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A review of human thermal comfort in the built environment

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ABSTRACT

The aim of this paper is to review the literature on human thermal comfort in the built environment. First an overview about the subject area is presented. This is followed by a review of papers published in the last 10 years that examine the various sub-areas of research related to human thermal comfort. Some remarkable works about both the Fanger's and adaptive thermal comfort models are also discussed. This review does not contain simulation works and/or experimental studies without subjective results of people. As a result of the literature review, 466 articles were classified and grouped to form the body of this article. The article examines standards, indoor experiments in controlled environments (climate chamber) and semi-controlled environments, indoor field studies in educational, office, residential and other building types, productivity, human physiological models, outdoor and semi-outdoor field studies. Several research topics are also addressed involving naturally ventilated, air-conditioned and mixed-mode buildings, personalized conditioning systems and the influence of personal (age, weight, gender, thermal history) and environmental (controls, layout, air movement, humidity, among others) variables on thermal comfort.

Contents

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1. Introduction

Urbanized areas worldwide have increased and according to the United Nations [1] it is expected that more than 70% of the world population will be located in urban centers by 2050. According to the world development indicators, 85% of the population will be located in developing countries in 2030 [2]. This growth is leading to an increase in the urban density of buildings, especially in the city center, thereby influencing the characteristics of indoor environments that increasingly rely on artificial systems to operate satisfactorily. The increased amount of time people spend inside buildings is significant. As architects and engineers think of ways to improve the user's environmental comfort while improving the performance of buildings, it is imperative they consider that people spend between 80% and 90% of their days indoors [3].

In developed countries, the building sector (residential, commercial and public) uses between 20% and 40% of final energy consumption [4]. Worldwide, buildings consume about 70% of final energy consumption through air-conditioning systems and artificial lighting [5]. The high energy consumption of air-conditioning is largely due to the uniform control of indoor temperature regardless of the building's location, yet as demonstrated in the literature, it is not really necessary to ensure thermal comfort [6]. Great energy savings could be achieved by allowing air-conditioning systems a wider range of indoor temperature fluctuation [6].

Specifically, thermal comfort and energy efficiency were the focus of multiple studies [7–16]. In recent years, the field of research in thermal comfort has attracted the attention of many researchers around the world, perhaps partially due to the increased public discussion about climate change. Overall thermal comfort and the assessment of indoor environmental quality do not depend solely on physical parameters. The human body's physiological and psychological responses to the environment are dynamic and integrate various physical phenomena that interact with the space (light, noise, vibration, temperature, humidity, etc.) [17]. The specialization of existing standards to study and improve each of these environments (thermal, lighting and acoustics, etc.) is an example of the difficulty in the whole evaluation of environments. In the area of thermal comfort, the international standards commonly used to evaluate the thermal environments are ISO 7730-2005 [18], ASHRAE 55-2013 [19] and EN 15251-2007 [20].

Despite the difficulty of conducting a whole evaluation of environments (thermal, visual and acoustic), there are several studies that deal with the topic. The literature review performed by Frontczak and Wargocki [21] presents an analysis of the main conditions of the indoor environment, characteristics of users, design of buildings and outdoor climatic conditions that have a greater impact on the comfort and satisfaction of the indoor environment. The nine studies investigated by the authors included work carried out in various cities and with adults both in controlled environments and in the field [21]. In seven of the studies, users rated the thermal comfort as the most important condition for improving satisfaction with the indoor environment [21]. The authors of the studies [21] highlighted the importance of providing users with controls over indoor conditions to improve thermal comfort. It is important to note that there are differences in thermal acceptability for users of naturally ventilated buildings compared to users of buildings with air-conditioning [21]. In the former, users are more tolerant of indoor thermal conditions [21].

Thermal comfort is defined by ASHRAE 55 [19] as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation". Thus, the vast majority of works in the area are carried out while people are awake, performing some activity and able to answer a questionnaire. However, there is also research dealing with thermal comfort during sleep [22–24] and brief reviews about thermal comfort for sleeping environments are found in the literature [25,23]. Other studies have shown the relationship between indoor climate and the quality of sleep [26–32], stating that the optimal thermal conditions for a good night's sleep are different from ASHRAE 55 [26,27]. For example, research indicates that in the summer indoor temperatures during sleep could be higher than those prescribed by ASHRAE 55. This is significant because it would result in a decrease of energy consumption [27].

In this work, we aim to conduct a review of thermal comfort in the built environment. In order to know the breadth of this research area, we searched for the term "thermal comfort" in four electronic databases: Google Scholar, Web of Science, Scopus and ScienceDirect.

2. Results of literature search

The results of the literature search carried out on 11/25/2014 with the term "thermal comfort" in Google Scholar, Web of Science, Scopus and ScienceDirect are presented in Table 1. Table 1 also shows the search mode, the chosen sort type and the meaning of classification for the four search engines.

Table 1
Results for general literature search on thermal comfort in different databases.

Parameter/database	Google Scholar	Web of Science	Scopus	Science Direct
Number of results	59,800	5979	8302	2285
Search in	All (not optional)	Title, abstract and keywords	Title, abstract and keywords	Title, abstract and keywords
Sort type	Relevance (not optional)	Number of citations	Number of citations	Relevance
Meaning of classification	Considers publisher, authors, number of citations, recent citations	Highest number of citations	Highest number of citations	Highest occurrence of search term

Table 2
Top 10 documents (out of 59,800) of thermal comfort in Google Scholar.

Google Scholar					
Top 10	Article title	Authors	Year	Published in	No. of citations
1	Thermal comfort. Analysis and applications in environmental engineering	P.O. Fanger	1970	Danish Technical Press	4690
2	Comfort and thermal sensations and associated physiological responses at various ambient temperatures	A.P. Gagge, J.A.J. Stolwijk, J.D. Hardy	1967	Environmental research	474
3	Developing an adaptive model of thermal comfort and preference	R. de Dear, G.S. Brager	1998	ASHRAE Transactions	828
4	Adaptive thermal comfort and sustainable thermal standards for buildings	J.F. Nicol, M.A. Humphreys	2002	Energy and Buildings	541
5	Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55	R de Dear, G.S. Brager	2002	Energy and Buildings	493
6	Thermal comfort of man in different urban environments	H. Mayer, P. Höppe	1987	Theoretical and Applied Climatology	309
7	Thermal comfort for free-running buildings	N. Baker, M. Standeven	1996	Energy and Buildings	160
8	Different aspects of assessing indoor and outdoor thermal comfort	P. Höppe	2002	Energy and Buildings	233
9	Thermal comfort in outdoor urban spaces: understanding the human parameter	M. Nikolopoulou, N. Baker, K. Steemers	2001	Solar Energy	245
10	Thermal comfort and psychological adaptation as a guide for designing urban spaces	M. Nikolopoulou, K. Steemers	2003	Energy and Buildings	236

Among the four databases used, ScienceDirect is the only one that does not provide the option to sort the search results by articles with greater impact; it is possible only to sort by year or relevance. When sorted by relevance in ScienceDirect, articles are ranked in order of occurrence of the search term in each article, i.e., the first article listed is the one in which the search term appears most frequently in the document. Google Scholar sorts articles by means of an algorithm considering factors such as number of citations, authors and publisher. Meanwhile Web of Science and Scopus sort the results by number of citations. Thus, Tables 2–4 show the top 10 documents in Google Scholar, Web of Science and Scopus databases, disregarding work on phase-change materials, heat stress and cold stress.

Due to the possibility of classification by number of citations and the amount of resulting articles, we chose Scopus to continue with this review. The recent interest in the field of thermal comfort follows an exponential trend (Fig. 1), with a considerable increase in publications in the last 10 years. As a result we honed our focus to articles on thermal comfort published in the last 10 years. We refined our search to only articles published in journals and written

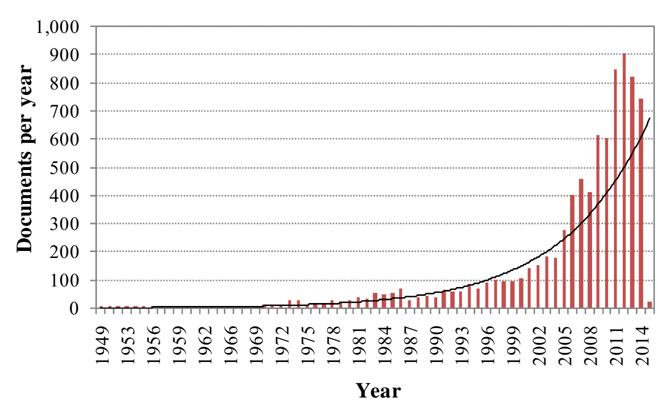

Fig. 1. Number of articles published per year—Scopus.

Table 3
Top 10 documents (out of 5979) of thermal comfort in Web of Science.

Web of Science					
Top 10	Article title	Authors	Year	Published in	No. of citations
1	The physiological equivalent temperature—a universal index for the biometeorological assessment of the thermal environment	P. Höppe	1999	International Journal of Biometeorology	269
2	Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55	R de Dear, G.S. Brager	2002	Energy and Buildings	220
3	Adaptive thermal comfort and sustainable thermal standards for buildings	J.F. Nicol, M.A. Humphreys	2002	Energy and Buildings	218
4	Thermal adaptation in the built environment: a literature review	G.S. Brager, R de Dear	1998	Energy and Buildings	215
5	Thermal comfort of man in different urban environments	H. Mayer, P. Höppe	1987	Theoretical and Applied Climatology	158
6	A model of human physiology and comfort for assessing complex thermal environments	C. Huizenga, Z. Hui, E. Arens	2001	Building and Environment	129
7	A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia	J. Spagnolo, R de Dear	2003	Building and Environment	128
8	Extension of the PMV model to non-air-conditioned buildings in warm climates	P.O. Fanger, J. Toftum	2002	Energy and Buildings	118
9	Relative contribution of core and cutaneous temperatures to thermal comfort and autonomic responses in humans	S.M. Frank, S.N. Raja, C.F. Bulcao, D.S. Goldstein	1999	Journal of Applied Physiology	118
10	Thermal comfort in outdoor urban spaces: understanding the human parameter	M. Nikolopoulou, N. Baker, K. Steemers	2001	Solar Energy	97

in English; other types of publications[1] such as conference papers, books, theses, etc. were excluded from the search. A general search in Scopus produced 8302 articles, while just 3235 papers remained after refining the search to only include those written in English and published in journals from 2005 to 2015. Tables 5 and 6 present the international journals while Table 7 presents the authors with the highest number of works from the general and refined searches.

The 3235 articles resulting from the refined search were cataloged in CSV (comma-separated values) and the Mendeley[2] program to facilitate their reading and classification. Mendeley was also used to carry out the citations in this document and generate the list of references. The authors of this review read the titles, abstracts and keywords of the 3235 articles. A second refinement was then performed to exclude simulation works and/or experimental studies without subjective results. Duplicate articles and other works that did not deal with human beings or thermal comfort were also disregarded. Thus, from the 3235 articles, 2769 were excluded. The remaining 466 articles, including 39 review papers, are the basis for the definition of topics (items) that compose the remainder of this review article. Thirty-three other important works in the area of thermal comfort that were not classified in these refinements were also included in this review because of their historical importance: classic works about Fanger's [33,34] and adaptive [35–41] models of thermal comfort, physiological models [42–50], a review about semi-outdoor thermal comfort [51] and a number of papers dealing with specific subjects were included [52,53]. Additional works are included in the introduction [1–6,17], as are works related to standards [18–20,54] and a recent review on personal comfort systems [55].

3. Standards for thermal comfort

In general, thermal comfort is classified in relation to the type of environment: outdoor, semi-outdoor or indoor. In terms of indoor thermal comfort, the current discussion centers mainly on two distinct approaches. The first approach is the classic steady-state model developed by Fanger in the 1970s [33] for air-conditioned spaces, which is based on a heat balance model of the human body. Fanger's model [33] aims to predict the mean thermal sensation of a group of people and their respective percentage of dissatisfaction with the thermal environment, expressed through the indices Predicted Mean Vote-Predicted Percentage Dissatisfied (PMV–PPD). PMV is calculated through six variables: metabolism, clothing, indoor air temperature, indoor mean radiant temperature, indoor air velocity and indoor air humidity. PMV method was the basis of the ISO 7730 [18] and ASHRAE 55 [19] standards and

[1] Nevertheless, it is noteworthy that a significant number of other types of publications dealing with thermal comfort are available in the literature, as the Chartered Institution of Building Services Engineers (CIBSE—UK) guides and technical memoranda, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE—US) guidelines, handbooks and reports and the Center for the Built Environment (CBE—University of California—US), publications and reports.

[2] Mendeley is a reference management software, that allows the user to import research papers and bibliographic information from Scopus to its online server (user's account). The citations can be integrated with word processors and then a reference list can be produced automatically during the writing process. For this paper the free version of the program was used.

Table 4
Top 10 documents (out of 8302) of thermal comfort in Scopus.

Scopus					
Top 10	Article title	Authors	Year	Published in	No. of citations
1	Developing an adaptive model of thermal comfort and preference	R de Dear, G.S. Brager	1998	ASHRAE Transactions	341
2	The physiological equivalent temperature—a universal index for the biometeorological assessment of the thermal environment	P. Höppe	1999	International Journal of Biometeorology	323
3	Adaptive thermal comfort and sustainable thermal standards for buildings	J.F. Nicol, M.A. Humphreys	2002	Energy and Buildings	322
4	Thermal adaptation in the built environment: a literature review	G.S. Brager, R de Dear	1998	Energy and Buildings	317
5	Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55	R de Dear, G.S. Brager	2002	Energy and Buildings	301
6	Comfort and thermal sensations and associated physiological responses at various ambient temperatures	A.P. Gagge, J.A.J. Stolwijk, J.D. Hardy	1967	Environmental research	235
7	The assessment of sultriness. Part I. A temperature-humidity index based on human physiology and clothing science	R.G. Steadman	1979	Journal of Applied Meteorology	228
8	Thermal comfort of man in different urban environments	H. Mayer, P. Höppe	1987	Theoretical and Applied Climatology	176
9	A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia	J. Spagnolo, R de Dear	2003	Building and Environment	173
10	A model of human physiology and comfort for assessing complex thermal environments	C. Huizenga, Z. Hu, E. Arens	2001	Building and Environment	150

Table 5
International journals with the highest number of papers in Scopus. General search. Number of articles: 8302.

Scopus (in parenthesis the number of articles per source)				
Top 10	Source	Source IF[1]	Source SNIP[2]	Source SJR[3]
1	Energy and Buildings (582)	2.465	2.381	1.978
2	Building and Environment (560)	2.700	2.544	1.634
3	ASHRAE Transactions (269)	–	0.436	0.436
4	SAE Technical Papers (150)	–	0.638	0.347
5	Advanced Materials Research (118)	–	0.198	0.144
6	International Journal of Biometereology (109)	2.104	1.308	0.762
7	Applied Mechanics and Material (102)	–	0.196	0.134
8	Renewable Energy (88)	3.361	2.681	2.256
9	Applied Energy (83)	5.261	3.262	3.385
10	HVAC and R Research (75)	0.745	0.862	0.621

[1] Impact Factor 2013.
[2] Source Normalized Impact per Paper 2013.
[3] SCImago Journal Rank 2013.

still is used in practice. More recently the model was extended to non-air-conditioned buildings in warm climates [34].

The second approach typically used to determine thermal comfort is the adaptive model[3], which is based on the adaptive principle [41] "If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort.", i.e., user's are active and not passive (as in PMV method) relating to their thermal environment. The adaptive model is based on field studies in naturally ventilated buildings by Nicol and Humphreys [35,39,56,57], Auliciems [36], de Dear, Brager and Cooper [37] and de Dear and Brager [38]. From the field studies, linear regressions relating indoor operative temperatures (acceptable ranges) to prevailing outdoor air temperatures were established, i.e., comfort temperatures varies according to outdoor climate, higher outdoor temperatures allowed for higher indoor temperatures. This was a paradigm shift compared to Fanger's theory. The adaptive model

[3] In 2012 a book entitled "Adaptive thermal comfort: principles and practice" was published by Nicol, Humphreys and Roaf aiming to be an introductory book on adaptive thermal comfort [41]. More information about the theory behind adaptive thermal comfort may be found in this book [41].

Table 6
International journals with the highest number of papers in Scopus. Refined search (first refinement). Number of articles: 3235.

Scopus (in parenthesis the number of articles per source)				
Top 10	Source	Source IF[1]	Source SNIP[2]	Source SJR[3]
1	Building and Environment (444)	2.700	2.544	1.634
2	Energy and Buildings (423)	2.465	2.381	1.978
3	International Journal of Biometereology (77)	2.104	1.308	0.762
4	HVAC and R Research (70)	0.745	0.862	0.621
5	Applied Energy (65)	5.261	3.262	3.385
6	International Journal of Ventilation (64)	0.303	0.212	0.225
7	Indoor and Built Environment (63)	1.716	1.099	0.715
8	Applied Thermal Engineering (57)	2.624	2.440	1.598
9	Renewable Energy (53)	3.361	2.681	2.256
10	SAE Technical Papers (50)	–	0.638	0.347

[1] Impact Factor 2013.
[2] Source Normalized Impact per Paper 2013.
[3] SCImago Journal Rank 2013.

was first included in the ASHRAE standard 55[4] [19] in 2004 as an optional method for evaluating naturally ventilated buildings. In 2007 the adaptive model was also included in EN 15251[5] [20]. The adaptive model was included in the Dutch ATG guideline [58] and in the proposal of the Brazilian standard of thermal comfort [54,59]. The adaptive model is based on three inter-related aspects (which are not fully taken into consideration in the PMV–PPD method, mainly in climate chamber studies): psychological (comfort expectation and habituation in relation to indoor and outdoor climate), behavioral (including opening windows—which was the most common, and the use of blinds, fans and doors) and physiological (acclimatization) [37]. The concept of alliesthesia proposed by Cabanac [52] and revisited by de Dear [60,61] was used to defend the physiological and the behavioral aspects of the adaptive method (thermal pleasure). The term “alliesthesia” was defined by Cabanac [52] to describe that “a given external stimulus can be perceived either as pleasant or unpleasant depending upon signals coming from inside the body”. People naturally attempt to avoid unpleasant stimuli and search for pleasant ones [52]. De Dear [60] differentiates thermal pleasure from thermal neutrality using as example the PMV method: a PMV = 0 is supposed to provide thermal neutrality, but not necessarily thermal pleasure (people may like or dislike it). For example, Humphreys and Hancock [62] analyzed the results of field studies in university lecture halls and in dwellings and found that by asking people how they would like to feel, 57% of the time the answer was different from “neutral”, varying according to the thermal sensation experienced at that moment. However, the concept of alliesthesia is not yet established in any standard or regulation and therefore more studies are needed in order to consider this concept when thinking about thermal comfort in the built environment.

Recently the Chinese Evaluation Standard for the indoor thermal environment was proposed [63]. It is based on Fanger’s and adaptive theories as well as field and laboratory studies from different climate zones in China. The proposal included different evaluation methods for heated/cooled environments (PMV model with different assessment criteria than ISO 7730) and free-running buildings (an adaptive graphic method or an adaptive predicted mean vote may be used) [63].

[4] The model of adaptive thermal comfort used in ASHRAE 55 was derived from the ASHRAE RP-884 database [37]. Such database contains around 21,000 actual votes from field studies in 160 office buildings from 9 countries located on four continents.

[5] The adaptive thermal comfort model used in EN 15251 was developed from the European project Smart Controls and Thermal Comfort (SCATs) [40]. The SCATs database is composed by approximately 5000 subjective thermal responses from field studies in 26 office buildings located in 5 countries in Europe.

Table 7
Authors with the highest number of articles in Scopus. General and refined search (first refinement).

Scopus (in parenthesis the number of articles per author)		
Top 10 Authors	General search (8302 papers)	Refined search (3235 papers)
1	Olesen, B.W. (52)	Matzarakis, A. (46)
2	Matzarakis, A. (48)	Orosa, J.A. (25)
3	Zhu, Y. (47)	Santamouris, M. (24)
4	Arens, E. (42)	Lin, Z. (24)
5	De Dear, R. (38)	Ghali, K. (23)
6	Khalil, E.E. (35)	Ghaddar, N. (22)
7	Santamouris, M. (34)	Lian, Z. (21)
8	Tanabe, S.I. (33)	Lin, T.P. (21)
9	Li, B. (33)	Chow, T.T. (21)
10	Fanger, P.O. (32)	Hwang, R.L. (20)

Review papers discussing the main thermal comfort approaches were also found [25,64–69], including an analysis of existing standards (ISO 7730, EN 15251). A review of several indices (among them, some from ISO 7730 and EN 15251) for the long-term evaluation of thermal comfort conditions in a building was conducted by [70]. A briefly overview of the adaptive approach was conducted by Nicol and Humphreys [71] and a discussion about actual comfort in buildings and expectations was carried out by Moezzi [72]. A critique of European Standard EN 15251 was performed by Nicol and Wilson [73] and a discussion about this standard is found at [74]. Another critique of EN 15251 and ASHRAE 55 relating to the effects of the mean radiant temperature on thermal comfort was conducted by [75]. The measurement/estimation methodologies of the mean radiant temperature was reviewed in [75,76].

ISO 7730 [18] classifies the environments in three classes: I (PMV ± 0.2), II (PMV ± 0.5) and III (PMV ± 0.7), as a function of variability of indoor conditions. Class I is supposed to offer users a higher percentage of thermal comfort, while consuming more energy. However, in practice, greater control over the variability of indoor conditions (class I environments) does not guarantee greater user acceptability when comparing spaces with greater thermal variation (classes II and III) [77]. Moreover, through a sensitivity analysis, the classification into the three classes of the environments was considered as random, because the widths of the ranges of each class of ISO 7730 are similar to the uncertainties of measurements of the variables for the PMV [78]. Thus, ISO 7730 needs to be updated, taking into account wider ranges of indoor temperature, to help reduce the higher consumption of air-conditioning systems and adapting to the needs of a world in an environmental crisis. Data from field work in offices in Japan during the summer, with campaigns for energy savings, using an air-conditioning set point temperature of 28 °C, show that users accept high temperatures and make use of adaptive opportunities to improve their thermal environment [79,80]. However, these results may be limited to the case of the Japanese population which was experiencing a supply crisis following a tsunami [79].

Further argument for allowing broader ranges of indoor temperature comes from the health perspective [81] because variable temperatures may have positive health effects [81]. Mild (seasonal) cold exposure may cause a reduction in weight, which could be helpful in combatting obesity [82,83]. The impact of the homogenization of the built environment goes beyond, as stated by Healy [84]:

> [T]he widely varied and, often deeply cultural and symbolic, thermal sensibilities of various cultures have become, and are increasingly becoming, subsumed by an innovative and inventive trajectory facilitated by science—thermal monotony. This is not simply a matter of the achievement of 'optimal thermal comfort' but also, particularly via the effect of standards on the form and content of the built environment, a matter of a reduced diversity in thermally influenced practices and behaviours, much of which are highly cultural in character (p. 321).

Broader ranges of indoor temperatures were proposed by Zhang et al. [85] for HVAC (mixed-mode) buildings based on the ASHRAE database. Between 19.5 and 25.5 °C buildings may operate in free-running mode. Above 25.5 °C up to 28.0 °C and even 30.0 °C, the use of ceiling fans and personally controlled fans may guarantee thermal acceptability [85]. In higher temperatures cooling is needed [85]. Below 19.5 °C the use of personal control heaters can be used [85]. These recommendations will not compromise thermal comfort, but will help save energy in buildings [85]. Recently, Zhang et al. [55] reviewed personal comfort systems and proposed an even wider range of indoor temperatures when using personal comfort systems.

4. Experiments in controlled environments

Studies in controlled environments have been performed around the world, including classic experiments in climate chambers where researchers have full control over environmental and human variables [86–89]. There is a tendency to emulate/simulate real environments in such climate chambers through the inclusion of windows looking to the outside and furnishing the space in a more harmonious way with the activity being studied, for example [90,91]. Another trend observed was an increase in studies in semi-controlled environments [92–94] usually carried out in adapted rooms in real buildings, where researchers set (control) some but not all variables, for example, allowing participants to freely choose their clothes during the experiment.

4.1. Experiments in climate chambers

4.1.1. The influence of control, thermal history and individual preferences

In a study performed in a climate chamber in China, the possibility of control over the thermal conditions improved occupants' thermal sensation and thermal comfort [95]. Thermal history was the focus of a work by Chun et al. [96] conducted in climate chambers in Seoul (Korea) and Yokohama (Japan) over the same indoor thermal conditions. Those exposed to higher temperatures prior to their time in the climate chamber responded with cooler thermal sensations than people who were first exposed to cooler temperatures [96]. Another study in climate chambers was conducted with young men in Beijing—where heating is commonly used in winter – and in Shanghai – where heating is not commonly used in winter. The subjects were exposed to the same variations in temperature (12 °C to 20 °C, cold indoor environment) [97]. The research shows that subjects accustomed to higher indoor temperatures (Beijing) feel colder thermal sensations than subjects accustomed to lower indoor temperatures (Shanghai) [97]. Yu et al. [98] used a climatic chamber to study whether the length of time in air-conditioned or naturally ventilated environments influences peoples physiological acclimatization. Results show greater physiological adaptability of people in naturally ventilated environments, especially under warmer conditions [98].

The individually thermoneutral zone is influenced by many factors (clothing, age and gender, among others) and varied between conditions and between individual subjects [99]. Interindividual differences in thermal comfort in young Japanese woman were identified by Yasuoka et al. [100]. Subjects were divided into two groups based on their preferred ambient temperature (H group preferred warmer sensations than M group) and they were subjected to temperature variations (33 °C to 25 °C) in a climate chamber. H group felt colder than M group (no differences in mean skin temperature were observed). In the Netherlands, another study in a climate chamber emphasized the importance of categorizing people based on their thermal preferences (narrow range preference, broad range preference, cool preference and warm preference), thus improving the predictions of thermal sensation [101].

4.1.2. The influence of weight, gender and age

A comparison of 27 lean and obese prepubertal girls (who were physically active) during and after exercise under heat and thermo neutral conditions was performed in South Brazil [102]. No differences in thermal sensation were found between the two groups in both thermal conditions [102].

Studies were also carried out, in a climate chamber, to examine the difference gender played in the thermal comfort of Chinese [103,104] and Dutch [105] participants. Women are more sensitive to temperature (mainly cool) [103,104] and less sensitive to humidity than men [103] and feel more uncomfortable and dissatisfied compared to males [105]. Women have a lower skin temperature than men [103,105]. Men prefer a slightly cooler environment and women prefer slightly warmer condition [103,104], despite presenting similar neutral temperatures and no difference in thermal sensation near neutral conditions [103]. In another study in a climate chamber, the effect of variation of temperature with height in skin temperature and thermal discomfort was more significant in women than in men [106]. Still another study showed that in women the overall thermal comfort sensation is significantly affected by the temperature of the skin and extremities, a fact that should be considered in non-uniform environments [86]. Furthermore, Schellen et al. [86,87] state that the operative temperature is insufficient for the evaluation of thermal comfort in non-uniform thermal environments.

The results obtained by Fanger when validating his model with elderly people indicate that there is no difference in perceptions of comfort with age, although the metabolic activity and the basal metabolism are lower in this type of users [107]. In steady and transient temperature conditions, Schellen et al. [108] found that older people (67–73 years) had more distal vasoconstriction than young adults (20–25 years) [108]. The thermal sensation results also indicate that elderly people prefer a higher temperature than young adults [108].

4.1.3. Steady/dynamic and uniform/non-uniform environments

Thermal comfort studies in steady and uniform environments and non-uniform and dynamic environments were carried out in climatic chambers in USA [88,89] and in China [109,110], where a personalized conditioning system was used to change the thermal conditions. Fanger's model only proved to be applicable to steady and uniform environment [109]. In another study in China in non-uniform and dynamic environments, the effect of temperature on thermal comfort and energy consumption by using local ventilation was assessed [111]. Also in China, but in steady and non-uniform environments, other studies were conducted to assess the effect of local thermal sensation on whole-body thermal sensation [112] and to investigate the temperature ranges for thermal comfort [113]. In transient and uniform environments, studies were performed in China, to investigate the human thermal perception and skin temperature due to step-change temperatures [114] and to research the effects of step changes of temperature and humidity on human responses [115]. They were also conducted in Taiwan [116] to analyze the effects of temperature steps (instantaneous change of air temperature) on thermal sensation, in Kuwait [117], to investigate the step change in environment temperature using a chilled ceiling displacement ventilation system aided with a personalized evaporative cooler on thermal comfort and in Austria [118], to assess the thermal comfort under spatial transition between a cold or warm controlled environment to a mechanically ventilated – unconditioned – during spring and winter. Another study aimed to create a new index to assess the ventilation performance in uniform and non-uniform thermal environments (assessing the indoor thermal comfort) [119].

4.1.4. Personalized conditioning systems

Personalized conditioning is another area of research that has emerged. Such a conditioning system aims to create a microclimate around a person, optimizing energy consumption and improving thermal comfort [120]. According to Veselý and Zeiler [120] in their review paper about personalized conditioning and its impact on thermal comfort and energy performance, the majority of scientific papers in the area were performed in climate chambers with studies involving the increase of the air velocity for cooling of the body [120]. In those situations thermal comfort was reached with indoor temperatures of up to 30 °C and relative humidity of 70% [120]. In heating mode, the use of personalized conditioning strategies can promote comfort at temperatures of 15 °C [120]. Thus, an annual energy savings of approximately 40% may be achieved considering the range of comfort temperatures (15–30 °C) and using personalized conditioning [120].

Different task conditioning systems were studied in a climate chamber involving users in Japan [121]. Other studies in climatic chambers, involving an individually/personally controlled system were performed in Denmark (with mechanisms for facial ventilation and heating [122] and ventilation, heating and cooling [123], radiant and convective cooling [124] and another system using a ductless personalized ventilation in conjunction with displacement ventilation [125]), in Hong Kong (chair-based personalized ventilation – PV – system) [126], in Lebanon (low-mixing ceiling-mounted personalized ventilator system) [127], in Hungary (a novel PV system with air flow coming alternatively from three different directions) [128,129], in the United States (heated/cooled chair [130], ceiling fans [131] and floor fans [132]), in South Korea (floor-standing room air-conditioner) [133], in China (electric fans were placed in front of subjects, directed at their faces) [134] and in Japan (chair equipped with fans) [135]. Results of the personalized conditioning systems with regard to thermal comfort were equal or better than conventional cooling systems [121–125,127–131]. The use of floor fans [132] and the chair equipped with fans [135] were able to maintain acceptable thermal comfort conditions with air temperatures up to 30 °C; the use of electric fans (China) could provide a comfortable environment at 28 °C to 32 °C [134]. Another type of chair with fans was studied in a chamber operating with displacement ventilation; users were satisfied with the cooling provided by the fans with air temperature of 26 °C [136]. The performance of a seat headrest-incorporated personalized ventilation system was studied showing acceptable air movement and cooling capacity [137].

4.1.5. Other studies

In a study in China, three different altitudes were simulated in a decompression chamber, to verify the impact on thermal sensation [138]. The research shows that with the increase in altitude, thermal sensation decreases (people feel cooler) and people are more sensitive to draught and expect lower air movement [138].

Regarding clothing, a study investigated the influence of cooling vests with phase change materials on thermal comfort [139] and another study determined the relationship between environmental temperature and actual daily clothing insulation during a year with Korean subjects [140].

In Taiwan [141] and in Hong Kong [142], in climate chambers, studies in different thermal conditions were performed comparing the actual sensation vote (ASV) and actual percentage of dissatisfaction (APD) with the PMV–PPD method. In Taiwan, the lowest value of APD (16%) was found for ASV equal to −0.4, contradicting the value predicted by Fanger, who said that the lowest percentage of dissatisfied (PPD = 5%) would be met with a PMV = 0 [141]. In the study in Hong Kong, the ASV also did not match the PMV when considering the different air velocities studied (air temperatures up to 28.2 °C with air velocity of 0.8 m/s were considered comfortable by users) [142].

Researchers also attempted to determine the thermal neutral temperature of different air distribution systems (mixing ventilation, displacement ventilation and stratum ventilation) [143], to evaluate a rule of thumb to assess the risk of downdraught during design phase [144] and to evaluate the effect of using fans with simulated natural wind [145] and with different airflow fluctuation frequencies [146,147] in thermal comfort.

In a climate chamber in Hungary, a study on the combined effects of two local discomfort parameters (radiant temperature asymmetry—a cold wall and a floor warmed through floor heating) was conducted with subjects in thermal neutral conditions [148,149]. In the testing conditions, the subjects felt comfortable and reported no discomfort by warm feet, which may have been due to the presence of the cold wall [148]. Another study compared the thermal comfort of South Korean subjects by using a forced-convection cooling system with a system combining radiant-floor and convective cooling [150].

Studies of thermal comfort involving subjects in climate chambers have been performed to evaluate the influence of local skin wettedness and overall thermal comfort [151], to study the regional (body parts) differences in temperature sensation and thermal comfort [152,153], to study the effects of skin temperature on the finger, hand and wrist in the assessment of overall comfort [154], to investigate the response of physiological parameters (skin temperature, electrocardiograph and electroencephalogram) to different ambient temperatures and its relationship with the sensation of thermal comfort [155], to study the relationship between floor surface temperature and the overall and local thermal sensation (feet) [156], to assess the effects of solar radiation (direct and indirect) on the thermal comfort [157], to analyze the influence of mean skin temperatures [158–163] and heart rate [164] to predict thermal comfort, to analyze the sensitivity range of the static thermal comfort equation [165], to investigate the effects of climatic characteristics and adaptability of people on the thermal comfort [166] and to investigate the impact of temperature differences between radiant and air temperature on mean skin temperature, thermal sensation and thermal comfort [167].

4.2. Experiments in semi-controlled environments

4.2.1. The influence of control and layout

In Germany, experiments in a semi-controlled environment simulating an office with different thermal environments and with diverse adaptive opportunities were performed in order to better understand the processes leading to adaptive comfort (physiological, behavioral and psychological) [90,91]. The experiment shows that the use of controls (fans, sun shading devices and windows) over the thermal environment is important to make people feel more comfortable [91].

In the Netherlands in an office building, researchers controlled indoor temperatures and the presence or absence of plants (quasi-experiment) [168]. Users felt more thermally comfortable when plants were present in the room [168].

4.2.2. Personalized conditioning systems

Studies in semi-controlled environments, simulating an office and operating with a displacement ventilation (DV) system [169,170], with under-floor air distribution + personalized ventilation (UFAD + PV) [171,172], with an individually controlled PV system [173] and with a ceiling-mounted PV system [174], were conducted with users in Singapore. Regarding studies with DV, the overall thermal sensation was mainly affected by local thermal sensations of the arm, calf, foot, back and hand [169]. When people felt a cold sensation or slightly warm sensation, they preferred that all parts of the body were more heated or more cooled, respectively [169] and in these two conditions, the temperature gradient did not affect the overall comfort sensation [170]. In the study with UFAD + PV, the use of the two strategies together led to improved thermal sensation of people with respect to the conventional air-conditioning system [171,172]. In Denmark, a study in a simulated office room equipped with different personalized ventilation systems shows that such systems have improved the perception of air quality and users evaluated the thermal environment as acceptable [175]. In Thailand a study was conducted to evaluate the influence of local air movement (small fans) in a semi-controlled environment operating with air-conditioning [176]. The thermal environment was considered acceptable by users with air temperatures of up to 28 °C, using small fans with air velocities between 0.5 and 2.0 m/s [176].

4.2.3. Other studies

In China, in a laboratory environment (furnished by the researchers) that was naturally ventilated and with no control over the environmental and personal variables, a study involving university student volunteers was conducted to assess their thermal comfort responses due to environmental changes that varied over the four-year experiment [177].

In India, a study was carried out with young male university students in a semi-controlled environment demonstrating that the PMV model overestimated the actual sensation vote (ASV) of people (subjects are less sensitive – more tolerant – to hot but more sensitive to cold) [178,179]. In South Korea, young adults participated in a study in a semi-controlled environment; PMV presented good correlation with ASV, but not with the votes of thermal comfort (authors stated that PMV may be inappropriate to control the indoor environment in order to establish thermal comfort) [180].

Thermal comfort studies with subjects in semi-controlled environments were conducted in Sweden to examine the effects of intermittent air velocity on thermal and draught perception [92], in China, to investigate the acceptable range of thermal, luminous, and acoustic environment (individually and cumulative effects) [93] and in United States, to study the effect of temperature, metabolic rate and dynamic localized airflow on thermal comfort [94].

5. Field studies in real buildings

Classic field studies involve the application of questionnaires and measurement of indoor variables (and outdoor in some cases). A review article about field studies grouped by climatic classification was presented by [181] and another review paper of thermal comfort studies in office, residential and educational buildings was written by [182].

5.1. Thermal comfort in kindergartens

Regarding thermal comfort in kindergartens or with children who have not yet developed their reading and writing skills, some works began to be developed since 2012. In the literature search performed, we only found three works with these users.

Conceição et al. [183] developed an adaptive model for evaluating the thermal comfort in kindergarten (aPMV). The model was applied during winter and summer in a kindergarten equipped with natural and forced ventilation and located in southern Portugal, a Mediterranean climate. Results showed that the aPMV in summer conditions is lower than PMV (user's thermal comfort sensation could feel less warm than PMV) while in winter conditions the aPMV is greater than PMV (user's thermal comfort sensation could feel less cold than PMV) [183]. In this study, the influence of the outdoor temperature in the thermal evaluation of indoor environment was identified [183].

In northern Italy, Fabbri [184] collected subjective evaluations of children between 4 and 5 years by adjusting the ISO 10551 questionnaire with a psycho-pedagogical approach. The analysis showed that children understand the concept of comfort and have the ability to define and choose their level of thermal comfort. However, the author points out that the PMV of children is slightly higher in relation to adults [184].

In Seoul, South Korea, Yun et al. [185] sought to provide data to propose a new model of PMV for children by studying the effects of metabolism and clothing on the thermal comfort of children. The study was conducted in naturally ventilated classrooms, between April and June 2013, with children from 4 to 6 years old. Results showed that children have a greater sensitivity to changes in their metabolism than adults and prefer lower temperatures than those predicted by the PMV model and the standard EN 15251. Such results may contribute to the development of a new model of PMV for children [185].

Overall, the research carried out with children in preschool, highlights the need for a comfort model that considers both their physical and physiological differences in their cognitive abilities. Additionally, studies of adaptive attitudes of children are needed.

Another issue to consider is the design of questionnaires for children and further studies are needed to help improve them. The questionnaires themselves can influence the reliability of the responses and must be improved the identification of the influence of the type of scale used in the response options according to the variable evaluated [186], the translation of some terms in other languages, the climate context in which the work is carried out and the age of the users, such as very young children [53,187].

5.2. Thermal comfort in schools

Research in schools has been widely developed in several countries to evaluate the thermal comfort of pupils from 7 years old.

In the hot humid climate of the southern region of Malaysia, Hussein et al. [188] conducted studies in two schools with fans. Although 80% of respondents found the thermal environment acceptable, the actual sensation vote (ASV) exceeded the one specified by ASHRAE 55, showing that people of this region have a higher tolerance and adaptability to the heat [188]. Hwang et al. [189]

studied the applicability of an adaptive model in naturally ventilated schools in Taiwan. The results show that the comfort zone for 80% acceptability has a wider band and the comfort zone for 90% acceptability has a narrower range than ASHRAE 55 adaptive model [189]. Mors et al. [190] studied the parameters of thermal comfort with children between 9 and 11 years of age in unconditioned environments in the Netherlands during winter, spring and summer. Through the PMV model the mean thermal sensation was underestimated at 1.5 points, an inaccurate result. When the thermal sensation was compared to the comfort zone of the adaptive model, authors found that children prefer lower temperatures [190]. Teli et al. [191] studied the applicability of the adaptive model of EN 15251 with children between 7 and 11 years old in naturally ventilated classrooms in England. Results indicated that the temperature of comfort achieved through the PMV was 4 °C lower than that obtained by questionnaires and the one obtained by the adaptive model was 2 °C lower, indicating that children are more sensitive to high temperatures. In another study, Teli et al. [192] show the adjustments that should be made in the current comfort criteria to evaluate the thermal perception of children in various climates. The current thermal comfort criteria lead to an underestimation of the thermal sensation of children during the summer [193]. The study of De Giuli et al. [194] held in a school in Padova (Italy), found no match between the PMV/PPD and the children's' ASV neither between the adaptive model nor the ASV [195].

Corgnati et al. [196] studied the thermal preferences of students in schools and in a university in the city of Torino, Italy. The mean of subjective votes was compared with the perception of the thermal environment and the results showed that people accept those environments judged as neutral or warm [196]. In the research of Teli et al. [192], held during the end of summer in Southampton (UK), children tended toward warm thermal sensations which was not complemented in the same way by strong preference for cooler spaces [192]. Another study by Corgnati et al. [197] performed during the mid season in schools under free running conditions in Turin (Northwest Italy) compared the subjective responses with those obtained in another study [196] conducted during the heating season. Results show a gradual change in thermal preference starting in the heating period until the mid season. During the mid season the preference was for neutral environments, while during the heating season the preference was for slightly warm or warm environments [197]. A study conducted in naturally ventilated classrooms in Beja (Portugal), in a Mediterranean climate, found that students preferred slightly warm environments in the mid season, with an acceptable temperature range beyond the comfort zone [198]. In Sweden, Wigo et al. [199] presented the evaluations of students who were subjected to intermittent air velocity in a school, during the spring and autumn. Results indicate that variations in air velocity cause people to perceive the air as being cooler and more refreshing than when the air velocity is constant. Pupils in the study also requested slightly more air movement [199].

Based on data from more than 4000 Italian students during the winter and the summer in about 200 naturally ventilated classrooms, the expectancy factor for the Mediterranean climate was proposed [200]. The expectancy factor when multiplied by PMV could correct the index for use in naturally ventilated environments. By doing that, authors concluded that PMV was effective in predicting thermal comfort in the studied naturally ventilated environments [200].

A study conducted by Montazami and Nicol [201] in 18 naturally ventilated schools in the UK analyzed the new version of overheating guidelines for schools with the old version, both published by the British government. Despite the new guidelines are more stringent, further development are needed [201].

In Taiwan, Liang et al. [202] found that the building envelope energy regulation has great impact on the thermal comfort sensation in naturally ventilated buildings. Katafygiotou and Serghides [203,204] showed that there is a relation between poor indoor quality conditions and the low-energy efficiency of buildings.

Zeiler et al. [205] evaluated the performance of thermo active building systems for heating schools during the winter in the Netherlands. According to the results of the questionnaires, these systems generate a slight improvement in the perception of thermal environment and greater user satisfaction with respect to the indoor temperature, when compared with traditional heating systems [205].

5.2.1. The influence of gender

Regarding the influence of gender in the evaluation of thermal comfort, the study by Katafygiotou and Serghides [203] in a typical classroom and a laboratory of a secondary school building in Cyprus, during different seasons, found differences in thermal sensation between girls and boys. During the winter, girls were more sensitive to low temperatures, which led to greater use of the heating system and affected the comfort sensation of the boys. During the summer, boys were more sensitive to high temperatures, feeling warmer than girls. The researchers attributed these differences in thermal sensation to the characteristics of the metabolism and the skin surface of each gender [203].

5.2.2. Adaptive behavior

A study by Chen et al. [206] analyzed the adaptive behaviors regarding the use of fans and air-conditioning in a mixed-mode school in Taiwan (under the control model fee-for-service) and the impact on energy savings. Results show that the least used mechanism (11%) was air-conditioning + fans while the most frequently used mechanism was to jointly opening the windows and running the fans (64%). The mechanism of fee-for-service restricted the use of air-conditioning by students and increased the temperature threshold at which the air-conditioning was activated [206]. Kurabuchi et al. [207] studied the behavioral differences in the indoor environment control and the thermal sensation of children before and after the installation of cooling systems at a school in Tokyo. Results of this research were used to produce guidelines for the use of equipment based on thermal sensations [207].

5.3. Thermal comfort in universities

Several studies have been conducted in university buildings in a hot and humid climate in China [208–214], India [215,216], Indonesia [217], Malaysia [8] and Brazil [218,219].

Hwang et al. [208] conducted field studies in 10 naturally ventilated and 26 air-conditioned classrooms in seven universities in Taiwan. The analysis found that relative humidity had no significant influence on the assessment of students' thermal sensation. Student responses point to wider ranges of thermal acceptability in Taiwan [208]. In a later study carried out in university dormitories in Taiwan [209], the neutral and preferred temperatures of students were similar in both classrooms and dormitories.

Zhang et al. [210] conducted a study in naturally ventilated classrooms with ceiling fans in Hunan University in China. Results showed that most students were satisfied with the thermal environment during the experiments (March–April). Authors analyzed a modified model of PMV, but the discrepancy between predicted and actual thermal sensations did not reduce noticeably [210]. In another study, Zhang et al. [211] evaluated the adaptive behaviors of students during a year in free-running buildings in a hot-humid area of China. A close match between the physical variables of the indoor environment and the clothing with outdoor climate was found. People in the analyzed climate are more tolerant of heat and humidity and less tolerant of cold environments when compared to studies conducted in temperate climates [211]. In a study performed in buildings with split air-conditioners in a hot-humid area of China, Zhang et al. [213] conclude that occupants of buildings with split air-conditioners keep their environment cooler, use adaptive opportunities early on and perceive their environment more sensitively and rigidly than users of naturally ventilated environments.

In the study by Yao et al. [212] carried out for a year in university classrooms in China, the comfort range found was broader than that recommended by the ASHRAE 55, with the exception of the hottest and coldest months, in which the range was narrower. In the oceanic temperate climate of Korea, a field study conducted in university classrooms during the spring and fall showed that the thermal acceptability range diverged from that recommended by ASHRAE 55 [220].

Wang et al. [214] conducted a study during the winter in Harbin (China) in university classrooms and offices, and concluded that the neutral temperatures were different in winter and spring (the neutral temperature was higher in spring than in winter), demonstrating the influence of the prevailing weather conditions in adaptation.

De Carvalho et al. [221] studied classrooms in an academic campus (university students) in Portugal and found that the level of insulation of clothing has the most significant relationship to the previous day's mean outdoor temperature.

A study conducted in the laboratories of a university in India showed high acceptance of the indoor thermal environment and adaptability by the students to high levels of humidity [216]. The answers from the questionnaires showed a strong correlation between indoor comfort conditions and the outdoor temperature [215].

Based on the results of two field studies conducted in two cities, Karyono [217] evaluated the applicability of the adaptive model in Indonesia. Results showed that user's comfort temperatures were in line with mean outdoor temperatures, as stated by the adaptive model [217].

A post-occupancy evaluation assessed the perception of students and staff of a zero-energy building, located in a French island in the Indian Ocean (tropical climate) [222]. The building was designed to be mixed-mode in some areas and uses passive strategies. Results indicate that during most of the year, users are in thermal comfort without using air-conditioning [222]. Serghides et al. [223] identified the inappropriate use of cooling and heating systems (very low temperatures in summer and very high temperatures in winter) in a university building in Cyprus. In the field study carried out in buildings of a university in Malaysia, the results of measurements and questionnaires showed that most of the buildings failed to provide a thermally comfortable environment and that the HVAC system should be changed [8].

During the fall, winter and spring, Buratti and Ricciardi [224] performed a field study in classrooms of three universities located in three cities in Italy. The correlation of the responses from questionnaires and PMV showed significant differences between them [224]. The results of the study by Memon et al. [225], at a university in the subtropical region of Pakistan, indicated that people in this area felt in thermal comfort with effective temperatures of 29.85 °C (operative temperature of 29.3 °C). Such a result was compared with the neutral effective temperature determined by the adaptive model, demonstrating that this model predicted it very well. PMV was compared with the actual sensation vote (ASV) and significant discrepancies were found, for example, an ASV = 0 was predicted by PMV as +1.34 [225].

The effect of ventilation was studied by Norback and Nordström [226] in computer classrooms (university students) with different air exchange rates. Higher air exchange was associated with a perception of lower temperature, higher air movement and better air quality [226].

The results of the study by Cândido et al. [218,219], performed in the hot and humid climate of the city of Maceió, Brazil, demonstrate the importance of the occupants' thermal history and their preference for higher air movement. According to the authors, people who are under steady conditions in their thermal environment (air-conditioned – AC – environments) have less tolerance and are less able to adapt to the dynamic conditions of naturally ventilated spaces. People who were constantly exposed to AC preferred this type of conditioning while people accustomed to free-running buildings preferred not to have AC [218]. The minimum air velocities required to achieve 80% and 90% of acceptability were closer or above the maximum velocity (0.8 m/s) recommended by ASHRAE 55 [219].

5.4. Thermal comfort in offices

Two office buildings of a university in Sydney (Australia), one operating with natural ventilation and the other with hybrid ventilation, were studied by Deuble and de Dear [227]. The authors compared the post-occupational evaluation (POE) of buildings with data from a classic field study of thermal comfort and concluded that the POE does not accurately assesses the performance of buildings [227]. Furthermore, the results of satisfaction and thermal acceptability indicate that the users of the naturally ventilated building are more tolerant with respect to their thermal environment, despite experiencing higher temperatures [227]. That conclusion was also carried out by other researchers: (i) Daghigh et al. [228], in a study in an office room with hybrid ventilation in Malaysia (users were more tolerant during the use of natural ventilation); (ii) Yang and Zang [229], in another study in different cities in the humid subtropical zone of China, during the summer, but comparing buildings with natural ventilation and others operating with air-conditioning (users were more tolerant in the naturally ventilated building).

In another study conducted in two cities in India (Chennai and Hyderabad, warm humid and composite climates, respectively) with air-conditioned and mixed-mode buildings, Indraganti et al. [230,231] determined thermal comfort temperatures and proposed an adaptive model of thermal comfort, respectively. Authors highlighted the increased air velocity by fans as one of the measures participants used to improve their comfort conditions [231]. Thermal comfort temperatures were also determined for an office building with hybrid ventilation in Seoul, South Korea and a new adaptive comfort model to that climate was proposed [232]. Nicol and Humphreys [233] determined adaptive comfort models (thermal acceptability ranges relating the outdoor running mean temperature and the indoor comfort temperature) for European office buildings operating with natural ventilation or during the heating or cooling operation, based on SCATs database.

In order to verify the applicability of the adaptive model of thermal comfort in mixed-mode buildings, studies were carried out in offices in Shenzhen (hot and humid subtropical climate) [234], China and Melbourne [235] and Sydney, Australia [235,236]. The different conditioning modes were perceived differently by users [234,236]. PMV–PPD model is inadequate to describe the thermal comfort in mixed-mode buildings [235]. The adaptive model is more applicable to this type of building, during the use of natural ventilation [234,236].

Classic thermal comfort field studies were carried out in naturally ventilated buildings in the cities of Douala and Yaounde (offices and schools), humid tropical climate of Cameroon [237], in the Southeast of France (offices) [238], in Karlsruhe (Germany) during the summer (offices) [239] and in Libya (offices and homes) [240]. When considering local discomfort, more than 40% of users were dissatisfied with their thermal environments in both cities in Cameroon [237] and over 50% in France during the warmer period (users preferred higher air movement) [238]. In the French and German studies, authors calculated PMV, which did not correlate well with the actual mean vote (the adaptive model described better the subjective responses) [238,239]. In the work in Libya, authors developed an adaptive model of thermal comfort and stated that Libya's population has a greater degree of adaptation than the European population (SCATs project) [240].

In the hot and humid climate of Taiwan, a classic study of thermal comfort in an air-conditioned office building retrofitted with a total heat exchanger resulted in improvements in thermal comfort and air quality after the air-conditioning retrofit [241]. Other studies of thermal comfort in office buildings with air-conditioning were carried out in Thailand (neutral temperatures and thermal acceptability were determined) [242], in Malaysia (the main problem was overcooling and the neutral temperatures proved to be higher than those predicted by PMV) [243], in China (low relative humidity was the main cause of thermal discomfort) [244], in Hong Kong (neutral temperatures were determined and in the summer these were lower than those predicted by PMV) [245] and in Saudi Arabia (63% of users felt dissatisfied during the summer) [246]. In this last study, a multi-phase approach proposed by Budaiwi [247] was applied for assessing and suggesting appropriate remedial measures for the thermal comfort problem [246].

Based on the available information in CBE's post-occupancy evaluation database (mainly offices), Kim and de Dear [248] identified that the type of conditioning (air-conditioning—AC, mixed-mode—MM and natural ventilation—NV) influences the expectation of users with respect to indoor environment quality satisfaction. In NV buildings, good thermal conditions improved overall satisfaction with the working environment (positive effects), while in AC buildings the thermal conditions were associated with negative evaluations in relation to the overall environment [248]. In MM buildings, thermal conditions provided both positive and negative impacts [248].

A comparison between the actual sensation vote and PMV conducted in air-conditioned office buildings in northern Italy, Singapore, Beijing (China), Belgium and Taiwan shows a weak correlation between these two parameters [249–252]. In Italy, the reason for the differences was the lack of thermal control by users, low air movement and the dissatisfaction generated due to the vertical temperature gradient [249]. In Singapore, overcooling was the main problem (users preferred higher operative temperatures) [250]. However, in another study during the winter in different office buildings in Germany, the authors concluded that the calculated PMV showed results close to the actual sensation vote [253].

In an air-conditioned office building in London (UK), a study was conducted during the summer comparing two groups of users in different thermal environments: (i) set point temperature of 22 °C and (ii) set point temperature of 24 °C (British Council for Offices—energy savings recommendation) [254]. While users felt the environment slightly warmer in the second case than the first, there was no significant difference with respect to thermal comfort [254].

Twenty federal office buildings in the United States were studied over periods of three [255] and seven years [256] through post-occupational evaluation. The thermal conditions of the spaces were kept within the thermal comfort ranges of the ASHRAE 55 (PMV) through air-conditioning use. However, 50% of users (especially women) expressed dissatisfaction with their thermal environments [256]. The authors recommended raising the summer set-point temperature by 2 °C to improve the thermal satisfaction of women and at the same time adjust the clothes of men in 0.57 clo (light trousers and short-sleeve shirts) to compensate for the increase in temperature [256].

5.4.1. Studies about environmental control and clothing

Healey [257] studied an office building with hybrid ventilation at a university in the Australian city of Gold Coast (hot and humid climate), where most users had a private room or at most shared with 3 people, thus having a considerable environmental control. The building was designed to work with natural ventilation and due to this, users tended to choose and prefer this mode of ventilation, although they could turn on the air-conditioning [257]. Other office buildings with hybrid ventilation located at a university in Changsha [258] and Chongqing [259], both Chinese climates with hot summers and cold winters, were studied for a whole year. The use of controls (windows, fans, heaters, air-conditioners, others) was observed and indicated that the main parameter for the adaptive thermal behavior of users was the outdoor air temperature (different seasons) [258,259]. On the other hand, in another study conducted during the summer in naturally ventilated office buildings in Switzerland, the authors concluded that the probability of users interacting with personal/environmental controls was best described by the indoor temperature [260]. Another analysis on the use of controls by users was carried out using data from classic studies of thermal comfort in Europe and Pakistan [261]. The authors concluded that the outdoor temperature was a better indicator for heating use, but the use of windows, fans and cooling was better described by the indoor temperature [261]. In the field of personalized conditioning, Karjalainen and Koistinen [262] identified users' problems controlling the personalized temperature through field study in Finnish office buildings. The main one is related to the interface of these systems and the assumption that users have knowledge of them [262]. Often people do not use the system or even know about it. Langevin et al. [263] studied the relationship between the perceived control of the thermal environment and the comfort sensation based on ASHRAE RP-884 database. Satisfaction with perceived control is more important to thermal comfort than just having personal control options [263]. Another study based on ASHRAE RP-884 database was performed in Hong Kong [264], where a comfort temperature chart for naturally ventilated buildings was developed.

Through observation data from ASHRAE RP-884 and RP-921, Schiavon and Lee [265] developed two dynamic models to predict the insulation of clothing in offices and found that climate variables explain only a small part of human behavior in relation to clothing. De Carli et al. [266] studied the clothing behavior in naturally ventilated and air-conditioned buildings based in others databases. The selection and change of clothes are affected by the parameters of the indoor and outdoor environment [266]. Huang et al. [267] performed a review about four standards (ISO 15831, ASTM F 1291, ASTM F 1720 and EN 342) for measuring the thermal resistance of the clothes and pointed out several suggestions to be considered in future revisions of these standards.

5.4.2. Green buildings studies

Baird and Field [268] studied various commercial and institutional buildings with sustainability labels in 11 countries. Overall, results indicated a good level of satisfaction with the indoor conditions of thermal comfort, which is better on average than the corresponding benchmarks [268]. However, in most of the analyzed buildings, users perceived the environment too cold in winter and too hot in summer [268].

A comparison of thermal comfort between conventional office buildings and green ones, operating with air-conditioning system was held in Taiwan [269], in Canada and the United States [270] and in Australia [271]. Another US study compared buildings with hybrid ventilation (most of them with green building certification) with a benchmarking database of 370 buildings (Center for the Built Environment-CBE) [272]. Users of green buildings were more satisfied with their thermal environments [269–272]. However, in another study in the US using the CBE database (144 buildings, 65 of them with a sustainability label), no significant difference between the two types of buildings was observed [273].

Green certified office buildings operating with an under floor air distribution system and with radiant slab cooling located in Calgary, Canada were studied by Bos and Love [274] and by Tian and Love [275], respectively. Bos and Love [274] concluded that, in general, the thermal environment was evaluated as satisfactory (actual mean vote = −0.5), although about 1/3 of users prefer higher air movement and higher temperatures.

5.4.3. Air movement studies

Zhang et al. [276] analyzed the air movement preference using the CBE database (data from office buildings in North America and Finland) and found higher dissatisfaction among users in lower air velocities, questioning the low air velocity limits set by ASHRAE 55 and ISO 7730. Yang et al. [277] investigated the air movement preference during the different seasons in naturally ventilated buildings in humid subtropical China, including offices, residences and classrooms and also found user's preference for higher air movement, mainly in warm conditions [277]. In ASHRAE 55-2009, SET model was implemented to assess thermal comfort in high air velocities, by compensating with air temperature [278]. Arens et al. [278] point out that this model is based on field studies with neutral and warm thermal environment, where people preferred higher air velocities.

5.5. Thermal comfort in residential buildings

Several research groups have found that there are differences between the PMV and the responses of the questionnaires (actual sensation vote-ASV) in residential buildings [279–283]. Becker and Paciuk [279] studied homes in Israel with and without HVAC systems during the summer and winter and found that the ASV was higher than PMV. Based on field study in 25 air-conditioned domestic buildings in Kuwait, Al-ajmi et al. [282] found that through the PMV neutral temperature was underestimated. The studies of Indraganti [284–287] in apartments in India found that the PMV overestimated the ASV of the residents. Another study in naturally ventilated apartment buildings in India determined neutral temperatures and a wider comfort band than Indian standards [288]. Based on studies conducted in 26 homes located in Central Southern China it was identified that the neutral operative temperature calculated by the Fanger model was lower than that obtained from questionnaires [9]. In another study performed in multi-story residential buildings in India, ASV had lower values than PMV, but when applied a expectancy factor of 0.6, the extended PMV model fit well with the ASV values [289].

According to the research results performed by Alexis et al. [290] in air-conditioned buildings in Cameroon, the comfort ranges of the ASHRAE 55 and ISO 7730 should be reviewed, as in the tropical climate users are acclimatized to higher temperatures, which could reduce energy consumption in air-conditioning [290].

In the hot humid climate of Venezuela, Bravo and González [291] investigated indirect evaporative passive cooling systems in a bioclimatic prototype dwelling and concluded that the house was thermally comfortable for most of the subjects. In Sweden, people who completed post-occupancy evaluations for nine passive houses complained about cold floors and high summer temperatures [292].

Yang et al. [293] studied residential buildings in high-latitude regions in China and determined an adaptive comfort model for that climate. Tablada et al. [294] proposed a comfort zone for the summer in residential buildings located in Old Havana, Cuba. In the questionnaires residents identified a preference for higher air velocities [294].

A study conducted in Leicester, UK, in 230 free running homes found that the indoor temperatures were much lower than anticipated by the EN 15251 model [295]. In low-income dwellings in England, Hong et al. [12] studied the impact of the Warm Front energy efficiency refurbishment scheme on the thermal comfort of residents. Results indicate that the energy efficiency refurbishment scheme was effective in improving user's thermal comfort [12]. In eastern Ukraine, Petrova et al. [296] identified that public policy on housing and energy regulation affect the performance of buildings, resulting in very cold thermal environments due to inadequate heating. In Sweden, Engvall et al. [297] reached a similar conclusion.

Based on the studies of Han et al. [281] in homes located in urban and rural areas of Hunan (South China) and Huang et al. [298] in suburban Beijing, it is clear that rural residents have greater cold tolerance.

Li et al. [299] compared the results of an artificial neural network model with an actual sensation vote obtained through evaluations that were carried out in residential buildings in China, where a maximum deviation of 3.5% was achieved [299].

5.5.1. Adaptive behavior and environmental control

A pilot experiment researched the adaptive behaviors (to heat) of people who have recently migrated to Spain [300]. The authors noted that people used various mechanisms of adaptation in their homes (change of clothes, food and drink intakes also changed in summer, as did the use of blinds) and that not all respondents possessed or were using air-conditioning because it was not necessary in the opinion of the users (some users also complained of overcooling in public spaces) [300].

By searching the adaptive behaviors of elderly people in homes in Taiwan, Hwang and Chen [301] found that their main strategy during summer was operating apertures, while during winter they wore more clothes to provide insulation [301].

Majid et al. [302] conducted a study in houses about the use of air-conditioning in the hot and dry weather of Oman. The survey revealed extended periods of air-conditioning operation and the preference of users for cooler environments, despite users reporting neutral to cold thermal sensations [302]. In naturally ventilated residential buildings in Harbin, China, users preferred lower air velocities even at higher indoor temperatures during the summer (cool conditions) [303]. During the winter in residential buildings in China, Luo et al. [304] and Cao et al. [305] found that residents with the possibility of personal control on the environment presented lower neutral operative temperature compared to those residents without control. In a study in passive houses in Denmark, users evaluated the thermal environment as hot in summer and cold in winter and reported feeling frustrated by not having control over the heating system, which was centrally controlled [306].

In Seoul, the behavior of users with respect to the control of cooling and heating systems was studied in houses [307]. Results indicated that the HVAC systems generated a comfort expectation for users, adjusting the comfort zone to warmer in winter and cooler in summer [307]. A research project conducted in naturally ventilated university dormitories in China demonstrated that user have a higher tolerance of temperature and that the effect of humidity on thermal comfort at high and low temperatures should not be ignored [308]. Sekhar and Goh [309] found that, although thermal acceptability was good in dormitories with naturally/mechanically ventilated (NMV) and others with air-conditioning, the thermal environment was better in the NMV rooms [309]. Regarding adaptive opportunities in naturally ventilated houses, a study in Japan showed that the opening of windows depends on the outdoor and indoor temperatures [310]. In Nigeria, the study by Adunola [311] identified the impact of urban microclimate in the comfort inside the residences. Another study performed in low to middle income housing in South Australia demonstrated that, due to the cost of using air-conditioning, people primarily tried to cool themselves through less expensive methods: by turning on fans, operating openings and curtains and by changing their clothes [312].

In Finland, Karjalainen [313,314] performed field studies in offices, and in homes—where a greater amount of data was collected. The results show better thermal comfort levels in homes; additionally, in the offices, people realized they had less control over the thermal environment and fewer adaptive opportunities [314]. Karjalainen also concluded that there are differences in the thermal comfort sensation, preferences and use of the thermostat according to gender.

5.5.2. The influence of age and gender

In his review paper, Karjalainen [315] concluded that women are less satisfied with the thermal environment than men in the same thermal environments, and that women prefer higher temperatures and are more sensitive to heat and mainly cold discomfort [313]. In a study conducted in homes in Harbin (China), results show lower sensitivity of men to temperature changes, as well as differences of 1 °C in the neutral operative temperature between men and women [316]. Indraganti [317] performed a field study in naturally ventilated apartments in India and found no significant correlation between age and thermal comfort. Another study conducted in naturally ventilated residential buildings demonstrates that the effects of gender and age, when compared with the effects of environment variables, are of little significance in the evaluation of thermal comfort [318].

5.5.3. Studies about traditional and modern buildings

Other studies compared the thermal comfort in traditional and modern houses located in Mardin (Turkey) [319], in Kerala (India) [320], in Indonesia [321] and in Cameroon [283,322]. Results show that the traditional houses provided a more comfortable indoor environment than the modern ones [283,319–322]. A study performed in traditional vernacular houses in different climates of Nepal indicates that indoor neutral temperature is highest in subtropical climates, medium in temperate climates, and lowest in cool climates [323]. The study by Singh et al. [324] evaluated the thermal comfort of vernacular buildings located in North-Eastern India and found that these buildings provided satisfactory comfort conditions, with the exception of winter months. In Japan, the temporary log houses built after the Great East Japan Earthquake, showed better thermal conditions during the summer than pre-fabricated houses, however during the winter, the indoor temperature in both houses was uncomfortable, especially in the temporary log houses [325]. The study conducted in homes (traditional and modern) during the period of the Harmattan (a cold-dry wind) in two cities in Cameroon (Ngaoundere and Kousseri, the last one located in a more severe climate), indicates that just 58% and 47% of occupants consider their thermal environments acceptable, respectively [326].

A study carried out in terraced houses in Malaysia identified the relationship between the perceived comfort and the health of residents (occupants with a higher level of comfort were healthier) [327].

5.6. Thermal comfort in other indoor environments

Studies in buildings with the most varied uses have been developed in several cities. The post-occupational study of Kavgic et al. [328] held in a theater in Belgrade, Serbia shows that the space was over-ventilated and the ventilation system was generating cold discomfort beyond the predicted point. Another post-occupational evaluation was carried out in the United States in a LEED platinum campus building (a multi-function structure that includes classrooms, seminar rooms, high-tech research laboratories, offices and studios). Despite the fact that users were overall satisfied with the indoor environment, there were complaints about overcooling and low air movement and thermal comfort was comparatively low [329]. In mosque buildings in Kuwait, the neutral temperature found through occupants' questionnaires was higher than the temperature obtained from PMV [16]. In a coalmine emergency refuge facility, Li et al. [330] proposed a simplified PMV equation that evaluated this type of environment [330].

Study by Yau et al. [331] evaluated the thermal conditions in the National Museum of Malaysia. Revel and Arnesano [332] studied the perception of the thermal environment in a gym and swimming pool in Italy and concluded that PMV could be used to evaluate sports buildings. A lobby working with air-conditioning in Malaysia was studied through field study with subjects and the results were analyzed by the extension of PMV (with an expectation factor) [333,334]. A guest service center with air-conditioning in Taichung, Taiwan was the subject of a field study investigating the influence of step changes in environmental variables (from outdoor to indoor) on comfort sensation and comfort expectations [335]. A field study of thermal comfort was conducted in naturally ventilated waiting areas of a railway station in Chennai, India [336].

Based on field study in workplaces and in residences in Taiwan, Hwang et al. [337] proposed a new equation to calculate the PPD in hot humid climates, increasing the value of the percentage of dissatisfied to 9% in the cold side of the scale [337]. Wijewardane et al. [338] studied the thermal adaptability of workers in naturally ventilated factories in Sri Lanka (a hot and humid climate), demonstrating the influence of air velocity in tolerance to higher temperatures (above 34 °C) [338]. At workstations in the automotive industry in Malaysia, Ismail et al. [339] identified the poor condition of the thermal environment. By using a metabolic analyzer in workplaces in an industrial company Broday et al. [340] set new values for the metabolic rate through calculations and measurements. The findings differ from the values provided in ISO 8996 (2004). By using the new metabolic rates the actual thermal sensation correlated better with PMV [340].

In four cities in three countries (Korea, the United States and Japan), Kim et al. [341] studied peoples' adaptation to air-conditioned environments in several building types (hotel, market, café, amongst others). Results demonstrated how cultural aspects (as in the Japanese case) influence user's adaptation to thermal environments and showed variations in the insulation of the clothes by the type of environment [341]. One specific finding indicates that people who are exposed to narrow range of temperatures (AC cooling) cannot stand hot indoor climates [341].

Simone et al. [342] studied a hypermarket, a large retail facility, in Italy and found discrepancies between subjective responses and PMV. This suggests that PMV could be unable to estimate thermal comfort when clothing insulation is unevenly distributed on the human body. This is more commonly a problem for women than men [342]. Della Crociata et al. [343] proposed a measurement protocol and questionnaires to assess the thermal comfort of the hypermarkets' employees. In commercial kitchens, the study by Simone et al. [344] also found that the use of PMV is not suitable for thermal evaluations in such environments.

Through interviews, Lai et al. [345] found that users of air-conditioned commercial buildings in Hong Kong were dissatisfied with the thermal environment and among the IEQ attributes evaluated, thermal comfort was perceived as the worst.

Lee et al. [346] studied the descriptors "warm" and "slightly hot", when translated from English to Korean and used in scales to assess the thermal comfort sensation. Results indicate that for Koreans, the term "warm" indicates thermal comfort, while "slightly hot" refers to some sort of discomfort [346]. The authors concluded that it is necessary for a Korean scale to consider such descriptors, when mild hot environments are evaluated [346]. A similar study was conducted by Tochihara et al. [347], but with Japanese, English and Indonesian people. The descriptor "cool" was associated with the thermal comfort sensation for Indonesians [347]. Both studies were conducted indoors [346,347], however authors did not specify the type of building.

5.6.1. Hospitals, healthcare facilities and elderly centers

In the tropical climate, Yau and Chew [348] assessed four hospitals and found that 49% of the occupants were satisfied with the thermal environments in the hospitals. Higher comfort temperature than that prescribed by ASHRAE 55 was required for Malaysians in hospitals [348], which was also corroborated by Azizpour et al. [349,350] in the study of a hospital in Malaysia. Based on staff evaluations from nine hospitals, Yau and Chew [351] developed an adaptive thermal comfort model for hospital environments with air-conditioning in a tropical climate. Verheyen et al. [352] found that in patients rooms at a Belgian healthcare facility, 29% of the thermal environments evaluated did not reach the conditions recommended by ASHRAE 55. Still, the patients' thermal acceptability was 95%. This indicates that the comfort bands of the standard could be wider for this type of users. Other studies in hospital settings were carried out by Wang et al. [353] in Taiwan and by van Gaever et al. [354] in Belgium. Khodakarami and Nasrollahi reviewed the literature on thermal comfort in hospitals [355]. An overview of thermal comfort for older people with dementia was presented by [356].

In Hong Kong, a study compared the results of thermal acceptability of the elderly in centers for older people with younger residents [357]. Results established that for every 25.3 years, a probable decay of one predicted mean vote was stated for people with 60 or more years [357]. The study by Mui et al. [358], performed in 19 elderly centers in Hong Kong, indicates that all users felt satisfaction with the conditions of the indoor thermal environment, as well as with the other three environmental conditions evaluated (air quality, lighting and noise level) [358].

5.6.2. Hostels

A study conducted in student hostels in Malaysia used questionnaire results to infer that students who live in rooms with projected balconies were more satisfied with their indoor environment [359]. Wafi and Ismail [360] and Dahlan et al. [361] also studied other student hostels in Malaysia. According to the work of Dhaka et al. [362] in India, there were a wide range of neutral temperatures (wider and higher than international standards) at 6 naturally ventilated student hostels. Based on the research of Guedes et al. [363], who performed a field study in offices, homes for the elderly and educational buildings in Lisbon (Portugal), people experience the sensation of thermal comfort in wider temperature ranges than specified in ASHRAE 55 [363].

6. Thermal comfort and productivity

A study in Tokyo, Japan during the summer under mandatory electricity savings after the Great East Japan Earthquake was held in office buildings [80]. The authors imposed a variation of indoor temperature and ventilation conditions and concluded that users expressed discomfort at higher temperatures and recommended a maximum operative temperature of 27 °C [80]. The user productivity compared to the previous year's survey was estimated through a self-assessment and resulted in a loss of productivity of 6.6% [80].

Climate chamber studies were performed in Japan (users could not change their clothes, nor the environmental conditions of the room) and demonstrated in short exposure time, no change in productivity in high temperature and humidity conditions [364]; on the other hand, in longer exposure time there was a decrease in productivity in a hot and dissatisfying environment [365]. Another study in a climate chamber in a non-steady thermal environment in Denmark (users could only change their clothes) found no difference in productivity amongst the analyzed thermal conditions (19.0–26.8 °C) [366]. In a US study, subjects were exposed to cold conditions (10 °C) and then to 25 °C [367]. The authors concluded that cognitive function is reduced during the cold exposure and that such reduction persisted for one hour during the rewarmed period [367]. In China, another study involving two groups of subjects (one exposed to temperature variations and the other exposed to 26 °C) concluded that a warm discomfort environment had a negative effect on performance. The study recommended an optimum range of temperatures for performance: 22 °C to 26 °C [368]. Also in China, another study evaluated the influence of constant mechanical wind (CMW) and simulated natural wind (SNW) on human thermal comfort and performance, indicating that both airflows would increase comfort in warm environments (CMW performed better at a close to neutral condition and the SNW performed better at a warmer condition), but no differences were found in human performance [369]. In Lithuania, three groups of subjects exposed to constant (22 °C), rising (22 °C to 26 °C; +0.1 °C/h) and dropping (22 °C to 18 °C; −0.1 °C/h) air temperatures were assessed with respect to office work performance; regarding the constant temperature conditions, the case with a rising temperature showed a decrease in performance of 2.5% and the case with a dropping temperature an increase of 1.6% [370].

A climate chamber study using task-ambient conditioning (TAC) evaluated productivity and concluded that TAC does not affect the task performance in relation to a neutral environmental condition [371]. Another study on productivity using TAC was conducted in an office building in Japan, where users were exposed to different environmental conditions (TAC off, TAC on and TAC controlled by users) [372]. When users controlled the TAC, they reported fewer symptoms and had a lower loss of vitality level, so the use of TAC is important to maintain the vitality level [372]. In another survey conducted in a climate chamber operating with personalized ventilation (PV), Bogdan et al. [373] determined thermal conditions (ambient room temperature and PV air supplied temperature) for summer and winter which led to better productivity results.

In Singapore and Thailand, in office rooms with air-conditioning (a semi-controlled environment) productivity studies were conducted [374,375]. In Singapore, despite causing lower thermal sensation and reduced thermal comfort, a lower air temperature (moderate cold exposure of 20 °C) increased mental arousal and increased performance in activities requiring attention [375]. In Thailand, research indicates that in order to maintain and increase productivity, indoor temperatures should be higher in the morning (26–28 °C, warmer thermal condition than PMV-ISO 7730) than in the afternoon and evening (24.5–26 °C) [374]. This finding may be related to the results obtained by Kakitsuba and White [376] in climate chamber experiments in Japan. The authors evaluated the core temperature of the human body (Tc, which is lowest during wake up in the morning and increased during the daytime) – circadian rhythm – and concluded that the best outcomes for thermal comfort and thermal sensation were obtained through daytime temperature variations—with higher air temperatures during the morning and lower temperatures in the afternoon.

In a Finnish study on productivity carried out in an office building during the summer, self-estimated work efficiency decreased when the temperature was above 25 °C [377]. In a Japanese call center an increase in air temperature from 25 to 26 °C resulted in a decrease in performance of 1.9% [378].

Katafygiotou and Serghides [204] studied the perceived learning performance (PLP) by comparing air-conditioned and fan-assisted naturally ventilated environments (FANV) in schools in the hot and humid climate of Cyprus. Students with uncomfortable thermal sensation reported worse PLP in FANV environments [204], but more research is needed in the area. Learning performance was also studied in a university building in Hong Kong [379]. The higher the number of IEQ complaints (including thermal comfort), the higher the student learning performance loss [379]. A performance comparison between green schools and conventional schools in Toronto, Canada shows that green buildings present improved productivity than conventional ones [380]. In addition, thermal comfort and other IEQ attributes were better at the green schools [380].

A study carried out in a climate chamber (simulating an office) in Denmark, included 12 subjects dressed with a clo of 0.9 and subjected to 22 °C (thermal neutrality) and 30 °C (Lan et al. [381,382]). The users were subjected to a series of tasks for the purpose of estimating their productivity in both thermal conditions. The authors concluded that task performance was reduced when people felt warm and that this loss was a result of elevated air temperature [381]. Such work generated discussion, resulting in a critical letter to the editor [383] and another one in response from the authors [384].

In a review paper [385] and in a letter to the editor [383], Leyten and Kurvers (and Raue, in the review article) point out the limitations of the work of Lan et al. [381]. The critique pointed out that the research was conducted in a climatic chamber and concludes that the findings of Lan et al. can not be extrapolated to real conditions in naturally ventilated buildings. In reply to Leyten and Kurvers, Lan et al. [384] argued that while there is no field work in naturally ventilated buildings proving a loss of performance of office work in high temperature conditions where the PMV and the adaptive model differ, they are satisfied with their conclusions.

A short time later, Wyon and Wargocki [386], two of the authors of the discussed article (Lan et al. [381]), wrote a letter to the editor criticizing a review article on thermal comfort of de Dear et al. [387], which contains a chapter on thermal comfort and productivity. Wyon and Wargocki [386] again argued that if the indoor operative temperatures vary according to the adaptive model, the productivity can not be maintained and would instead be reduced. In response, de Dear et al. [388] together with Leyten and Kurvers, asserted that the conclusions of Wyon and Wargocki should be limited to the experimental conditions of their study (Lan et al. [381]) performed in a climate chamber.

In this context, it is evident that the relationship between thermal comfort and productivity requires more attention from researchers. Typically, research in the area uses different methods to estimate productivity, therefore hindering any comparison between studies. The standardization of methods to estimate productivity would result in a better understanding of the subject.

7. Overview of physiological models

In the field of physiological modeling, studies conducted have shown great progress. Review papers about physiological modeling are available in the literature [25]. A review about the human thermoregulatory behavior was presented by [389]. According to the review articles of de Dear et al. [387] and Cheng et al. [390], the first thermoregulation models of the human body and thermal comfort divided the human body between one (whole body) [42] and 15 segments [43–45]. Each part of the body was again divided into nodes, with a minimum of two nodes to the model of Gagge, Stolwijk and Hardy [42] and Gagge, Stolwijk and Nishi [46]: the Pierce two-node model. The nodes compose anatomical segments (fingers, hands, head, etc.) and have inherent physical properties (conductivity, for example) which are modeled numerically to solve the heat balance equation [387].

The models of Stolwijk and Hardy [43] and Stolwijk [45] laid the foundation for several more current physiological models such as Fiala et al. [47,391], UC Berkeley [48], Tanabe et al. [49], ThermoSEM [50,392] and JOS-2 [393], which use between 15 and 19 segments and hundreds of nodes.

Another promising field of research, 3-D human body models, is more complex and requires better computer resources using thousands of nodes [390].

The physiological models have been validated by experimental studies (subjective responses) in order to predict the thermal sensation and thermal comfort of each body part, as well as of the whole body. A great effort in this direction has been conducted by researchers at UC Berkeley [394–396]. Recently, in partnership with Tsingua University, UC Berkeley further reviewed and refined their comfort model [397,398], which can be used in uniform and non-uniform, transient and steady-state environments. In another study, a predictive model of local and overall thermal sensations for non-uniform environments was proposed based on studies with subjects in a climate chamber in China [399].

In recent years a number of new approaches have been proposed, for example, a new adaptive predicted mean vote (aPMV) model was developed with the goal of extending the application of PMV in free-running buildings [400]. The aPMV uses an adaptive coefficient that is based on field study. Such a coefficient was determined in naturally ventilated buildings at Chongqing University in China [400]. A new framework for modeling occupants' adaptive thermal comfort that considers adaptive actions probability, as well as feedback of users' perceived comfort from these actions, was developed and applied in a building in Switzerland [401]. A new simplified three-node model for non-uniform thermal sensation (bare and clothed parts of the human body) was developed based on Gagge's model [402]. A new approach (multi-segmental – MS – Pierce model) to predicting the local skin temperatures of individual body parts was proposed based on the Pierce two-node model [403], which later was used as the thermoregulatory control mode for thermal manikins [404]. A new predictive thermal response index was proposed for use in steady-state and transient conditions based on the 1991 Ring and de Dear model [405]. A new simplified predict thermal sensation equation – using only the air temperature and water vapor pressure – was proposed based on field work in office buildings [406]. Another new model for predicting thermal sensation based on the neurophysiology of thermal reception was developed and validated through subject experiments in the Netherlands [407]. A new equation for the prediction of whole-body thermal sensation in the uniform and non-steady state based on skin temperature was built and validated through subject experiments in climate chambers in Japan [408]. Revised and new PMV–PPD curves for offices representing the relationship between PMV and direct thermal acceptability and preference ratings were developed using Bayesian probit analysis [409]. A novel two-stage regression model of thermal comfort was developed and validated in an office building in the United States [410]. In China, a data-driven method describing personalized dynamic thermal comfort was proposed and tested [411]. A new methodology to evaluate the thermal environment based on operative temperature thermal levels (decitherms, analogous to decibels in acoustics) was proposed by Jokl [412]. A new PMV (nPMV) based on the adaptive comfort theory was proposed and compared with the original PMV and with the actual thermal sensation of subjects in an air-conditioned office building in South Korea show better results than the original PMV [413].

In 2011, Foda et al. [414] compared the predictions of skin temperature from three different models of human thermoregulation (Fiala, UC Berkeley and MS Pierce model) with experimental data, showing that the MS Pierce model presented a good performance. The model was then coupled with the UC Berkeley comfort model to predict the local thermal sensation and the results were compared with subjective votes, showing a positive match for most body segments [414]. In 2013, Schellen et al. [415] compared experimental data in a climate chamber with Fanger's, ThermoSEM and UC Berkeley models (the latter before the 2014 review [397]). Results confirmed that when local effects have significant influence, the PMV is not a good predictor of the body's overall sensation [415]. The combination of ThermoSEM and UC Berkeley models is promising to predict local and overall thermal sensations in steady-state non-uniform environments [415].

Recently, a new approach using exergy analysis instead of energy analysis (commonly used by thermal comfort prediction methods) was proposed, showing interesting results [416–423]. A review about the exergy balance equation can be found at [424]. This may be a field of research with a promising future.

8. Thermal comfort in outdoor and semi-outdoor environments

8.1. Outdoor thermal comfort models

In outdoor environments people are directly exposed to local microclimate conditions of solar radiation, shading and changes in wind direction and speed [425]. Despite these dynamic conditions, the use of PMV–PPD index is common for the evaluation of thermal comfort outdoors [425]. As pointed out in a review paper by Chen and Ng [425], the use of the PMV–PPD in the outdoors leads to considerable discrepancies between the actual sensation vote (ASV), collected subjectively through questionnaires of thermal comfort, and the PMV. Another static method that has been widely used, but that has presented better results than the PMV in outdoor environments, is PET (Physiological Equivalent Temperature) [425]. However, static methods have the limitation of not taking into account the dynamic adaptive aspects of human beings [425]. Thus, specific indices for outdoor environments are being developed and are presenting improved results [425]. In order to assist with future research in the area, Chen and Ng [425] proposed a general framework for outdoor thermal comfort assessment, which covers the physical, physiological, psychological and social/behavioral aspects.

More recently, a new outdoor thermal index indicating universal and separate effects on human thermal comfort for uniform conditions (ETVO) [426] and for non-uniform conditions (the universal effective temperature—ETU) [427] were proposed by Nagano and Horikoshi. Another proposed thermal index is the Universal Thermal Climate Index (UTCI) based on an advanced multi-node model of thermoregulation [428].

Another outdoor thermal comfort model (COMFA) was assessed in field tests (walking, running, and cycling activities) in Canada [429,430] and improvements to the model were also made [431]. A new conceptual model of direct and indirect influence of place-related parameters on human responses was proposed and applied in a outdoor space in Gothenburg [432]. A new thermal index for outdoor environments (ETFe-enhanced conduction-corrected modified effective temperature) was proposed by Kurazumi et al. [433] based on ETF (conduction corrected modified effective temperature) index [434] and the new index was compared to subjective responses from field studies during the summer [435] and winter [436,437] in outdoor places in Nagoya (Japan).

8.2. Outdoor field studies

Field surveys at 14 different outdoor sites, across five different countries in Europe, led to the finding that at least 75% of people are comfortable on a yearly basis [438]; the actual thermal sensation votes were compared with PET, the Temperature-Humidity Index (cTHI) and the wind chill index (K) [439].

Field studies were conducted at outdoor sites in Gothenburg (Sweden) and Matsudo (Japan) [440,441], in Lisbon (Portugal) [442], in Matsudo [443], Tajimi [444] and 14 forests and urban areas in Japan [445], in Taichung [446–449] and Chiayi [450] (Taiwan), in Marrakech (Morocco) and Phoenix (US) [451], in the Hague, Eindhoven and Groningen (Netherlands) [452–454] and in Beirut (Lebanon) [455]. Additional field studies were also conducted in Xi'na [456], Guangzhou [457], Nanjing [458], Chengdu [459], Tianjin [460], Wuhan [461] and others [462] (China), in Cairo (Egypt) [463], in Curitiba (Brazil) [464–466], in Hong Kong [467,468], in Szeged (Hungary) [469,470], in Malaysia [471,472], in Athens [473–476] and Crete [477] (Greece), in Damascus (Syria) [478], in Glasgow (UK) [479], in Singapore [480,481], in Mendoza (Argentina) [482], in Barranquilla (Colombia) [483], in the Caribbean islands of Barbados, Saint Lucia and Tobago (with beach tourists) [484] and in Israel [485]. The results were analyzed through PET and/or other indices (UTCI, OUT_SET-outdoor standard effective temperature, for example) and variables (air velocity, solar radiation, clothing, for example). Another study measured the solar absorptance of the clothed human body in Japanese subjects [486]. In outdoor environments and based on data from field studies conducted in Taiwan, Tung et al. [487] concluded that women are less tolerant of heat and, for cultural reasons, protect their skin more from solar radiation [487].

The literature includes review papers on outdoor comfort studies [488] about different approaches for outdoor thermal comfort [489] and about the mean radiant temperature for outdoor places [490]. Another review paper examines the instruments and methods used to assess outdoor thermal comfort and subjective thermal perception [491].

8.3. Semi-outdoor studies

Regarding transitional spaces, Chun, Kwok and Tamura [51] defined them as spaces in between outdoor and indoor. This includes balconies, lobbies and bus stations: areas that are influenced by the prevailing weather conditions, but that are limited by a construction. In these spaces, the transitional zone is modified without mechanical control systems [51]. These types of environments are also commonly referred to as semi-outdoor environments. In order to avoid possible confusion, as pointed out by Chun, Kwok and Tamura [51] through the use of the term "transitional" and "transient", in this review paper we chose to use the term "semi-outdoor environments". The regulations and existing standards do not provide guidelines for the thermal environment of such spaces [107] and these spaces have not been studied in great detail. Fanger's model (PMV–PPD) is not applicable for research in the area of semi-outdoor environments [51].

The review paper presented by van Hoof [107] collects some of the findings of research conducted in applying PMV model in outdoor and semi-outdoor environments. The changes in clothing, metabolic rate and the high variability of physical parameters limit the use of this model in outdoor and/or semi-outdoor environments [107]. The author also points out the validity of the model exposed by Fanger himself: PMV is only applicable for indoor spaces and constant environmental conditions [107]. Kwong et al. [492] state that in tropical climates like Malaysia the air velocity is important to maintain thermal comfort.

Thermal comfort ranges were proposed based on a field study in outdoor and semi-outdoor environments in Taiwan [493] and the effect of seasonal thermal adaptation was also studied [494]. Outdoor and semi-outdoor environments were also investigated in Wuhan (China) [495] and in Nagoya (Japan) [496].

In semi-outdoor environments in a university in Singapore (two food centers, one with misting fans and the other without misting fans, as well as one coffee store with a misting line system), a field survey was conducted. The survey concluded that for the same outdoor effective temperature (ET*), lower votes of thermal sensation were achieved by using misting fans [497]. A field study in a workshop in a university in Beirut was used to validate a thermal comfort model proposed for semi-outdoor environments [498].

9. Conclusions

In this paper, a review of human thermal comfort in the built environment was performed. The review focused on articles published in the last 10 years however remarkable works and some standards were also discussed.

The methodology used to select the literature allowed the authors to identify the difficulties that still exist in the selection of keywords and writing for abstracts. The term “thermal comfort” is often used indiscriminately, which hindered the process of searching for articles by area of interest. The abstracts themselves also had inadequacies. Many of them did not include enough information to facilitate the identification of the type of building used in the study (real environment or climate chamber or simulation, for example), the period of the study, the results and the main conclusion. In many cases it was necessary to read parts of the article to be able to extract such basic information about the work.

Over the past 10 years, several research topics involving thermal comfort have emerged, as the occupant behavior studies and the exergy analysis in physiology. Still others were rescued, such as the growing interest in naturally ventilated and mixed-mode buildings and personalized conditioning systems, the development of more complex and accurate physiological models, the increased interest in thermal comfort in the outdoors and studies aimed at productivity. The latter is deserving of more attention from researchers. Also in the last 10 years, different authors in many countries around the world developed several new adaptive thermal comfort models and others worked to correct or adjust the PMV/PPD model for actual building types and different conditioning modes. These new data have been contributing to the improvement of models of thermal comfort. While there have been many field studies bringing valuable information from the people conducting their activities in their everyday environments, including research into the person-environment relationship and the factors that affect thermal comfort in the built environment, studies are still numerous in controlled environments and analyze issues individually. In some situations thermal comfort cannot be fully explained by the classical six variables (two human and four environmental). There are a number of other factors that influence the sensation of thermal comfort, like cultural and behavioral aspects, age, gender, space layout, possibility of control over the environment, user’s thermal history and individual preferences. Static and homogeneous environments leading to thermal monotony, an expensive solution, previously preferred, are giving way to dynamic environments, in which wider ranges of indoor temperature are preferred and the natural ventilation is desired. The use of personalized conditioning systems is probably the best ways to increase user acceptability with the thermal environment. Thermal comfort is a complex topic and we are far from understanding all its interrelated aspects.

Through this review of the literature it became evident that there is a gap in thermal comfort studies in relation to interdisciplinary research. The association with other professionals like psychologists, physiologists, sociologists, philosophers and even with other building related ones (architects and engineers that work with visual, aural and olfactory comfort) could be of great value for the development of an integral (systemic/holistic) research approach that may help to a better comprehension about sensation, perception and thermal comfort and its physiological and psychological dimensions.

If the trend of exponential growth of papers in the area continues in the coming years, it is likely that research into many subjects in the area will be deepened and new ways of looking at thermal comfort will be explored. We certainly need a better understanding of thermal comfort to face climate change and the demands for more energy efficient buildings.

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