spaces, and just 2 % have both windows to the outdoors and the indoors (Figure 4). Among the 14 experimental facilities built outside, only one does not have windows [46]. At the same time, five include an adjustable envelope to vary the window-to-wall ratio (WWR) [35,37,41,43,45], five have a WWR lower than 0.5 [38,39,42,44,47], and three have a WWR in between 0.6 and 0.8 [34,36,40]. Concerning the shading system, it is clearly stated that there are external blinds in three test rooms [34,36,47], four present internal shading systems [38,40,42,44], while just one has both [39].

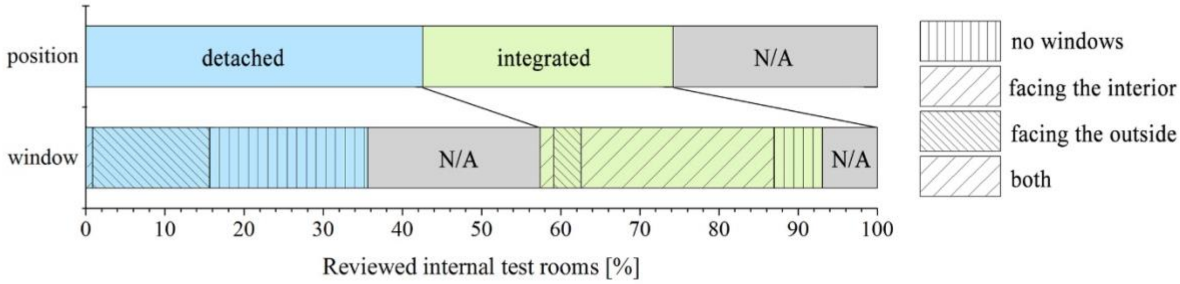


Figure 4. Overview of the most common combination of characteristics for inside test rooms, in terms of its position with respect to the main structure and the windows availability.

Half of the test rooms have no specific internal layout, meaning that there is no intention to simulate a real space but only to expose subjects to controlled environmental stimuli. Equipment for performing physical exercises are included in 10 % of these test rooms [49,50,59–64,51–58]. All the others have no specific furniture, even if 49 % are larger than 20 m^3. Finally, 12 % of the analysed test rooms are presented in different papers with different internal layouts, 32 % are equipped as offices, 3% as classrooms [65–69], and less than 1 % present other configurations[70–73].

The above presented physical characteristics of the reviewed test rooms can be associated with their capability of performing different types of experiments, focusing on different domains of human comfort. The external test rooms are more commonly devoted to visual-related experiments. Indeed, six out of the 14 exterior test rooms are associated with visual-only experiments, while only one was used for testing human comfort conditions due only to thermal boundaries. When more than one domain is explored, four test rooms hosted experiments providing combinations of thermal and visual stimuli; the air quality influence was additionally explored in one test room while all the four domains of comfort were explored in only two of the 14 external test rooms.

With respect to performed experiments, it is more complicated to deduce the most common combination of construction details for the test rooms located inside other facilities due to a lack of information on all the analysed features. Only 82 out of 155 reviewed test rooms are described in terms of both (i) their position in the hosting facility (detached or integrated) and (ii) windows availability facing the inside or the outside. Accounting for these two aspects, detached test rooms generally have no window (56 %) and are more commonly adopted for investigating human comfort under thermal stimuli only (46 %). Those test rooms that are integrated into the main structure, as specially equipped rooms, commonly have windows facing the outside (68 %) and are mainly used for experiments on visual domain only (54 %).

3.2 Technical details

Similar to the presentation of construction details, the technical capabilities of the test rooms directly inform what types of experiments can be conducted. Specifically, this subsection outlines which parameters are controllable and to what degree. As a first step, an analysis of the most common parameters that could be controlled by the test room systems was conducted. For this purpose, the relevant information was extracted from the corresponding papers for each test room and categorized as presented in Table 3.

Table 3. Categorization of technological systems and related controlled parameters.

Technological control system for comfort	**Controlled parameters**
Ventilation and space conditioning	Air temperature Air velocity Air humidity

	Air quality (gas concentration, air changes per hour)
Heating/cooling surfaces	Envelope superficial temperature Radiator or other element temperature (e.g., clothes, furniture)
Light sources	Illuminance Solar radiation (artificial, e.g., solar simulator) Solar radiation (natural, e.g., actively controlled blinds and shades, electrochromic glass)
Acoustic systems	Background noise level (sound intensity, sound pressure level) Sound typology (soundscape)

This categorization is more granular than the multi-physics domains introduced in Section 2 (thermal, visual, air quality and acoustic comfort) to better characterize the specific system types used to influence each domain parameter. Indeed, in some cases, multiple controlled parameters will impact a single domain such as air temperature, mean radiant temperature and incoming solar radiation, all impacting thermal comfort. Additionally, the controlled parameters were subdivided into centralized and personalized systems (generally located at a desktop or at a participant/manikin). In the process of this categorization, 91 test rooms were selected for further analysis because related publications provided relevant and sufficient information. Figure 5 summarises the number of test rooms which can control each of the listed parameters. In some cases, one test room is counted multiple times in this plot, once for each parameter its system controls.

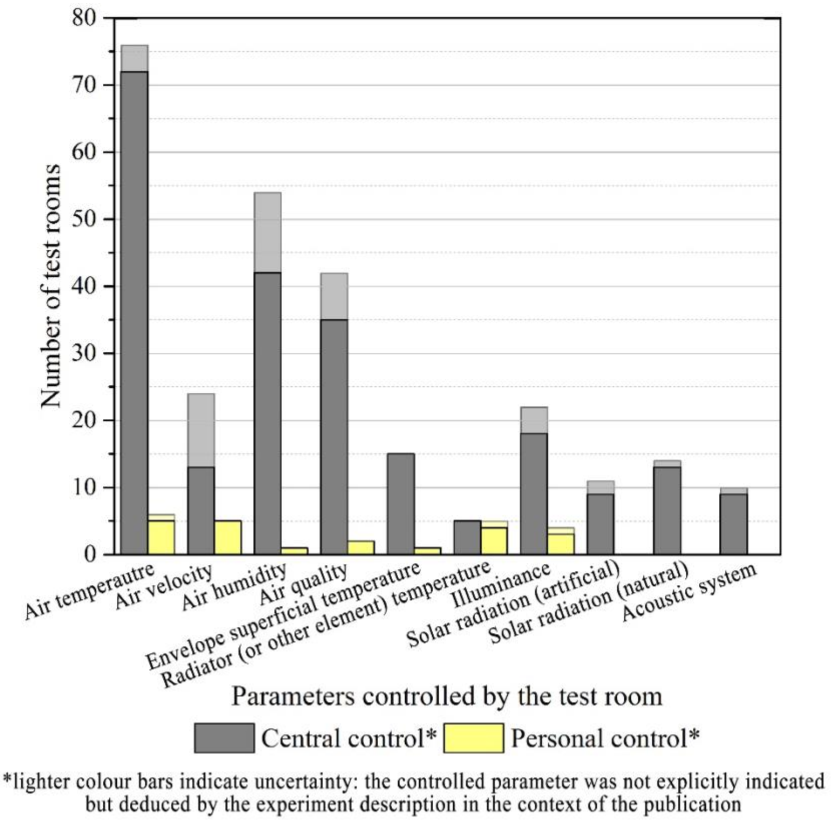


Figure 5. Frequency distribution of reviewed test rooms which can control the listed parameters.

The most common centrally controlled parameter is air temperature, followed by humidity and air quality control. All these three parameters can potentially be controlled by HVAC (Heating, Ventilation and Air Conditioning) systems with a humidifier and/or dehumidifier equipment, heating and/or cooling coils, and air filtering. The common practice of controlling thermal conditions in actual buildings, together with the predominant focus on thermal comfort studies (highlighted in Section 2), is likely why these controlled parameters are found to be so common. Figure 6 summarises the ranges for each of these three controlled parameters for all of the test rooms where ranges were reported. As shown, nearly all the test rooms can control air temperature between 15-30 °C, and relative humidity between 30-70 %, but air-speed control was more variable. Almost all test rooms were able to control these parameters at least in the ranges covered by indoor comfort standards such as ISO 7730 [74] and, in many cases, well beyond this range, particularly with respect to the seven low-temperature chambers.

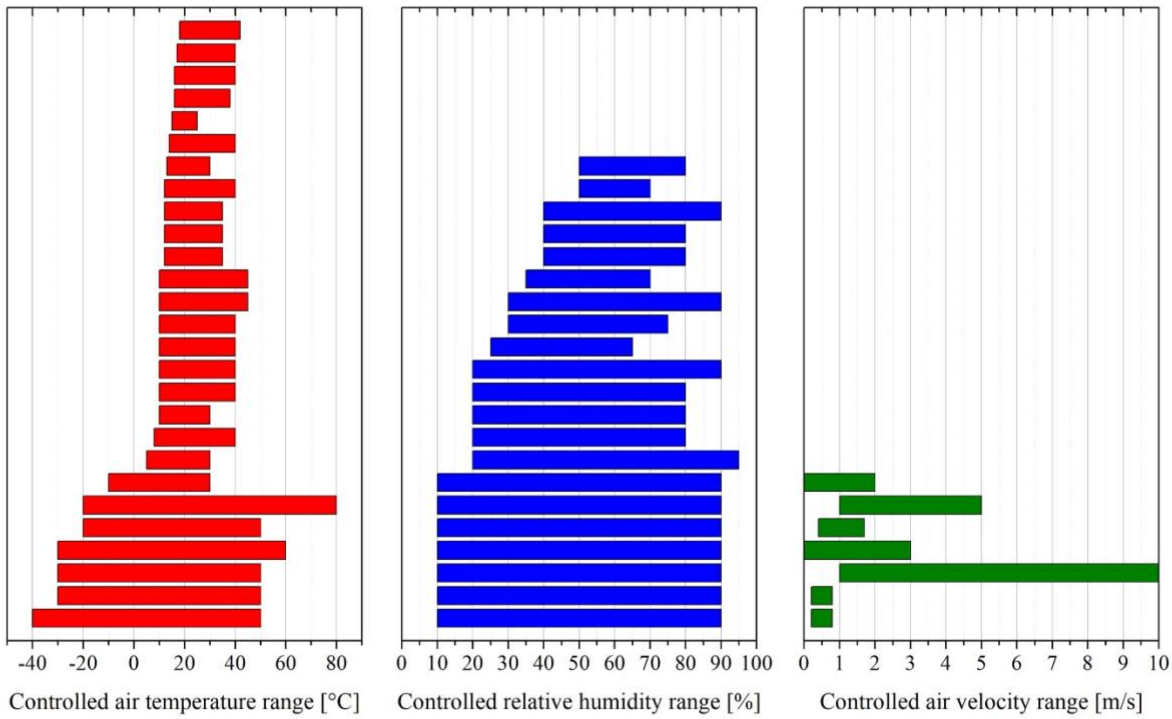


Figure 6. Ranges of controlled air temperature, relative humidity and air velocity in the reviewed test rooms.

Only a few papers included details of the other parameter ranges. Control of air change rates in the test rooms, which is accomplished through multi- or variable speed fans, ranged from 0-36 air changes per hour (ACH) but generally allowed for control within the minimums required by the EN 12931 (0.5-3.6 ACH for residential buildings) [75] and by EN 16798 part 3 for offices (1-8 ACH) [76]. Only five test rooms reported the temperature range at which their radiant wall systems (either electric or hydronic panels) could be controlled (generally between 10-40 °C). For rooms with reported artificial lighting, the range 100-800 lx covered and exceeded the requirements (e.g., EN 12464) [77]. A few publications also reported the ability to vary the correlated colour temperature of the artificial light (2,000 K to 10,000 K). There was insufficient information about artificial solar radiation and acoustic systems to report ranges here.

Only 11 of the reviewed test rooms included parameters that could be controlled at a personal level. Furthermore, most of these personalized systems were only temporary for specific experiments and not a fixed part of the test room. Typical setups would be ventilation tubes aimed at a desktop, heated/cooled clothing and chairs, electrical heated mats or computer equipment (mouse, keyboard), and electrical radiators.

The parameters controlled by the test rooms were also examined based on the estimated date of construction of the test room to identify trends or most prevalent innovative technologies, as shown in Figure 7. It is also unknown if or when test rooms have been upgraded, nor do we have insight about the upgrades made. Thus, the results in Figure 7 represent the latest built stage of the test rooms according to the publications and may differ from their technologies at the given date of construction. The graph suggests a trend towards incorporating the control of acoustic sources, artificial and natural solar radiation, illumination, and radiant heat sources, including radiators and radiant wall panels.

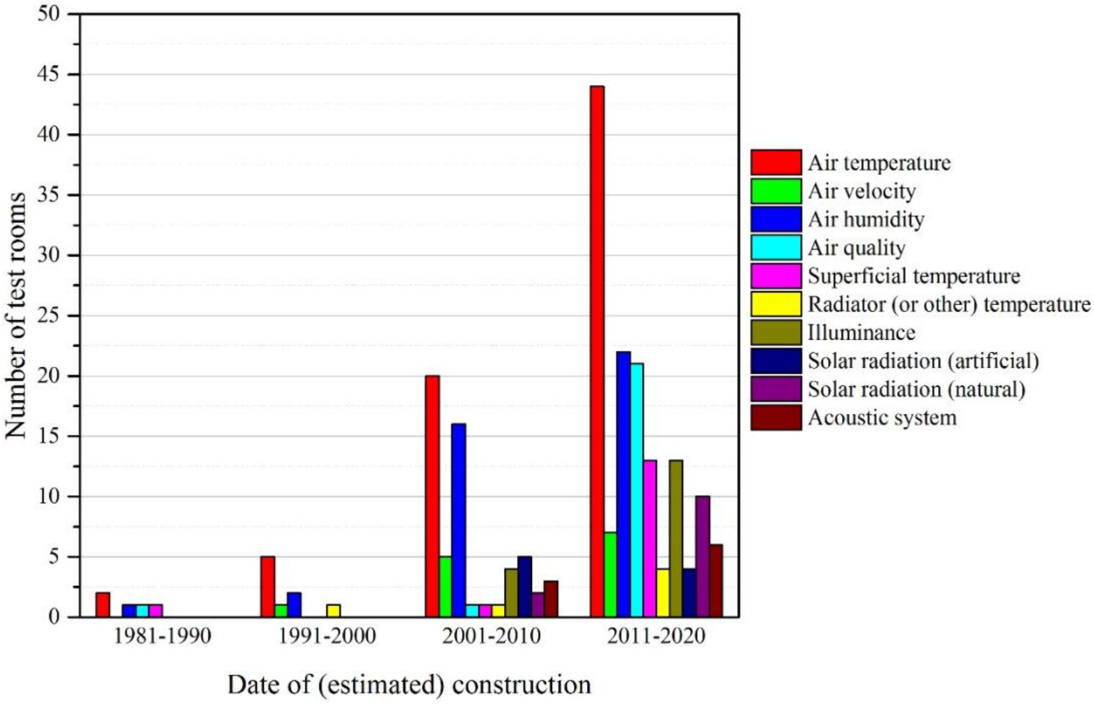


Figure 7. Time distribution of implemented technologies for controlling specific parameters (see the legend) identifying trends in test room construction.

Furthermore, the analysis revealed that personalized control systems are becoming popular in newer test rooms constructed after 2000. Finally, in the latest test rooms built between 2011-2020, there also seems to be a trend for controlled multi-domain installations with six test rooms since 2013, controlling at least three domains.

3.3 Economic investment

The economics of test rooms is rarely reported. Therefore, a survey to assess key elements related to this topic was designed. All co-authors of this manuscript and authors of identified literature were invited to complete it. In total, 18 responses related to separate test rooms were obtained, of which 14 have been completed, and four are still under construction. Except for one completed in 1990, all others have been built within the last ten years. The majority of the test rooms is either a test room constructed within an existing building (N =8) or a building itself (6). Three test rooms are newly built test rooms within a new building, and one test room is an existing room refurbished and upgraded to serve as a test room. The vast majority is located in Europe (13), followed by Asia (3) and North America (2).

Local currencies have been converted to EURO based on currency rates from September 4th 2020. The total budget ranges from EUR 45,500 to EUR 943,000 (mean = EUR 347,000±299,000, median = EUR 240,000). For eight test rooms, information was provided in more detail. On average, shell construction costs (especially for those test rooms built as stand-alone test rooms within new buildings) are highest (mean = EUR 175,000), followed by costs for design, contracting, and commission (EUR 91,000), heating and cooling system (EUR 31,000 and 34,000), and in-built sensors and the Building Management System (EUR 33,000 and 19,000). This large variety can be explained partly by the variety in the type of construction, controlled and monitored variables and the ranges within which these variables can be controlled. In addition, it can be expected that prices vary locally and between countries. Seven out of 18 test rooms were fully funded by governmental sources, either from basic funding (N=3) or project funding (4). In addition to public and project funding, five test rooms were partially funded by the industry (min 5 %, mean 24 %, max 70 %).

In addition to initial construction and installation costs, running costs (e.g., electricity, gas, water) and/or maintenance costs were assessed. Running costs were reported solely for three test rooms, but differed largely (EUR 2,500 to 17,500 per year). Interestingly, the source of funding for running costs was provided for 14 test rooms, of which nine responded that the university pays for running costs, three state project funding, and the other shared funding either between the university and the lab (10/90 %) or the university and project funding (20/80 %). The large discrepancy in response numbers between actual costs and funding source may signify that researchers are not aware of the running costs. Maintenance costs were provided for eight test rooms and range between EUR 930 to EUR 10,000 per year (EUR 5,100±3,500). Funding sources for maintenance costs vary more than running costs for 12 out of 14 facilities, for which such information was provided. In three cases each, maintenance is paid fully from the laboratories' basic funding or project funding. In two cases, the university covers all maintenance costs. In the other cases, maintenance costs were shared between the university, basic funding of laboratory and project funding with varying degrees. Only in one case, 25 % of maintenance costs are provided by industrial partners.

3.4 Commercial test rooms

Commercial test rooms are available on the market to provide researchers who want to use an already existing and tested product with an off-the-shelf option. These test rooms tend to use a similar structure and envelope materials as prefabricated foam-insulation panels with stainless steel, galvanized or coated aluminium (usually white) interior surfaces for fast and easy installation. This is for protecting the test room surface from being damaged or corroded by moisture and chemicals. The stainless-steel chamber can also help minimize the adsorption of VOCs by the surfaces, which is critical to some indoor air quality studies. However, for human-centred thermal studies, the reflective properties of the interior surfaces also determine the radiative heat exchange in the space, thus additional materials or painting are needed to simulate a 'real-life' condition. The test room usually has at least one hinged door made of the same material and optional windows of different sizes. Important differences between offerings tend to be in the type of airflow achieved in the test room. Cheaper and smaller systems tend to have the heat exchangers inside the room and achieve spatial stability by producing turbulent flows. More laminar flows are achieved with wall-to-wall or floor-to-ceiling air flows across the whole wall/floor, which requires a plenum space inside the test room, thereby increasing the external size. Most of the rooms come with predesigned and pre-packaged conditioning systems that can provide space heating and cooling, ventilation, humidification, and dehumidification to the room. Air temperature, relative humidity, and ventilation rate are under control and monitored. Some test rooms are even equipped with pressure, CO_2, and O_2 sensors.

The operating condition of commercial test rooms depends on their application that can be testing equipment, storing experimental materials, and also human-centric tests. Here, since we only focus on the test rooms for the human-centric test, the surveyed test rooms only include those capable of providing conditions indicated by the green box in Figure 8.

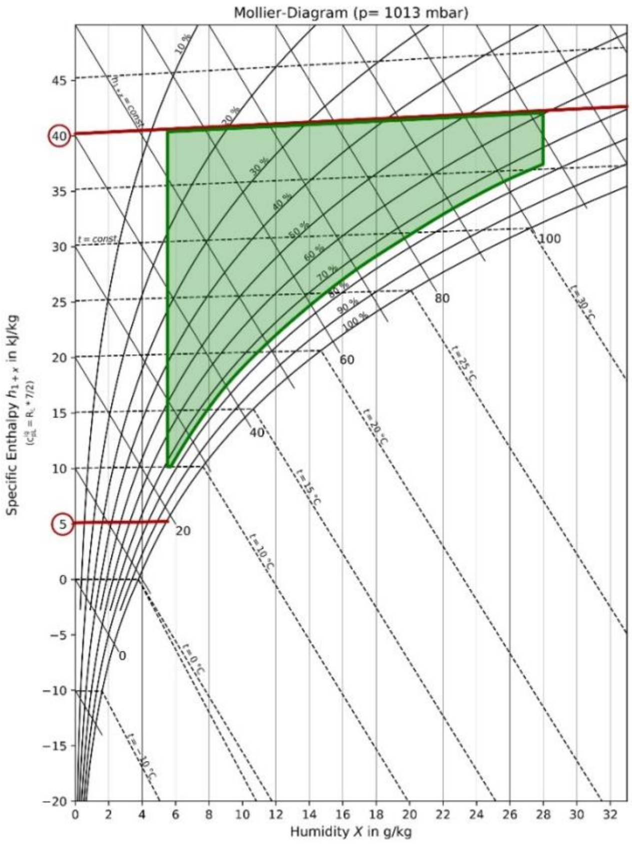


Figure 8. Required operating conditions of the surveyed commercial test rooms.

These commercial test rooms can be as small as 1.5 m^2 and as large as up to 10 m^2 with a height in between 2.4 and 2.6 m. The price of the test rooms (N = 13 units personally contacted by the authors) ranges from EUR 54,600 to 210,000. The average quote from U.S. companies is around EUR 128,100 with a standard deviation of EUR 44,000, while the average quotation from Europe is around EUR 99,800 with a standard deviation of EUR 27,400. On average, the test rooms from the U.S. (8) are a little more expensive than in Europe (5). The explanation may include regional reasons such as shipping and labour, material and sensors cost, and size difference. One should note that the size and quotes obtained in this study are based on the smallest test room with the basic features of temperature, relative humidity, and ventilation control with at least one occupant. The quotes were obtained in August 2020, and for the commercial test rooms made in the U.S., the quote was converted to EUR based on the exchange rate on September 4th, 2020 [1 USD = 0.84 EUR].

4. **Test room experiments on human-environmental comfort**

This section focuses on the experiments conducted in the test room above presented in terms of their structure and main functionalities. Each subsection presents an overview of the main aims and procedures of test room experiments answering the question, what is the scientific community looking for through test room experiments? Scopes of the experiments are broadly clustered in the presented subsections with respect to (i) the comfort domain of interest (sections 4.1-4.5), (ii) the subjects' involvement (possibility to interact with the test room during an experiment, section 4.6), and (iii) the investigation of the energy related aspects (section 4.7), which are all relevant aspects for human comfort studies. Concerning the applied procedures, the main distinction is adopted between stationary and dynamic conditions.

4.1 Thermal-only experiments

This subsection reviews 204 papers on test room studies that explored the effects of thermal conditions on participants. The scope of the reviewed thermal experiments can be broadly classified into three categories: (i) fundamental research aiming at providing a better understanding of human thermal comfort; (ii) technology-oriented experiments, whose purpose is to test the thermal comfort performances of specific types of heating and/or cooling systems or newly developed clothing; (iii) predictive studies with the purpose of data collection to test and train novel predictive models. Fundamental studies are more common than technology-oriented and predictive studies, respectively 57 %, 36 % and 7 %, and their distribution over the last four decades is shown in Figure 9a. Fundamental studies include research focusing on a variety of different aspects influencing human thermal comfort such as thermal adaptation [78–82], thermal acclimatization [83–86], increased air velocity [87–90], relative humidity [60,91–94], gender [95–98], age [52,99–102], transient thermal conditions [93,103–107], perceived control [108], and the influence of emotional states [109,110]. About 30 % of the thermal experiments are dedicated to the study of non-uniform thermal conditions. Non-uniformities and thermal asymmetries are not seen only as a cause of discomfort; indeed, many recent studies aim to understand how comfort can be enhanced with local thermal stimuli [111–120].

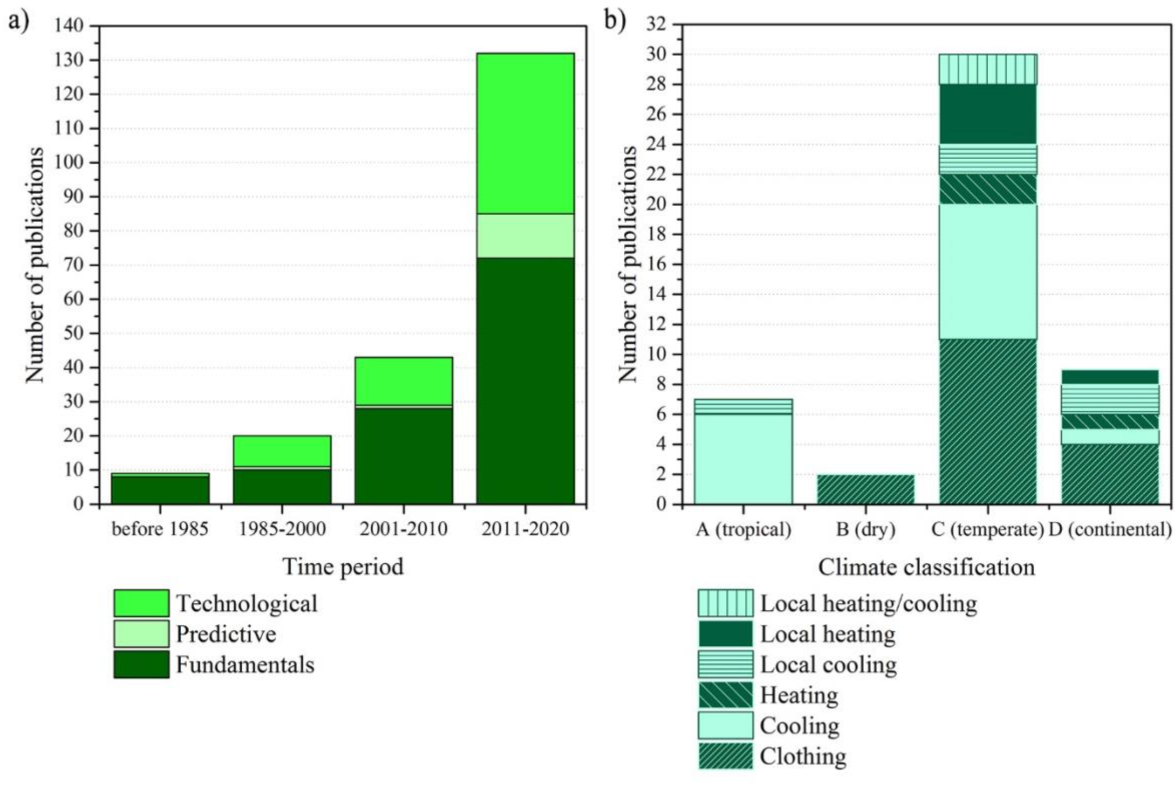


Figure 9. (a) Thermal studies aim distribution over time periods; (b) thermal technology-oriented studies, studied system over climate classification.

The technology-oriented experiments mainly look at the thermal comfort performances of specific types of equipment, such as innovative heating and/or cooling systems (thermo-electric air cooling systems [38,121], stratum, mixing and displacement ventilation [122–124], underfloor air distribution systems [122,125], radiant cooling/heating panels, floors and ceilings [126–129], ceiling fans [130], etc.). In particular, the last 20 years have seen a progressive increase in the number of experiments dedicated to local heating and/or cooling systems (personal cooling with phase change materials [112,113], heated/cooled chairs [114–116], seats heated with encapsulated carbonized fabric [120], feet heaters [117,118], etc.). About 40 % of the technology-oriented experiments aim to test new clothing (uniforms for heat strain or cold thermal stress attenuation in the construction industry [50,51,131,132], sports clothing [53,133–135], protective clothing systems [136,137], cooled/heated garments [138,139], etc.). The distribution of the technology-oriented experiments based on the type of system studied (heating or cooling, local heating and/or cooling, clothing) over the four different climate groups is shown in Figure 8b. As expected, in tropical climates there is a prevalence of experiments studying cooling systems, while in continental climates, the focus is on new clothing systems.

The predictive studies provide experimental data to either develop, test and train novel data-driven predictive models. Many of them aim to predict either thermal comfort or thermal stress (e.g., heat strain indexes [140,141]). Instead, others are attempting to build models for predicting metabolic rate and clothing insulation levels [64,142].

A majority (46 %) of the reviewed thermal experiments deal with both warm and cold thermal conditions, 39 % of them only focus on warm conditions and the remaining 15 % on cold conditions. They mainly consider sedentary activity levels (77 %), only a few of them focus on high metabolic rate activities (21 %) and a minority on sleeping (2 %). Furthermore, most of them consider stationary thermal environments, while the experiments dealing with dynamic conditions mainly study step-change transients [93,103–107]. In the last 20 years, female and male participants have been equally represented in the thermal experiments; nevertheless, elderly and children continue to be underrepresented groups (in only 3 % of the experiments). Concerning the sample size, a majority of the experiments (57 %) employ between 10 and 50 participants, 31 % of them recruit less than 10 participants, and only 12 % more than 50 participants. In most of the experiments (about 70 %), participants are passive recipients of thermal stimuli without any possibility of adaptation/control.

The ASHRAE 7-point thermal sensation scale is the most used metric of thermal perception, followed by thermal comfort, thermal acceptability, thermal preferences, and cognitive performances. Air temperature is the most frequently monitored environmental variable (in 90 % of the experiments), followed by relative humidity (75 %), air velocity (63 %), globe temperature (36 %), and wall surface temperatures (9 %). Air turbulence intensity, luminance, and solar irradiation (artificially provided) are more rarely monitored. Oxygen and carbon dioxide measurements are mainly used to estimate the metabolic rate, less often as a proxy of air quality. Skin temperature is the most common personal measurement (60 % of the experiments), followed by heart rate/heart rate variability (27 %), rectal/body core temperature (18 %), body weight for sweat rate determination (7 %), skin wetness (6 %), ear/oral temperature (5 %), skin surface blood flow (4 %), blood pressure (3 %), and skin heat flux (2 %). Some very recently emerging topics are the use of immersive virtual reality [143–145] and the monitoring of brain electrical activity patterns [109,146].

4.2 Acoustic-only experiments

This subsection looks at 11 test room studies exploring the effects of acoustic conditions on participants by investigating different human responses and developing or evaluating new metrics for soundscapes description (Figure 10). The test room experiments' aims include investigating maximum heavy-weight impact sound levels for perceived comfort [147], effects of sound pressure levels (SPL) and sound types on children's task performance [148], factors that contribute to sound complexity [149], effects of speech noise and speech transmission index (STI) in offices on cognitive performance [150,151], suitable masking sound frequency distribution for offices [152], effects of low-frequency noise in offices [153], effects of various noise sources on occupants in multi-family buildings [154], useful acoustic parameters that effectively describe to perceived sensations of urban sounds [155,156], and effects of introducing natural sounds to urban noise [157].

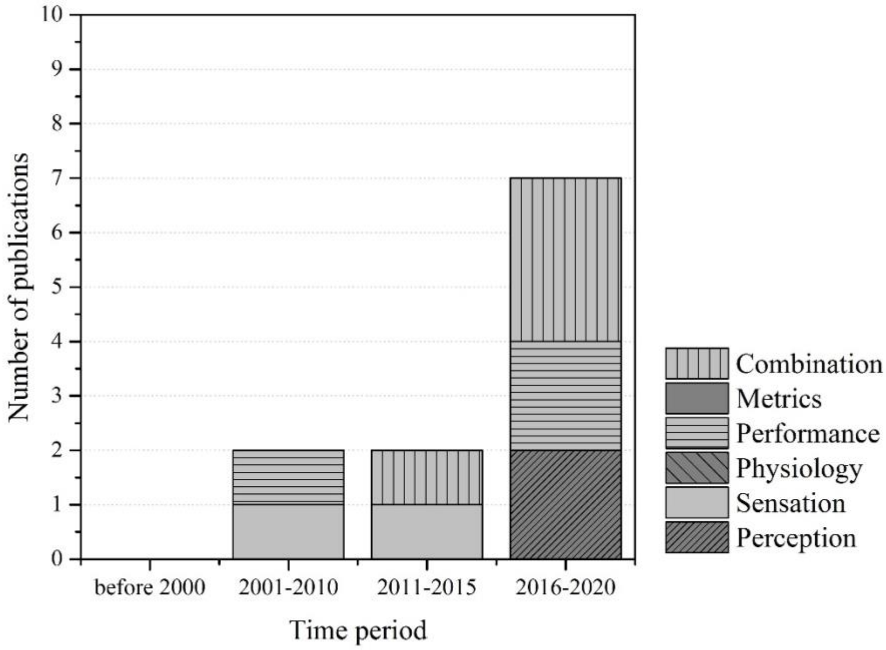


Figure 10. Distribution of acoustic studies' aim over time.

Many of the studies followed the general procedure of exposing participants to stimuli (recordings of sounds at various SPLs, frequencies, or decay rates) while performing cognitive tests and/or completed subjective assessments of the acoustic environments.

Test room setups and specific data collection procedures varied considerably among the studies. For instance, the provided stimuli length ranged from 10 seconds to 45 minutes, and the time that participants were given to respond to objective and subjective assessments ranged from 5 seconds to as long as the participants wanted to take. Most of the studies used loudspeakers to play the studied sounds, except Hermida and Pavón [156] and Hong et al. [157], who used headphones, and Jeon et al. [147], who used both loudspeakers and headphones. Only three studies [150–152] had test room setups that mimicked the type of real-world environment that they were investigating. Concerning the overall environmental control, three studies [150,152,153] mentioned that other indoor environmental conditions (such as temperature and lighting level) were kept constant in the test rooms. In contrast, others did not give any description of non-acoustic environmental conditions in the test rooms that could potentially affect the study outcomes.

For acoustic experiments involving human participants, it is common practice to screen participants' hearing abilities before conducting listening tests to avoid bias in the perception analysis. However, only four studies [147,149,153,157] screened their participants' hearing abilities using audiometers and other devices, and three studies [148,152,155] used subjective assessments to determine hearing abilities. Other studies either did not do similar screening or did not specify how they determined participants' hearing abilities. In addition, only three studies included evaluation of the effects of demographics, for example, age [147,148,150] and gender, and personal factors, such as personality traits [150], on participants' responses. Finally, just one study [153] monitored the physiological responses of participants (including the electrical activity of the brain, eye activity, heart rate, and heart rate variability) to low-frequency sound exposure using electroencephalography (EEG), electrocardiogram (ECG), electromyography (EMG), and electrooculography (EOG) signals.

Regarding sample size, six out of the 11 reviewed studies involved between 10 and 50 participants, with a minimum of 23 [152], while all the others involved more than 50 participants up to a maximum of 290 [148].

4.3 Visual – lighting-only experiments

The following overview focuses on visual-related experiments aiming at studying subjective evaluations of the visual environment performed in controlled environments. Studies conducted with the use of a scale model (e.g., [158–160]), with a small apparatus (e.g., [161–163]), in a booth (e.g., [164]) or in virtual reality (e.g., [165,166]) were excluded from the analysis as they were not performed in real-scale controlled environments. Investigations on electric lighting evaluations primarily aiming at testing lamp brightness and colour rendition based on lamp characteristics (e.g., [167–170]) were also not included. The resulting sample analysed consisted of 70 papers.

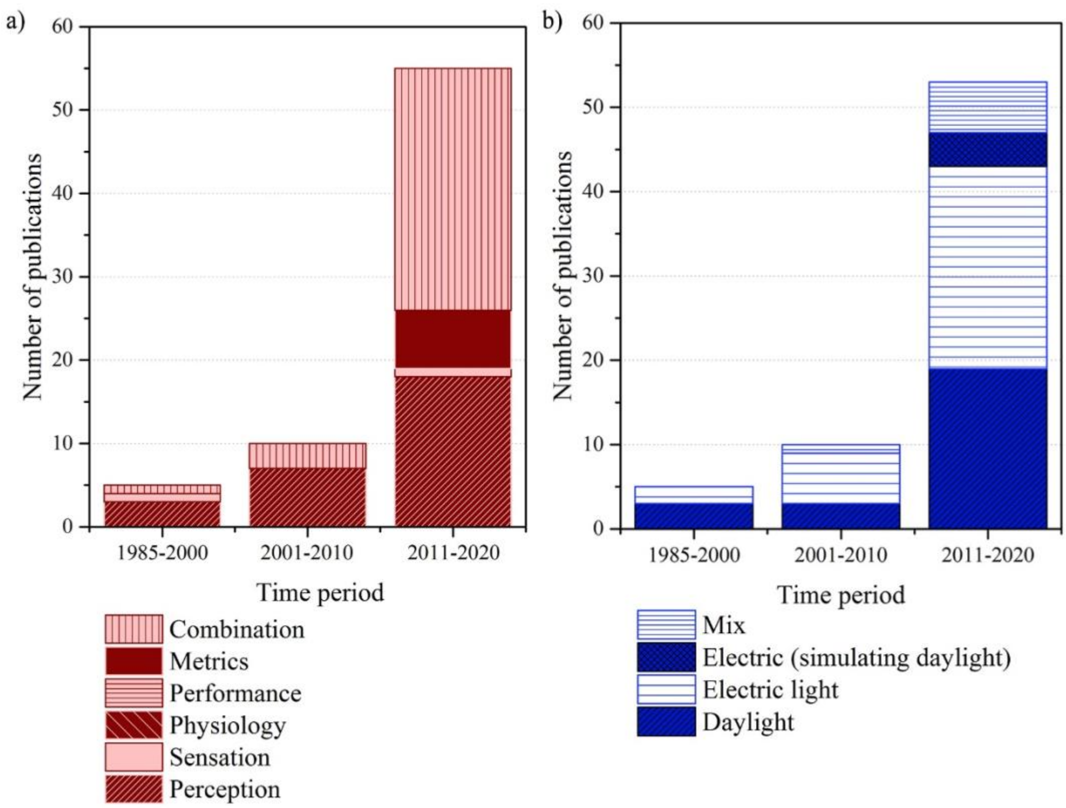


Figure 11. (a) Distribution of visual studies' aim over time; (b) investigated light source distribution over time periods.

As introduced in Section 2, visual-related studies in controlled experiments have increased over the last decade, with more than 77 % of the considered studies conducted between 2010 and 2020 (Figure 11Figure 11). The type of light source investigated has been relatively constant throughout the years, with an equal number of studies focusing on electric light and daylight (Figure 11b). The majority of studies focused on glare (more than 50 %), either to evaluate subjective perceptions due to variations of lighting conditions or other factors' influences (such as time of the day or openings and blinds features) [21,22,175–182,37,39,42,66,171–174], develop, evaluate or validate metrics, thresholds or indexes [35,68,191–193,183–190], investigate glare influence on performance and physiology [187], [194–196] or study a combination of such objectives (Figure 11a). Other studies investigated visual perceptions of the visual environment, surface finishing preference, physiological responses, performance, sleepiness, vitality, arousal, tension, mood, self-control and cognitive-biological processes (light-reactive hormones of melatonin and cortisol) mainly related to the light quantity and correlated color temperature (CCT), but also in relation to light uniformity, wall luminance, light source type, flicker rate, view and chromatic glazing [164,197,206–215,198,216,199–205]. The majority of the studies did not allow for personal control of the environment, testing pre-defined conditions, and were conducted with 10-50 participants. Only in a few studies participants were requested or simply allowed to vary their visual environment through the operation of blinds and electric lights, either to evaluate glare conditions or to assess how occupants perceived their visual environments associated with diverse luminous ambiences created by daylight in apartment buildings [73,189,191].

Most of the investigations were conducted in re-configured office spaces located in existing buildings, transformed into experimental test rooms in which it was possible to control or at least measure visual parameters. The traditional configuration was a side-lit single office, generally bigger than 20 m^3. Still, some investigations used a corner office [193], a mock-up of an open-plan office with multiple workplaces [209], a re-configured classroom [66], a full-scale mock-up conference room [208], or divided an existing office room with internal vertical partitions, resulting in smaller experimental spaces [217,218]. Some glare experiments used full-size apparatuses consisting of a semi hexagonal lighting chamber equipped with a chin rest [22,172,173,176] or of a semi-spherical screen with two halogen lamps mounted on a 1-m radius round boom [21,185]. Only fewer studies were conducted in a stand-alone test room, either located indoor [197,198,213,219,200–204,210–212] or outdoor [35,42,179,188,192,194,220,221]. Some of the outdoor facilities were rotating structures [35,179,192,195,220], allowing daylight conditions to be tested with a reduced impact of the daylight variations due to the season and time of the day. Very few test spaces were designed to have a side-by-side configuration with two identical spaces, one for participants and the other for measurements [35,171,183,187,189,190,194,220]. This particular setting, aiming at decreasing interventions in lab experiments, is particularly suitable for visual-related investigations as photometric data are relatively affected by the presence of people, contrary to the other indoor factors that have to be measured close to participants. The presence of a window to the outdoors was linked to the type of experiment investigated. Almost all experimental spaces provided with a window investigated daylight, except for those studies that performed the experiments at night [222] or in which windows were shaded with a black-out fabric or blocked [164,180,199,207,217]. The studies investigating a mix of daylight and electric light were provided with shading devices [189,190,205,220,223]. On the other hand, not all the studies on daylight were provided with a real window to the outdoor (intended as an opening with a view), but used artificial windows [37,177,181,192,204] or anidolic systems on the southern façade [224]. Non-visual factors were measured, controlled, or balanced across experimental conditions in almost all stand-alone test room experiments, and only in fewer re-configured offices [199,205,217,218,223,225]. The factors considered were primarily air temperature and humidity, but also noise [217,218] and air quality [37,197,198].

4.4 Air quality-only experiments

This subsection describes the controlled air quality-only experiments in test rooms summarised in 18 papers according to the reviewed database. Additional four papers that fall under two-domain experiments are included in the analysis since thermal and air quality aspects are hard to disentangle as the thermal analysis is ancillary to the air quality assessment [72,226–228]. Among the representative selections of 22 air quality studies in test rooms, researchers have focused on the three main topics: (i) understanding perceived air quality, productivity and health under a range of environmental parameters [71,72,229–235]; (ii) human inhalation exposure and spatio-temporal variation of air pollution in a space [20,228,236–241]; and (iii) airflow distribution in occupied spaces and ventilation effectiveness [226,227,242–244] (Figure 12). These topics were pursued through a combination of questionnaire surveys, environmental measurements (near a study participant, in bulk air or ventilation ducts), and physiological measures. Discrepancies in facilities among the selected studies include test room layouts (office space, classroom, aircraft cabin, hospital room), test room volumes (small below 10 m^3, medium 10-50 m^3, or larger than 50 m^3), surface materials (stainless steel, polytetrafluoroethylene, aluminium, glass or their combination), type of air pollutant generation (continuous or episodic), ventilation type (mechanical or mix-mode ventilation), ventilation strategy (mixing, displacement, underfloor or personalized ventilation), degree of air mixing (ventilation only or additional use of mechanical fans), operating procedure (dynamic or stationary conditions), and participant type (real occupancy or use of breathing thermal manikins).

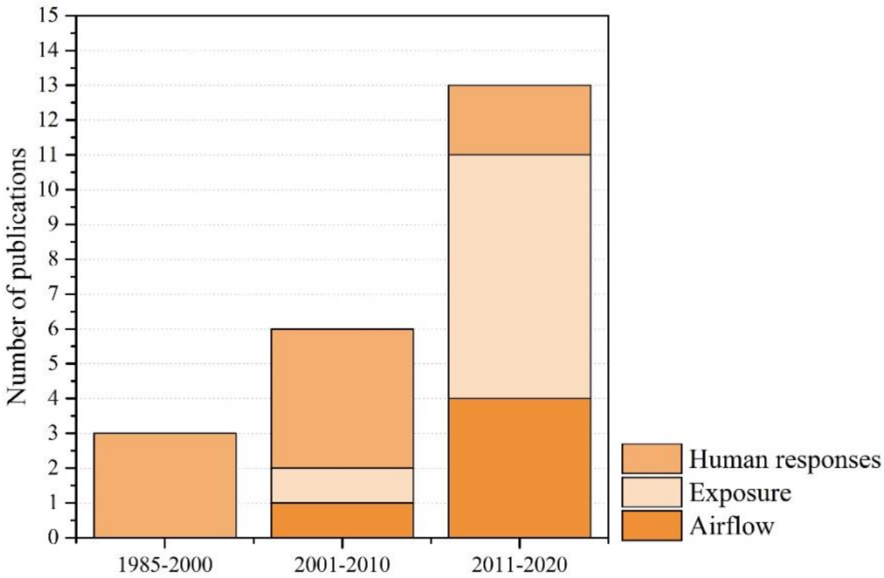


Figure 12. Distribution of air quality studies' main topic over time.

In the reviewed air quality papers, all test rooms were located inside of the building and had control over the ventilation rate, air temperature and relative humidity. While nearly all studies reported air temperature and relative humidity values and associated uncertainties, only 12 out of 22 studies reported air change rate values (mean = 3.89 h^{-1}), out of which only three described the method of estimation [237–239]. These studies used the tracer gas decay method by means of low adsorption tracer gases such as CO_2. The majority of the selected studies were performed in test rooms larger than 20 m^3 (mean floor area = 30 ± 27 m^2), which is important for mimicking various indoor layouts occupied with people and for studying air contaminant distribution in the space. Twelve studies focused on mimicking office environments, whereas other studies focused on aircraft (2), classroom (1), hospital (1) and other unspecified environments (6). Studies involving perceived air quality, Sick Building Syndrome (SBS) symptoms and productivity under variable levels of gas-phase pollutants [71,72,229–235] had a significantly higher number of study participants (76 ± 9.3) compared to studies focusing on human inhalation exposure and spatio-temporal variation of indoor air pollutants (8.2 ± 13.6) [20,228,236–241] and airflow distribution in occupied spaces and ventilation effectiveness (2.3 ± 2.1) [226,227,242–244]. The majority of studies focused on measurements of CO_2 (9), followed by VOCs (7), particulate matter (4), and other inorganic gasses such as NO_2, N_2O, O_3, and CO. Measurements of these air pollutants were performed with scientific instruments, which were not an integral part of the test rooms. None of those studies reported the adoption of the optimal inner coating of the test room surfaces, which is essential to determine how these coatings influence heterogeneous reactions with volatile organic compounds and other gaseous pollutants. Among the selected papers, only a fraction (2) reported issues that could arise due to pollutant uptake or emissions in the test rooms. Furthermore, in all studies, there was a lack of integration between advanced online and offline instrumentation and analytical techniques within the test rooms.

4.5 Multi-domain and whole comfort experiments

The goals of a multi-domain experiment can be categorized into (i) evaluate the effect of specific building technologies or control strategies on occupant multi-domain comfort [119,245–250]; (ii) understand cross-modal and interaction between different domains [46,72,259–268,251–258]; (iii) model the physiological [97,100,228,269,270] or behavioural [271–273] response of occupant to combined multi-domain stimuli and to understand the effect of IEQ on stress [274,275]; (iv) identifying new multi-domain metrics such as air enthalpy [251], air distribution index [276] and bio-signals such as skin temperature [277] for the whole comfort. In some cases, the energy consequences of such multi-domain interactions are also captured, as for the studies investigating novel personalized thermostats [272,278,279] or novel visual comfort systems [39,45] to improve energy efficiency and comfort. Among the studies focusing on the effect of specific building technologies or control strategies on occupant multi-domain comfort, the development of novel personal comfort systems in buildings [113,116,285,286,245,246,248,280–284] and vehicles [118] has received particular attention.

The interest in studying occupant response to multi-domain stimuli has increasingly grown since 2000, especially after 2010. Multi-domain experiments constitute 23 % of the overall 396 occupant comfort experiments in test rooms, as given by the review database. Most of these studies investigated the relationship between two physical domains, while studies focusing on three or more physical domains were just 4 % of the whole database. In terms of investigated combinations of domains, thermal and air quality represent the most studied one, followed by thermal with visual and thermal with acoustic (Figure 13).

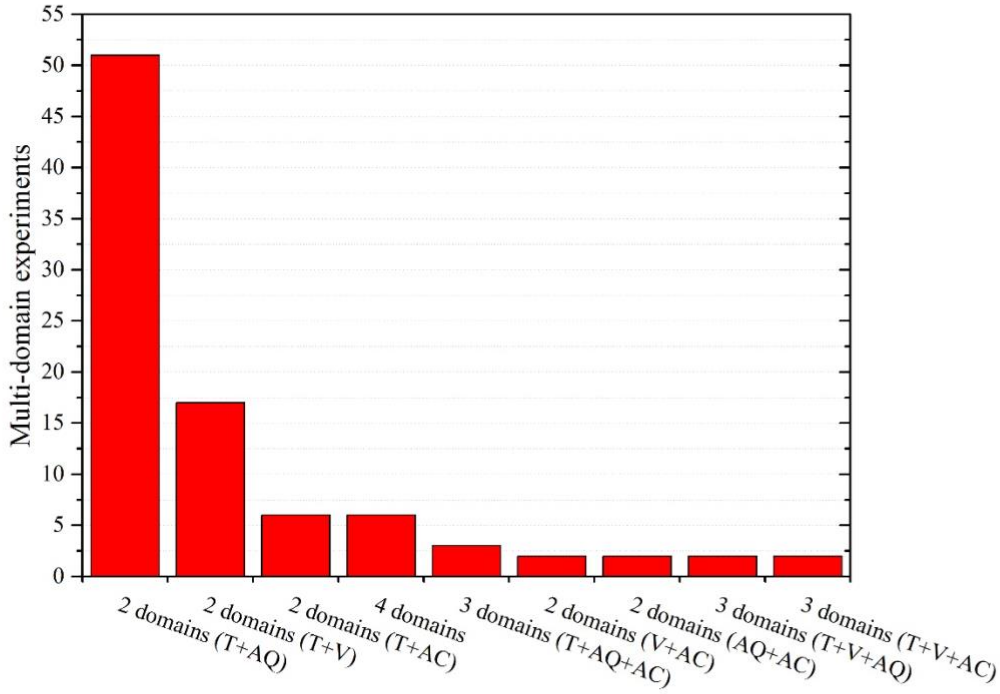


Figure 13. Multi-domain experiments by combination of each domain

The majority of the studies were conducted under stationary conditions, while only a third of the studies exposed occupants to changing environmental or dynamic conditions. Dynamic conditions were achieved either by step changes in indoor conditions [246,248,251,257,274,287–289] or, especially concerning thermal-related studies, by fast and long changes [79,265,275,290], meaning that a rate of change greater than 2 K per hour is provided for more than 1 hour of exposure. Only a few studies investigated multi-domain effects under high-speed conditions [91,250,291] or slow and long dynamical changes [263,271,292].

In addition to highly accurate monitoring of environmental parameters, most studies capture occupants' responses as a combination of subjective and physiological parameters. Nearly half of the studies (53 %) relied only on subjective occupants' responses. Table 4 shows the subjective metrics and physiological parameters monitored in the experiments. In terms of subjective measurements, based on survey or behavioural observations, environmental sensations are the most employed, followed by environmental preference and acceptability. In terms of physiological parameters, skin temperature and heart rate are the most monitored ones, also due to the thermal domain being investigated at least in 94 % of the overall multi-domain experiments. Lastly, the use of EEG, ECG, and EDA has just recently started to be adopted, mostly after 2015, to understand multi-physical occupants' responses in test rooms, especially when investigating interactions between different comfort domains.

Table 4 Different approaches for capturing occupants' responses in multi-domain experiments in test rooms

Occupant response		**References**
Subjective (survey based or from behavioural observations)	Environmental sensation	[44,46,90,91,99–101,118,120,122,124,125,47,126,245,250,253,256,257,264,267–269,60,273,275–277,290–295,67,296,297,78,79,85,86,89]
	Environmental comfort	[44,47,120,122,125,245,252,253,267–269,291,60,294,296–299,72,85,89,91,99,100,118]
	Environmental preference	[44,47,257,267,268,291,295,297,79,86,99,102,122,248,252,253]
	Acceptability	[47,85,294,295,297,86,91,122,124,248,249,253,275]
	Environmental satisfaction	[46,78,252]
	Emotion response	[46,264,289]
	Alertness	[50]
	Stress level	[274]
	Work performance	[90,268,273,275,289,294,295]
	Clothing level	[125,249,261,269,277]
Physiological parameters (sensing device based)	Skin temperature	[44,46,125,253,258,259,292,300,79,86,99–102,117,120]
	Skin moisture	[301]
	Core temperature	[86,102,258,259]
	Electrodermal activity (EDA)	[44,46]
	Electrocardiogram (ECG)	[47,100,294]
	Electrooculography (EOG)	[297]
	Electroencephalogram (EEG)	[47,274,289,294,297]
	Acceleration	[46,302]
	Heart rate	[44,46,266,289,292,303]
	Nasal dimension by acoustic rhinometry	[301]
	Photoplethysmography	[302]
	Metabolic rate	[277]
	Frequency of blinking	[303]
	Mucociliary transport	[303]
	Saliva and tear mucus film samples	[295]

4.6 Participants interacting with the environment

This section focuses on those experiments whose protocol allowed participants to freely interact with the test room components and systems. The interactions taken into account for this further classification include adjusting settings of the test room conditioning system, dimming/switching lights, opening/closing windows and shading systems, adjusting personal comfort devices. According to the reviewed scientific publications, this section is based on 21 papers (see Table 5). Nine of those 21 have been published in 2018-2020, and ten originate from European universities or institutes.

Two papers describe a test room facility developed and constructed to test all environmental factors (lighting, acoustics, air, and thermal quality) [43,304], including interactions with the environment through design and systems, making it possible to provide both input data to and output data from the occupants. Most of the publications were concerned with thermal quality in relation to thermal comfort, sensations and/or preferences [102,124,305–307], in combination with (personal) control [36,111,281–283,308,309], together with air quality [232] or visual quality [45,310]. The latter was studied in three reported studies [73,189,191], of which one was concerned with daylight, glare, shading and control [73]. Only one study included all the IEQ aspects [311].

The participants involved in the different studies mostly comprise of students and healthy young adults. Only one study was concerned with children (primary school children with an average age of 10 years) [311]. One study included a comparison between young (average23 years) and older males (average 67 years) [102], and one study looked at the impact of ethnicity [309]. In most publications, the responses or interactions of a participant with an object or variable/parameter in the environment are reported. The studied controlling devices varied from (local) heating or ventilation devices [283], light dimmers [310] or blind/solar shading control device [73], wearable conditioning devices [111], and furniture [281]. Table 5 summarises the 21 papers concerning those experiments where the building occupant is able to interact with the test room in the form of personal judgments or specific actuator-to-reaction.

Table 5. List of reviewed studies concerning human comfort experiments in test rooms where the participants could directly interact with the facility.

Year pub.	Investigated domain	Studied parameters/object	Interaction between the participant and the test room	Reference
1991	Thermal	Adjust ambient temperature	Adjustment of test room temperature	[307]
1995	Thermal	Two age groups	Adjustment of test room temperature	[102]
2000	Thermal	Adjusting air movement (supplied via ceiling)	Adjustment of the Personal Comfort System (PCS)	[308]
2007	Thermal	3 task air-conditioning systems	Adjustment of the Personal Comfort System (PCS)	[306]
2009	Thermal	Control of 2 fans at chair (under seat, behind backrest)	Adjustment of the Personal Comfort System (PCS)	[282]
2009	Visual	Dimming of light; airflow from ceiling-based nozzle	Adjustment of the Personal Comfort System (PCS)	[310]
2012	Thermal	4 fans at corners chair to enhance displacement vent	Adjustment of the Personal Comfort System (PCS)	[124]
2012	Thermal & Air quality	Air movement (air terminal device), air pollution, temperature and RH	Adjustment of the Personal Comfort System (PCS)	[232]
2012	Visual	Artificial lighting and blinds control, daylight	Adjustments of shading system	[73]
2014	Thermal	Ceiling fan	Adjustment of shading system, ceiling fan, operable windows	[36]

2014	Visual	Daylight	Adjustment of shading system	[189]
2015	Thermal	Heated/cooled chair	Adjustment of the Personal Comfort System (PCS)	[281]
2018	Thermal	Control of personalized heating system	Adjustment of the Personal Comfort System (PCS)	[283]
2018	Visual & Thermal & Air quality & Acoustics	Facades, controls, interior, etc.	Adjustment of shading system, façade properties, thermal settings	[43]
2018	Visual & Thermal & Air quality & Acoustics	Walls, lighting, sound, thermal, air, interior, etc.	Control of HVAC and lighting system	[304]
2019	Thermal & Visual	Windows, blinds and ceiling lights	Adjustment of desk light, ceiling light, solar shading, operable windows	[45]
2019	Visual & Thermal & Air quality & Acoustics	IEQ in their own classroom	IEQ problems in classrooms and solutions for those problems	[311]
2020	Visual	Daylight, glare, shading	Adjustment of shading system	[191]
2020	Thermal	Thermal sensation, thermal preference	Adjustment of the Personal Comfort System (PCS)	[305]
2020	Thermal	Wearable wrist devices for warming or cooling	Adjustment of the Personal Comfort System (PCS)	[111]
2020	Thermal	Self-selected air temperature, thermal sensation, comfort and preferences; skin temperature	Adjustment of the personal comfort system	[309]

4.7 Energy-related human comfort experiments

Out of 396 reviewed papers, 85 considered energy-related issues while carrying out thermal-, visual-, indoor air quality-, and acoustic-related experiments. Of these, 28 papers had a multi-domain focus with 22 papers considering both thermal and air quality-related experiments, five papers presenting thermal- and visual-related experiments [97,232,281,312–314], and only one paper discussing the effect of personal control on thermal, visual, and air quality perceived by building occupants [310]. Among the single comfort domain studies, thermal investigations are by far the most widely carried out (50), followed by visual investigation (5). Olfactory and aural comfort were studied together with energy considerations in just one article each [156,232].

The first document of the database was published in 1978. For the following 30 years, much slower growth was observed in the number of publications on energy-related human comfort experiments. After 2008, the scientific interest in this topic has progressively increased because of the increasing research interest in human-centric building design [315], personalized control strategies [316], and perceptual and behavioural environmental studies [32] (Figure 14).

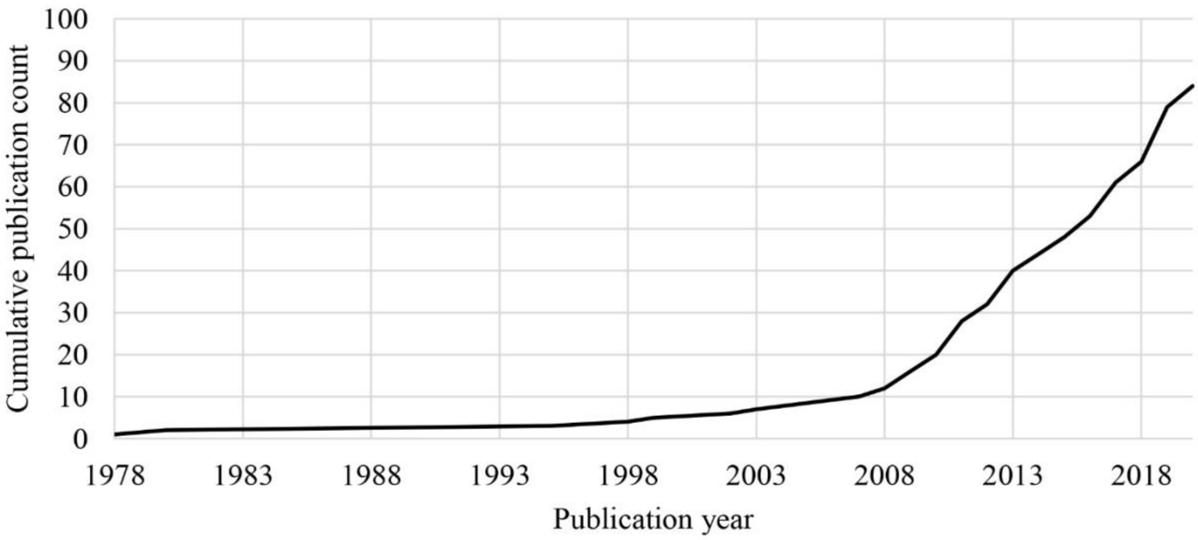


Figure 14. Cumulative number of publications describing energy-related issues in human comfort experiments in test rooms.

The majority of experiments have been conducted in test rooms located inside buildings with controlled environmental conditions, and only three experiments were run considering the actual outdoor weather [46,97,312]. Furthermore, 45 experimental procedures employed dynamic conditions and 32 studies used steady-state conditions. Dynamic studies are generally more recent (the average publication year is 2013), while steady-state conditions are more common in older studies (the average publication year is 2011); this can be explained by the recent availability of easier and user-friendly control interfaces and power modulation for electric motors and pumps.

Regarding the technical systems used during the experiments, only considering the documents where this information was expressed, most of the investigations used air-conditioning systems and only a few tested hypotheses under radiant systems (9 papers), controlled mechanical ventilation (8), artificial lighting (10), and sound equipment (1) [156]. Additionally, 38 papers reported experiments, which adopted personal environmental control systems, which are effective means of testing energy-saving control strategies and are well received by the occupants.

5. Summary of key findings

This review analysed a wide range of test rooms for the experimental investigation of human comfort indoors and provided an overview of scientific experiments that are conducted in such facilities and that were published in scientific papers. All reported information was deducted from reviewed papers. According to such an approach, it has to be mentioned that experimental facilities may exist which have not (yet) published any results in peer-reviewed journal articles. The reason may be because (i) it is too new to present results, or (ii) the facility is dedicated to industrial or other research not meant for public sharing of results. This limitation may affect some of our conclusions. Nevertheless, while accepting this limitation, we believe that the number of facilities not included in our review is small due to the two search strategies applied and that the knowledge generated in those facilities not publishing their work, for one reason or the other, is in any case not directly available for the scientific community and less suitable to enhance human comfort theories.

A general observation pertains to the growing number of such facilities. The total number of 187, specifically referred to in the present contribution, is about eight times higher than the number of comparable facilities before 2000. However, the geographic distribution of these facilities does not reflect the variance of climatic regions around the world: 82 % are located in moderate climatic regions. Notwithstanding, the increasing number of test rooms may reflect the growing realization of the influence of indoor environments on human health, comfort, and productivity. This trend is reflected in the increasing number of publications reporting research conducted in these facilities. In this review, a total number of 396 publications were considered.

Looking at the publications from a topical standpoint reveals the scientific community's primary interest in human thermal comfort (204 papers), followed by energy-related studies (85), visual comfort (70), air quality (18), and acoustic comfort (11). Roughly a quarter of the reviewed publications explored indoor-environmental exposure situations involving more than one domain. Only a small number of publications (21) investigated circumstances in which participants could assume an active role and had the opportunity to interact with relevant features of the indoor environment.

Our findings suggest that about 92% of the test rooms were built inside of a building. This is interesting: while the performance characterization of building components has mainly been tested in outdoor testing facilities [317], the investigation of indoor comfort has been conducted either in actual occupied buildings or in dedicated test rooms located indoors with better controlled experimental procedures. However, based on the reviewed publications alone, it is not possible to draw up a more detailed picture of the test rooms' design and construction. For instance, in 47% of the reviewed publications, it was not possible to ascertain whether the test room envelope entailed any type of openings. Lack of such details makes it difficult to independently replicate and subsequently validate the results coming from experiments in test rooms. Our review also addresses another critical point: there is a lack of information regarding investment, operation, and maintenance costs associated with the facilities. A dedicated survey designed and distributed on our side received responses only from 18 facility owners or operators, pointing to the need for further efforts in the transferability of know-how with the test rooms.

Certain observations apply to studies that focused exclusively on thermal comfort: studies on fundamental issues dominate in this area (57 %) versus technology-oriented (36 %) and predictive studies (7 %). An increasing number of experiments in the last 20 years focus on local heating/cooling systems. A large share of technology-oriented studies (40 %) focuses on developing new, insulating, and thermally active clothing. This may indicate a shift in the industry from the traditional room-air-conditioning design perspective to a more personalized thermal comfort approach. The majority of the reviewed studies were conducted in office-like environments with small samples (10-50 people) engaging in sedentary activities. Few papers focused on the elderly or children (3 %), and in 70 % of the studies, participants were passive recipients only. Some studies introduced new, recently emerging methods such as immersive virtual reality and monitoring of brain activity patterns.

Studies related to acoustic comfort mostly followed a general procedure where participants were exposed, on a short-term basis, to stimuli while performing cognitive tasks or completed subjective tests. Interestingly, only four studies (less than 40 %) screened the hearing abilities of the participants. This may have introduced bias in their results.

Studies on lighting and visual comfort significantly increased in the last decade, addressing both daylight and electric light: their bulk is concerned with glare problems in the workplace, primarily deal with glare perception and entail the development and evaluation of related metrics, thresholds or indexes. The investigations also pertain to various human responses related to light quantity and CCT. Most of these latter investigations focused on the non-image-forming effects of light. Only a few studies allowed participants to change the visual conditions by interacting with blinds and electric lights.

IAQ-related studies mostly addressed three topics, namely the perceived air quality's impact on productivity and health, the spatio-temporal variation of air pollution and inhalation exposure, and the airflow distribution and ventilation effectiveness. Some reviewed publications did not report the experimental conditions (e.g., ventilation rates) in detail. In contrast, none of the studies reported surface materials, which is essential concerning how they influence heterogeneous reactions with volatile organic compounds and other gaseous pollutants. The majority of the studies were conducted in sufficiently large test rooms, hence allowing for the consideration of realistic room layouts and air contaminant distribution patterns.

About investigations of multi-domain exposure situations, thermal and indoor air quality represent the most frequently studied combination, followed by thermal-visual and thermal-acoustic combinations. Only one-third of the studies exposed participants to dynamic environmental conditions. 53% of the studies relied solely on subjective responses. In the last few years, a new trend can be seen in the related scientific literature, whereby diagnostic methods from neurophysiology (such as EEG, ECG and EDA) have been applied to explore multi-domain exposure situations.

6. Research gaps and future trends in test room experiments for human comfort

Despite a growing interest in multi-domain studies, we still do not have an agreed-upon conceptual framework and a systematic methodology for a mature and holistic science of human-centric indoor environments. Common design guidelines and a shared terminology for innovative test rooms and experimental procedures would allow establishing a shared understanding of the driving phenomena and the inclusion of the non-physical (psychological and contextual factors) dimensions. This can be further supported by the deployment of low-invasive physiological sensing techniques. A better understanding of the visual, IAQ and acoustic factors and their mutual influence on human comfort and occupants' perception requires further investigation. Future trends in test room experiments (and thus facility design) must account for a multi-domain and multi-disciplinary approach.

On a geographical and demographic basis, despite the increased interest in human comfort and the large availability of test room setups, these facilities are limited to specific climatic regions, while concerning tested subjects' composition, these are mainly students and faculty members. These sociological and geographical weak points may cause a non-negligible bias in the interpretations of experimental results and knowledge generation. We see the need for dedicated studies in those climatic and demographic contexts where experimental data are still not available to increase diversity and cross-validation.

In terms of test room design: test rooms mostly emulate office spaces with a limited number of occupants. Therefore, another research gap to close is the analysis of other settings and contexts, such as realistic open-plan offices and different building typologies (educational, residential, hospitals, etc.). This factor may affect the quality of the collected data and limit the research findings to office-only investigations (difficult to replicate and extend).

Concerning experiments, increased attention is being paid to occupants, also driven by the recent trends toward human-centric building design and operation. This is also reflected in the fast growth of multi-domain studies in the last decade, where the focus is the whole comfort perception analysis. Additionally, even technology-oriented studies are focused on human applications. About

40 % of the technology-oriented studies aimed at developing and testing wearable systems for improved personal comfort, such as smart clothing and sensing techniques. This observation shows the necessity for a more systematic collaborative research framework whereby the environmental comfort is not handled exclusively by building physicists or engineers and architects. The topic requires a significant and proactive interaction with researchers in human factors, human-machine interaction, big data analytics, and social science, as we see more studies are focusing on psycho-physiological factors alongside IEQ and human-centric approaches.

From the operation perspective, the economic analysis showed the necessity for a better common understanding of the economic model behind test room design and construction. This may be helpful to foster local and global collaboration and connection to industry, taking advantage of the unique resources that each location provides. For this purpose, a higher transparency of existing business/economic models is recommended. Private-public partnerships may also be established with shared economic models allowing both researchers and industry partners to use these facilities to conduct controlled experimental studies, e.g., for technology development. Such models can also help sustain and expand the test rooms' role in underlining the importance of whole comfort experiments. Toward this end, funding agencies/industry partners should be informed and engaged in providing funding support to maintain/sustain and expand existing testbeds dedicated to a better understanding of human comfort in buildings.

In this context, standardization in the design and experimental validation procedures is still missing, with the consequent limitations in error and uncertainty analysis, quality control and replicability potential. Therefore, the creation of a unified framework for keeping track of the functionality of the test room facilities is expected to establish a common ground for collaboration and cross-validation and would help to identify cultural and geographical differences and biases.

This cannot be done without a joint effort in terms of open-source research in and for society, where the resources of test room facilities and collected data are freely available for fostering the impact of these multi-domain and multi-disciplinary investigations. In this scenario, future efforts by the authors and their institutions would support research via a systematic data sharing process and a publicly available and continuously updated test room portfolio. Finally, a first Round-Robin test in test room facilities worldwide is expected to emerge as a follow up to this review.

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