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Current Issues and Way Forward

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Review

Advancement on Thermal Comfort in Educational Buildings: Current Issues and Way Forward

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Abstract: The thermal environment in educational buildings is crucial to improve students' health and productivity, as they spend a considerable amount of time in classrooms. Due to the complexity of educational buildings, research performed has been heterogeneous and standards for thermal comfort are based on office studies with adults. Moreover, they rely on single dose-response models that do not account for interactions with other environmental factors, or students' individual preferences and needs. A literature study was performed on thermal comfort in educational buildings comprising of 143 field studies, to identify all possible confounding parameters involved in thermal perception. Educational stage, climate zone, model adopted to investigate comfort, and operation mode were then selected as confounding parameters and discussed to delineate the priorities for future research. Results showed that children often present with different thermal sensations than adults, which should be considered in the design of energy-efficient and comfortable educational environments. Furthermore, the use of different models to analyse comfort can influence field studies' outcomes and should be carefully investigated. It is concluded that future studies should focus on a more rational evaluation of thermal comfort, also considering the effect that local discomfort can have on the perception of an environment. Moreover, it is important to carefully assess possible relationships between HVAC systems, building envelope, and thermal comfort, including their effect on energy consumption. Since several studies showed that the perception of the environment does not concern thermal comfort only, but it involves the aspects of indoor air, acoustic, and visual quality, their effect on the health and performance of the students should be assessed. This paper provides a way forward for researchers, which should aim to have an integrated approach through considering the positive effects of indoor exposure while considering possible individual differences.

Keywords: thermal comfort; indoor environmental quality; educational buildings; energy consumptions; local discomfort

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1. Introduction

Students spend a good part of the day in schools, and, especially when considering children, they are particularly exposed to an unfavourable indoor environmental quality (IEQ) [1]. Therefore, the relations between classroom characteristics and comfort should be carefully investigated [2]. As the aim of educational buildings is to provide the best learning conditions for students and teachers [3], classrooms should be designed to improve concentration and to stimulate the learning process [4–6], but also be climate-responsive [7]. Since the thermal environment can largely affect students' wellbeing, it is also fundamental to ensure thermal comfort in classrooms to improve students' health and productivity [8].

For the assessment of thermal comfort, several indices have been developed [9], but Fanger's rational (or heat-balance) [10] and the adaptive models [11–13] are the most commonly used. Indeed, it is necessary to raise questions regarding students' possibility to adapt, as at different educational levels adaptation may differ, and, especially at low educational levels, teachers are the only ones who can actively modify the thermal environment [14]. Nevertheless, it should be noted that children and adults do not always have the same thermal perception, therefore pupils' preference on the thermal environment should be considered, as it could help to co-design classrooms [15]. Furthermore, in educational buildings, different activities are carried out, which can influence the thermal comfort evaluation especially at a high metabolic rate [16].

In educational buildings, the duration of field studies varied largely from less than a week to a whole year [17], and they were performed according to three classes [18]: (i) Class III, based on measurements of indoor temperature and humidity at a certain height; (ii) Class II, including field measurements of the six basic parameters in one location at a certain height; (iii) Class I, comprising the measurement of all the environmental parameters at three different heights (0.1, 0.6, 1.2 m) to evaluate local discomfort. Most studies in schools were performed according to Class II [17], while Class III was used for investigations of the adaptive model [19,20]. Only a few papers have been based on Class I [21–24], and in these cases draught, radiant asymmetry, vertical air temperature difference, and floor temperature were measured [22,25,26]. Alternatively, other IEQ aspects were included in the investigation, such as CO_2 concentration [4,27,28] or other factors of IEQ, such as noise level [29–31] or illumination level on the work plane [32–34]. Furthermore, as the goal for the buildings of tomorrow is to combine the aspects of energy efficiency and comfort [35], studies were also focused on the impact of thermal comfort on energy efficiency [22,36]. Indeed, due to the complexity of the parameters that influence buildings' performance and indoor environment, it is crucial to focus on the aspects that contribute to determining the health and wellbeing of the occupants, also in relation to architectural and HVAC system design, towards a multi-objective approach to building performance.

The measurement of environmental parameters has been often combined with subjective measurement, which consisted of various types of questionnaires [17]. The first ones included questions regarding thermal sensation and preference, while recent studies also include the evaluation of local thermal comfort, humidity sensation and preference, air velocity sensation and preference, personal regulation, preferred adaptive strategies, information on the clothing worn, and the activity performed prior to the survey [25,37,38]. Simplified questionnaires for children were also provided, to ensure the correctness of the collected data [39,40]. Recently, questionnaires have also included aspects of health and performance of students [6,41,42]. Both longitudinal and transversal surveys were used by researchers, but it was never defined how long the survey should be and how many respondents are necessary for the evaluation of thermal comfort in educational buildings [17,43].

Given the complexity of these environments, there is a lack of standards dealing with thermal comfort in educational buildings, as current regulations such as ISO 7730 [44], ASHRAE 55 [45], and EN 16798-1 [46] seem to be not sufficient to provide comfortable conditions for students and teachers. Indeed, these standards refer to data recorded in laboratories [44] or field studies using comfort data recorded on healthy adults in buildings across the world [11,13], which do not take into account student and teacher individual preferences. Indeed, standards were often developed for environments such as offices, thus, they do not include the peculiarities of educational buildings and they are often based on dose-response models that are not able to explain people's individual preferences and needs.

In conclusion, thermal comfort in educational buildings has been largely investigated and there are many models and indices that have been used with this purpose. However, there are still problems that should be solved, which do not emerge clearly due to the rapid growth of scientific literature. Studies have been often carried out based on the experience of single researchers, rather than adopting a coordinated effort of predetermined directions to develop consistent solutions and guidelines. There is then the need for a collection, a rationalised classification, and analysis of these studies to inspect the present state, aimed at identifying the current issues and to guide future research towards solutions to such problems. This paper aims at filling this gap, highlighting the current issues in thermal comfort studies, and proposing new directions for research with the purpose of integrating the interactions between humans and the environment.

2. Methods

2.1. Search Strategy

The literature search was performed on the electronic databases Scopus, ScienceDirect, Google Scholar, and Researchgate in the period from March to November 2020. The search keywords used in the databases were {"thermal comfort"} AND {"classroom" OR "class" OR "educational buildings"}, using an integrated search in the title, keywords, and abstract of the papers. Moreover, the selected references were analysed individually to extract relevant information. The following inclusion criteria were selected: (i) original peer-reviewed articles; (ii) field studies investigating thermal comfort and related aspects of IEQ in educational buildings; (iii) full text published in English. Exclusion criteria were: (i) studies not focused on building engineering (e.g., articles focused on physiological or psychological aspects only); (ii) articles investigating energy consumptions only; (iii) simulation studies which did not include field measurements; (iv) books, book chapters, and conference reviews. Review articles were inspected, but not included in the classification of the studies in educational buildings.

Thanks to the possibility to analyse the number of resulting articles, Scopus was used as the primary database to continue this review. From the initial search using the selected keywords, 958 documents were extracted, and following removal of the ones without an English full-text, 916 articles remained. Of these, 445 were research articles, 409 conference papers, 27 were reviews, 18 book chapters, 2 books, and 15 conference reviews. In total, 854 papers (research and conference articles) were then analysed, as well as the 27 review articles. From the title and abstract inspection, the final number of articles considered was 143. Figure 1 shows the geographical distribution of thermal comfort studies in educational buildings, while Figure 2 shows the increase in thermal comfort studies in educational buildings over time.

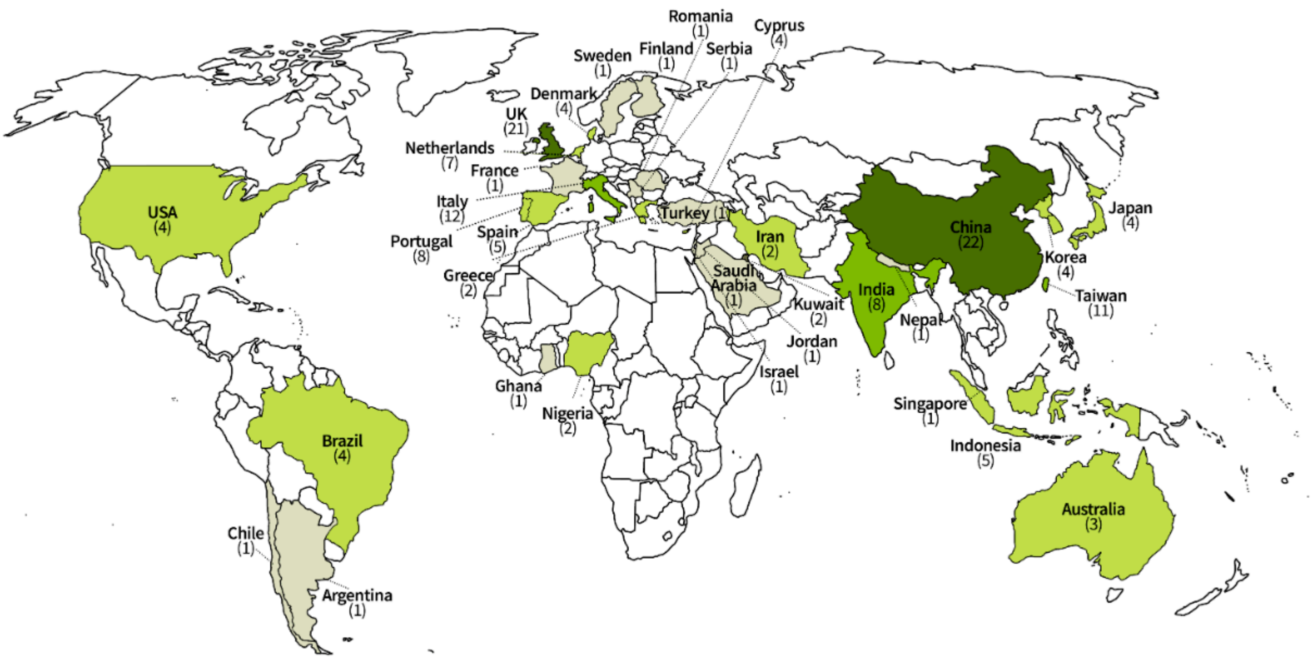


Figure 1. Geographical distribution of the studies on thermal comfort in educational buildings over time.

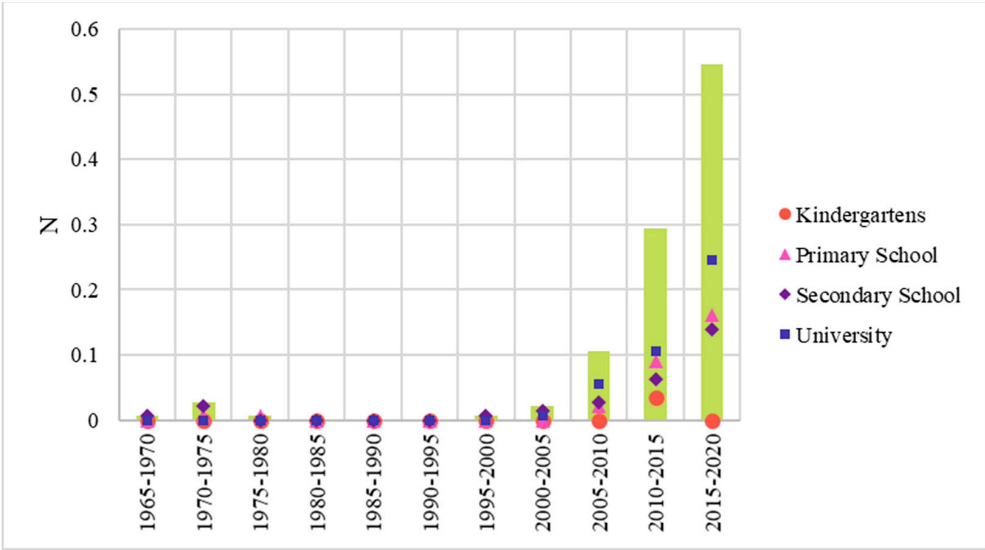


Figure 2. Normalized number of studies (N) on thermal comfort in educational buildings. The normalization is done with respect to the total number (143) of considered publications.

2.2. Data Extraction and Analysis

Data were extracted from the selected articles, analysing the full text. For the discussion, the year, location of the study, educational stage, climate zone, model used to determine thermal comfort, building's operation mode, and period of the survey were derived, when available. These characteristics were selected because they can possibly explain individual differences in thermal perception. From the analysis of the existing literature, the current issues were identified, and new directions of research were proposed (Figure 3).

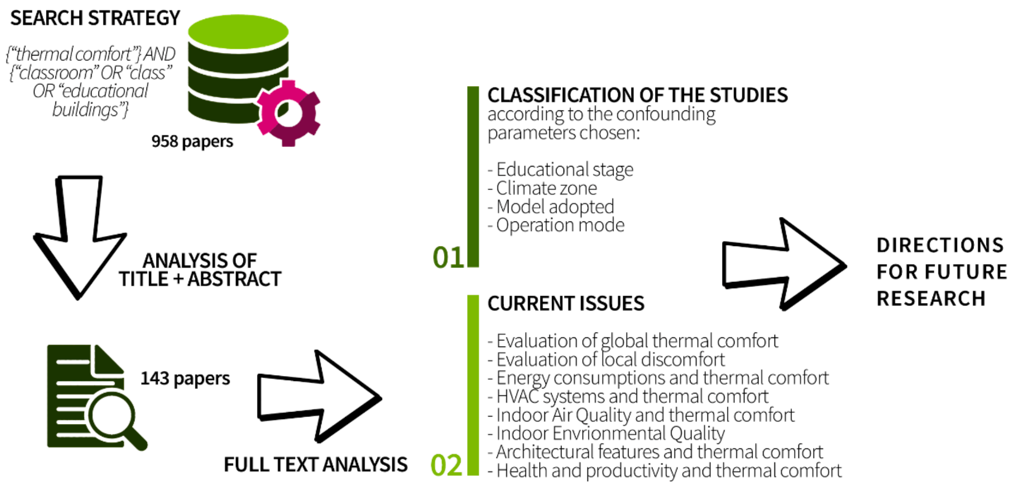


Figure 3. Methodology and supporting material used to define the directions for future research.

3. Classification of the Studies

By conducting a detailed analysis of the obtained results, it was possible to identify the main categories in which the studies, currently present in the literature, can be grouped. The investigation was based on manual grouping, which was conducted after an accurate inspection of the full text of the selected papers. It resulted that there were four main confounding parameters often identified by researchers as the main causes of differences in thermal sensations among students: the educational stage, climate zone, the model adopted, and operation mode. Table 1 shows the variability of comfort temperatures between the different categories found in the analysed studies. The influence of these confounding parameters on the thermal perception and the results of the analysis are discussed below.

Table 1. Variability of comfort temperatures between the different categories found in the analysed studies. The number of papers considered are reported in the parenthesis. Data extracted from [47].

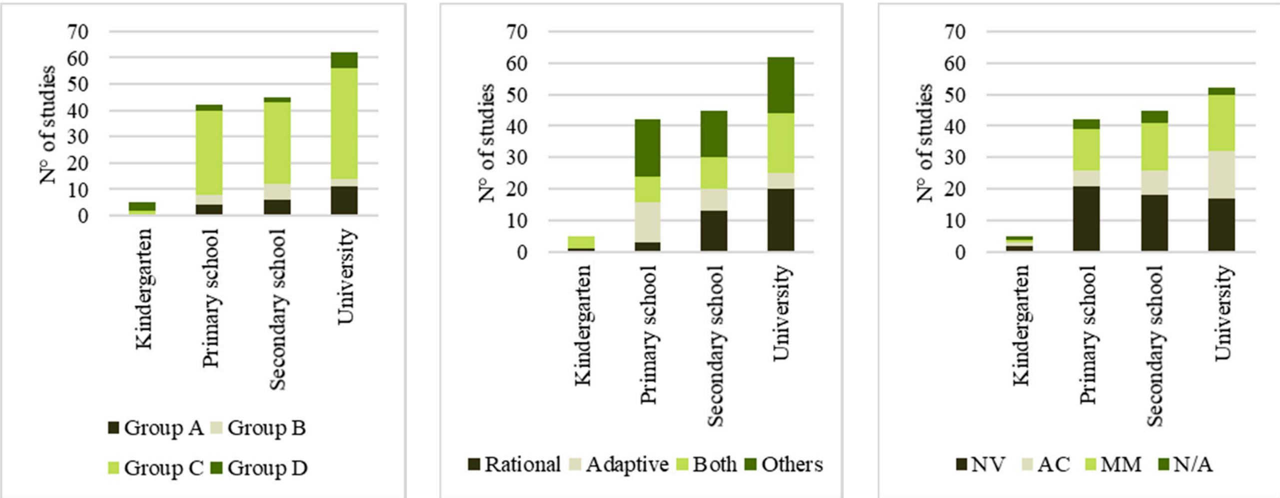
Characteristics		Comfort Temperature	
		Min (°C)	Max (°C)
Educational stage	Kindergarten (4)	20.7	26.0
	Primary school (40)	14.7	30
	Secondary school (39)	14.7	35
	University (60)	15.5	31.5
Climate zone	Group A (21)	20.0	31.0
	Group B (13)	14.7	25.0
	Group C (97)	14.7	35.0
	Group D (12)	16.0	26.0
Model adopted	Rational (38)	15.0	30.7
	Adaptive (23)	14.7	29.2
	Both (34)	16.0	31.0
	Others (48)	14.7	35.0
Operation mode	Air conditioned (38)	14.7	26.9
	Naturally ventilated (51)	14.7	31.5
	Mixed mode (45)	15.7	30.0

3.1. Educational Stage

The educational stage is the most important aspect that should be evaluated when considering thermal comfort in educational buildings. At different educational stages, students present various ages, diverse possibilities to adapt, and carry out different activities, which can influence their metabolic rate and their capability to respond correctly to questionnaires regarding thermal sensation and preference. Indeed, the age can be a crucial factor for the perception of the thermal environment, also due to the different physiological and psychological characteristics of the pupils. Furthermore, the presence of outdoor activities and stationary or transient conditions, which are determined by the duration of lectures, is also a function of the educational stage. Finally, the density of the classroom can also affect the perception of the thermal environment. Most studies were carried out in universities, followed by secondary and primary schools, and kindergartens (Figure 4).

The evaluation of thermal comfort in kindergartens is a recent topic, developed for the first time in 2012 [48], and only a few works can be found in the literature. The focus of previous studies was mostly on the development of new comfort models for the children, both rational [49] and adaptive [50]. Since children at that age do not present with reading or writing skills yet, researchers also aimed at creating a specific questionnaire for thermal comfort assessment [51]. Studies indicated that pre-school children present comfort temperatures 0.5 °C lower in summer and 3.3 °C in winter [52].

In primary schools, the first work on thermal comfort dates back to 1975 [19], which estimated thermal neutrality from over 6000 assessments obtained. At this educational stage, in most cases children prefer cooler environments, showing that the PMV model underestimates mean thermal sensation up to 1.5 scale point [53], and children present comfort temperatures about 4 °C to 2 °C lower than the predictions from rational and adaptive models, respectively [54]. It is also important to highlight the differences between children's and teachers' thermal sensation [55], as it is more difficult to reach thermal comfort for pupils. Indeed, children present with a lower comfort temperature [56], at least 3 °C lower than adults during cooling seasons [57], and they are also less sensitive to temperature changes than adults [11]. This different perception can be attributed to children's higher metabolic rate, as their activities involve several games including physical exercise, as well as their limited possibility to adapt [52], the influence of the characteristics of their home environments, and outdoor playing, which may alter their thermal perception [47]. It was also demonstrated that social background and behaviour can influence children's thermal preference [58]. Furthermore, thermal comfort models seem to predict inaccurately the thermal sensation of pupils, as the PMV index usually overestimates the perception of scholars, while the adaptive model predicts higher comfort temperatures than the actual ones [59–61].



(**a**) (**b**) (**c**)

Figure 4. Number of studies divided according to the educational stage in different climate zones (**a**), the model adopted (**b**), and operation mode (**c**). Legend: NV = naturally ventilated, AC = air-conditioned, MM = mixed-mode, N/A = not available.

In secondary schools, students can give more reliable information on their thermal state and preference, therefore it is easier for researchers to compare their subjective response to the objective analysis. At this educational stage, several studies showed differences in thermal sensations and neutral temperatures despite the climate, season, and operation modes being the same [17], which can be a specific problem when trying to set the comfort temperatures for the achievement of students' wellbeing. For example, children preferred cooler environments than adults [62–64] even in the tropics [65], and thermal preference changed during summer months [66]. Moreover, students generally accepted cool thermal sensations faster than warm thermal sensations [67]. In the past, more emphasis has been given to the importance of energy savings rather than learning conditions [68,69], therefore there are gaps in the literature considering the improvement of students' performance in relation to the indoor environmental conditions. For air-conditioned buildings, there is evidence that HVAC systems do not always enhance comfort, but they may also be a cause of global and local thermal discomfort [70].

In universities, students have a greater possibility to adapt, and they may be in transient conditions since the duration of the lectures is shorter than at other educational stages. However, even though Fanger's theory was based on experiments carried out on university students, researchers found some divergencies between the predicted thermal sensation obtained with PMV and the real thermal sensation from questionnaires. This can be attributed to several problems related to students' possibility to adapt, adjusting their clothing [24,38,71], or controlling the environment [38,71,72]. Even psychological adaptation can play a fundamental role in adapting to the thermal environment [24].

Furthermore, students may be in transient conditions, as the time they remain in the classroom is limited and they often move outdoors. Differences in neutral temperatures were found in laboratories and classrooms [73,74], in different seasons [23,75,76], and due to gender differences [77].

3.2. Climate Zone

The classification per climate zone is relevant, since different climatic conditions can influence the thermal perception and preference of students due to adaptive processes. Considering that thermal history can affect students' thermal comfort [78], the classification per climate zone is relevant in the perspective of improving environmental conditions and reducing energy consumptions in the global warming era. Indeed, the current challenge for building designers is to provide low-energy buildings while enhancing thermal comfort, especially under warmer conditions caused by climate change [79]. According to the Köppen–Geiger climate classification [80], there are five different climate groups (from A to E), divided according to the seasonal precipitation and temperature patterns. The climate zone can influence students' possibility to acclimatise, influences the indoor environment from the outdoor conditions, but also affects the thermal insulation of the clothing worn by students. Most studies have been carried out in the climate Group C, as can be noticed in Figure 5.

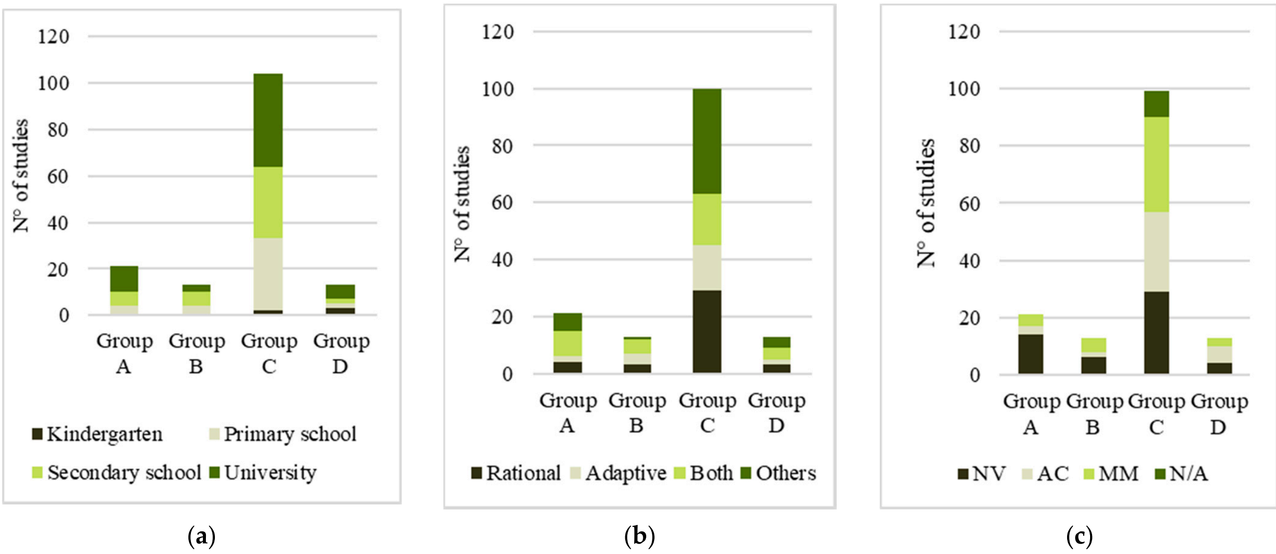


Figure 5. Number of studies divided according to the climate zone at different educational stages (**a**), model adopted (**b**) and operation mode (**c**). Legend: NV = naturally ventilated, AC = air-conditioned, MM = mixed-mode, N/A = not available.

Group A includes the tropical climates and about 15% of the studies (22 studies) were carried out in this climate, mostly in naturally ventilated classrooms, applying both rational and adaptive models (Figure 5). Studies were carried out in India, Brazil, Indonesia, Malaysia, Singapore, Nigeria, USA, and Ghana, as reported in Appendix A. In Group A, the range of comfort temperature varied between 20.0 °C and 31.0 °C, indicating large differences in the same climate zones [17], which makes the comparison of neutral temperatures difficult. In Group A, students had a higher heat tolerance and they adapted to the thermal environment, while the temperatures largely exceeded the comfort range given by the standards [17]. These facts are particularly relevant, as they can have a consistent impact on energy conservation strategies, although some studies show that in the past twenty years the comfort temperature has decreased due to the increasing use of air conditioners [81].

Group B includes dry (arid and semi-arid), hot, and cold climates. In this climate zone, only 9% (13 studies) of the studies were carried out. Thermal comfort was investigated during the whole year and used both rational and adaptive models (Figure 5). Studies were carried out in Jordan, Cyprus, Chile, Iran, China, Kuwait, and Saudi Arabia (Appendix A). In Group B, comfort temperature varied between 14.7 °C and 25.0 °C, indicating less of a difference than in Group A [17]. Nevertheless, these values also exceed the comfort range given by standards, probably due to adaptation.

Group C includes temperate climates and comprises various types of climates, therefore temperature variations and adaptability within it can be large. Most studies were carried out in this group (69%, 99 studies) (Figure 5), and included investigations in several countries (Appendix A). Studies were carried out in all the seasons in naturally ventilated and air-conditioned buildings, using both adaptive and rational models (Figure 5). The first studies were carried out in the UK [66,82], which also presents the highest number of investigations along with China and Italy. The comfort temperatures varied between 14.7 °C and 35.0 °C [17]. This variation is probably because in Group C there is a wide range of climates, therefore students are exposed to various weather conditions. In this climate zone, students showed a great capability to adapt, especially the ones exposed to wider climate variations [83].

Group D includes continental climates, and limited research has been performed in this climate zone (8%, 12 studies). Studies were conducted in naturally ventilated and air-conditioned buildings during all the seasons using rational and adaptive models (Figure 5). They were carried out in China, Korea, Romania, Sweden, Finland, Turkey, and Nepal (Appendix A). The comfort temperature ranged between 16.0 °C and 26.0 °C [17], showing a large variability in students' preferences.

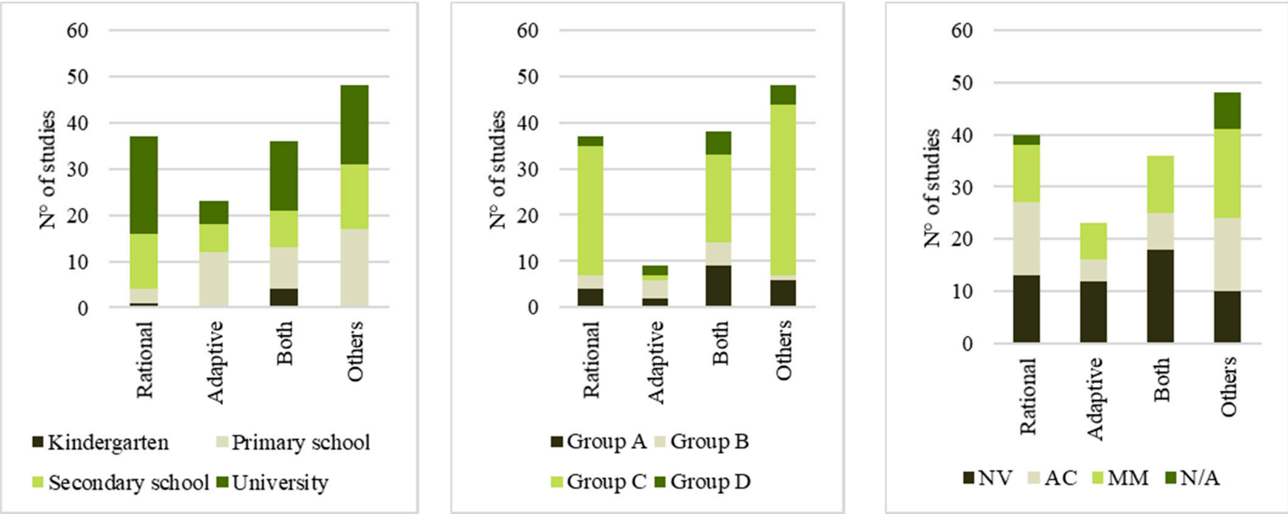
Group E includes polar and arctic climates, with an average temperature below 10 °C. No study on thermal comfort in educational buildings was found for this climate zone.

3.3. Model Adopted

The model adopted to analyse thermal comfort in educational buildings is relevant, as it can influence the predicted thermal sensation. Studies were carried out using the rational model (27%, 38 studies), adaptive model (16%, 23 studies) separately or together (24%, 34 studies), or other indicators (33%, 48 studies) (Figure 6). Indeed, different models can lead to diverse conclusions on the thermal state of students; therefore, it is fundamental to choose the model that is the closest to their real thermal sensation, according to their diverse characteristics and needs. Studies showed that none of the models accurately predict the thermal sensation of students. Rational and adaptive models should be combined to improve the prediction of the thermal environment, as they are complementary and not contradictory [18].

The rational model is generally applicable to air-conditioned spaces where occupants are in steady-state conditions with limited possibility to adapt. However, these conditions do not always occur in educational buildings, which leads to an overestimation or underestimation of the thermal sensation. Furthermore, the rational model is often incompatible in temperate and tropical climates [17]. To overcome these problems, corrections of PMV index, such as ePMV [63,67] or aPMV [84] have been provided and used by researchers to assess the thermal environment in educational buildings (Appendix A). Even though this model seems to be, in most cases, too inaccurate to predict thermal comfort in educational buildings, it is still widely used by researchers. However, it should be noted that the reliability of the PMV index largely depends on the precision of the assessment input parameters [85], which must be carefully evaluated to avoid misleading results.

In educational buildings, students often have adaptive opportunities. Most studies reported higher comfort temperatures than the ones predicted by the adaptive model, while lower comfort temperatures were found in secondary schools and compatible results in universities [17]. These results are consistent with the assumption of the adaptive model that considers occupants as able to modify their environment to achieve thermal comfort. This type of adaptation is typical of university students, which show comfort temperatures in line with the ones predicted by the adaptive model [17].



(a) (b) (c)

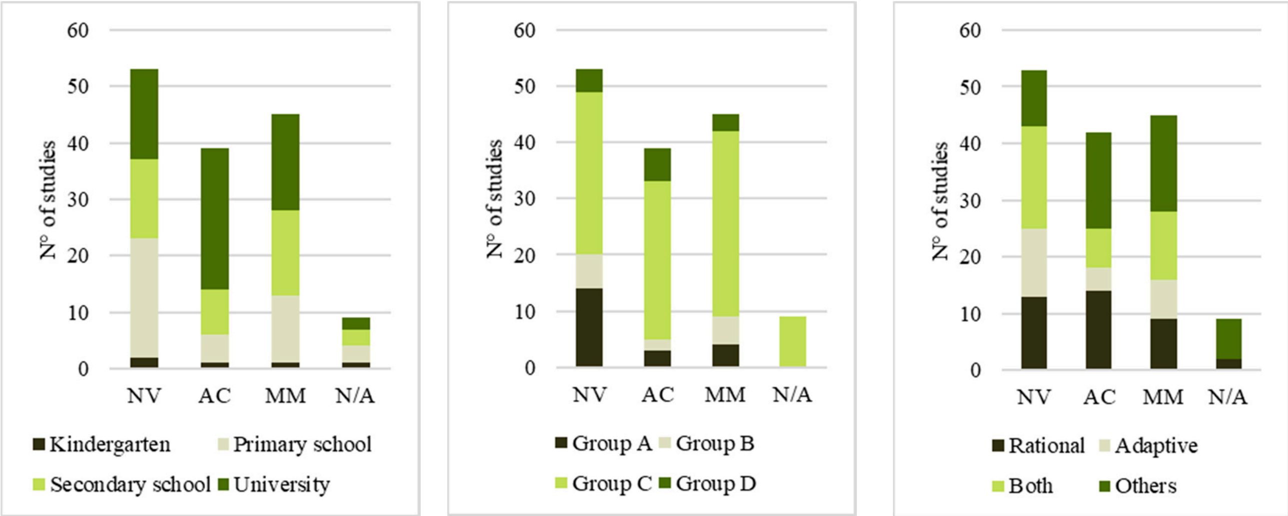
Figure 6. Number of studies divided according to the model adopted, at different educational stages (**a**), climate zone (**b**) and operation mode (**c**). Legend: NV = naturally ventilated, AC = air-conditioned, MM = mixed-mode, N/A = not available.

3.4. Operation Mode

The operation mode of the classroom can also influence the thermal perception of the students, as they experience diverse thermal environments in them (i.e., steady-state in air-conditioned, transient in free-running buildings). The operation mode influences the indoor environmental conditions also as a function of the outdoor climate, and different comfort temperatures can be found in relation to the operation mode. Furthermore, it defines the adaptation of the students and their control of the thermal environment, which can regulate their thermal perception. Most studies were carried out in naturally ventilated (NV) classrooms, followed by mixed-mode (MM) and air-conditioned (AC) schools (Figure 7).

In naturally ventilated buildings, the possibility to adapt is limited to the opening/closing of doors and windows. Several studies on primary schools were performed in naturally ventilated classrooms, and less in secondary schools, universities, and kindergartens (Figure 7). In climates A and B, natural ventilation is often used as the operation mode of classrooms, and less in climates C and D, as the colder climates need the presence of HVAC systems to achieve comfort in buildings (Figure 7). In most studies, the adaptive and rational models were both used, while when considered separately, the adaptive model was used in more cases than the rational (Figure 7). In particular, in hot-humid climates, observed comfort temperatures in naturally ventilated classrooms were found to be about 1.7 °C lower than the ASHRAE-recommended value [86], showing the importance of carefully evaluating comfort temperature also for energy savings. Furthermore, in naturally ventilated classrooms, students expressed comfort even when the environmental parameters were out of the standard's comfort zone [67,87]. These results are consistent with the adaptive hypothesis [13], which implies that humans can adapt behaviourally, physiologically, and psychologically to the environmental conditions to which they are subjected.

About 30% of the studies (38 papers) were performed in air-conditioned classrooms (Figure 7), where HVAC systems were switched on during the investigation period. The highest number of studies in air-conditioned classrooms was in universities, followed by secondary, primary schools, and kindergartens (Figure 7). The heating system was switched on during the winter in temperate climates and longer in colder climates (Group D), while the increasing use of cooling systems during summer, especially in warmer climates, could be detected. Climate Groups C and D were often investigating air-conditioned classrooms, and researchers usually used the rational model to assess thermal comfort. Only a few studies used the adaptive model as well as both models (Figure 7), even if adaptive behaviours were observed in air-conditioned schools [87]. Field studies in air-conditioned schools were also carried out to design energy efficient classrooms [88], with evident implications on students' wellbeing and energy consumptions.



(**a**) (**b**) (**c**)

Figure 7. Number of studies divided according to the operation mode, at different educational stages (**a**), climate zone (**b**) and model adopted (**c**). Legend: NV = naturally ventilated, AC = air-conditioned, MM = mixed-mode, N/A = not available.

Studies in mixed-mode buildings were often investigating the thermal environment during several seasons (Appendix A). Most studies in mixed-mode classrooms were equally distributed in secondary, primary schools, and universities (Figure 7). Climate Group C was the most investigated and both rational and adaptive models were used, both separately or together (Figure 7). This operation mode should be carefully evaluated, as the comfort temperatures and needs of the occupants vary according to the season of investigation and the operation mode of the classroom. Differences in students' performance between conditioned and naturally ventilated classrooms were also evaluated [89], but no significant difference was found. In this direction, studies comparing air-conditioned and naturally ventilated spaces did not show different neutral temperatures, preferred temperatures, and thermal acceptability [75].

4. Current Issues

In this section, the complete selection of the studies was analysed to identify the most common issues that are present in the evaluation of thermal comfort in classrooms, which are reported in the following paragraphs.

4.1. Evaluation of Global Thermal Comfort

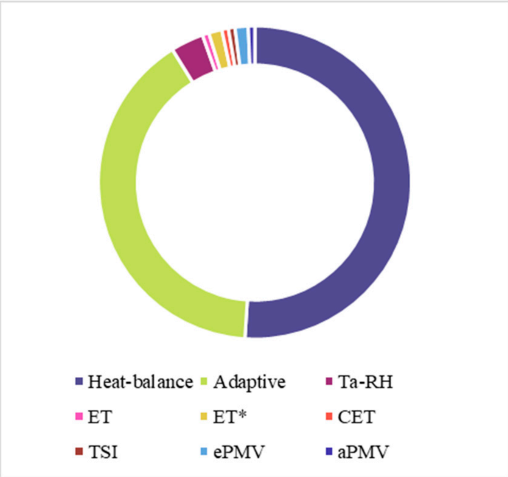
Most of the investigations on global thermal comfort have been focused on field measurements only, both objective and subjective, while few studies compared on-site measurements with simulations. There is no agreement on how global thermal comfort should be assessed, as different models and indices to assess thermal comfort were applied (Figure 8). Among them, the most common were the rational and the adaptive models (Appendix A). Some researchers were focused on the assessment of air temperature and relative humidity only in Portuguese school buildings [68,69], evaluating the impact of refurbishments on the indoor environment [69] and also in relation to other aspects of IEQ [2,34]. Indices such as effective temperature ET [19], new effective temperature ET* [73,77], corrected effective temperature CET [19], tropical summer index TSI [90], or the PMV correction for naturally ventilated buildings [91] were also calculated. The corrections of PMV index, ePMV [63,67] and aPMV [84], were also applied. In several studies, the operative temperature was assessed, and the neutral temperature was derived from the subjective responses of the students [75,92,93]. It was deduced that pupils' thermal sensation is higher than adults [59], and that their thermal sensation is not related to indoor temperature only, but also to their home environment [58]. Furthermore, thermal sensation changed during the class hour and adaptation occurred after about 20 min after entering the classroom [94]. In some cases, the outdoor environmental conditions were considered [49,58,95], as they can also influence the perception of the indoor environment. The main purpose of these studies was to assess the environmental conditions in educational buildings [51]. For this reason, new algorithms and models were provided for scholars [49,96,97], and adaptive comfort equations obtained from regression analysis were developed for children [50,61] to assess the comfort temperatures in different educational stages and all classrooms [47]. Ranges of comfort temperatures were also provided for classrooms, considering different educational stages and climate zones [17,47]. To consider the applicability and the differences between predictive models of thermal comfort, some researchers performed a comparison between them [63]. However, it lacks agreement among researchers in regards to the model that should be used to evaluate global thermal comfort, which is one of the current issues that should be faced.

4.2. Evaluation of Local Discomfort

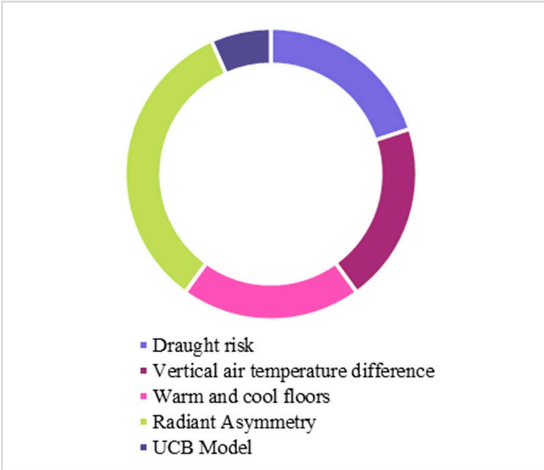
Recently, the assessment of local discomfort has become increasingly relevant, as it can have a great influence on people's wellbeing, but also on energy consumption. However, it lacks sufficient scientific evidence regarding the importance of local discomfort on students' wellbeing. The main causes of local discomfort found in classrooms were draught risk [21,31,98], vertical air temperature difference [21,99,100], warm and cool floors [21,99,101], and radiant asymmetry [21,25,98,99,101]. Studies were performed using the UCB Berkeley model for thermal comfort [26], questionnaires including specific questions on local discomfort [21] and its causes [25], and in some cases, occupants were asked to report the part of the body that was subjected to local discomfort [22]. The purpose of these studies varies from evaluating the percentage of dissatisfied students due to local discomfort [98] and the difference between global and local thermal comfort [22], to investigating the relation between local thermal comfort and productivity [25]. Even if a growing interest in this topic can be detected, only a few studies were carried out, and broader knowledge on the issue of local discomfort is needed.

4.3. Energy Consumptions and Thermal Comfort

The impact of thermal comfort on energy consumption is a debated topic that was faced by researchers in different ways. The evaluation of energy consumption has been carried out through on-site measurements, simulations, or in climate chambers approximating the conditions of the typical classrooms. In some cases, researchers investigated the direct relationship between energy consumption and thermal comfort [22,36,102]. Energy consumption was also compared to thermal comfort in association with indoor air quality [103] and visual comfort [104,105]. The concerns about energy savings were compared to ventilation strategies [95,106], HVAC systems operation, and architectural features [107,108]. Researchers also compared refurbished and non-refurbished educational buildings, which resulted in a reduction of consumption for renovated schools [93,102,109]. An investigation into the influence of shading devices on indoor environmental quality and energy consumption was also performed [110]. Finally, an algorithm to improve thermal comfort and indoor air quality and reduce consumption, using the least amount of energy from air conditioning and ventilation fans, was developed [111]. This analysis showed the importance of combining the issue of consumption with thermal comfort studies to enhance students' wellbeing and reduce energy requirements. However, it is still difficult to propose solutions that reduce energy consumption without compromising thermal comfort for children and adults.



(**a**)



(**b**)

Figure 8. Indices used by researchers to investigate global (**a**) and local (**b**) thermal comfort in classrooms.

4.4. HVAC Systems and Thermal Comfort

The evaluation of thermal comfort is fundamental for heating, ventilation, and air conditioning system installation and settings, and has become increasingly important in recent years [17]. Regarding heating and cooling systems, studies have been carried out to compare traditional and innovative systems in terms of thermal comfort improvement [112]. Other investigations have been carried out to design better conditioning systems in educational buildings [88]. Through assessing comfort temperatures, it is possible to reduce the need for heating and cooling systems and maximise the energy savings without impairing thermal comfort [113]. Concerning ventilation strategies, their impact on thermal comfort and IAQ was investigated [27]; as well as the effectiveness of different types of ventilation, such as natural, hybrid ventilation, and air conditioning [114]; the acceptance of thermal conditions; and energy use considering different ventilation strategies and exhaust configurations [106]. Thermal comfort was also analysed considering stratum ventilation using a pulsating air supply [115], and in relation to gender differences [116], showing an improved thermal comfort in comparison to a conventional constant air supply. Then, field studies were carried out to compare the conditions found in educational buildings with the criteria in the standards [117]. Since ventilation systems often create a non-uniformity into the environment due to the air distribution, researchers analysed the possibility to improve comfort through managing these non-uniformities, considering thermal preferences [118]. The investigations of the HVAC systems' impact on thermal comfort are very heterogeneous because different types of conditioning systems exist. To provide guidelines for their design and installation, it is necessary to understand their impact on students' wellbeing, while being aware of their individual needs, and not only focusing on energy consumption.

4.5. Indoor Air Quality and Thermal Comfort

Indoor air quality (IAQ) has been often investigated together with thermal comfort, as they are important aspects to ensure health and wellbeing in classrooms. CO_2 concentration was the parameter measured most frequently [68,119] and was compared with the threshold limit values given by standards. In some cases, the CO_2 concentration was found to be below the threshold values given by standards [117,120,121], and, in other cases, no correlation was found between CO_2 concentration and number of people [94]. Instead, in naturally ventilated buildings, CO_2 concentration was found to be very high when windows were closed [122]. No correlation was found in classrooms between CO_2 values and students' feelings of tiredness [59]. From CO_2 concentration decay in classrooms, the air change per hour and the ventilation effectiveness in these spaces were determined [123].

From a comparison between refurbished and non-refurbished buildings, it was seen that the renovated constructions improved thermal comfort, but increased the CO_2 concentration, and therefore reduced indoor air quality [109]. The impact of different ventilation modes on thermal comfort and CO_2 levels was also evaluated [27,69,124], as well as the relation between IAQ and thermal comfort [2]. In some cases, the concentration of other pollutants, such as VOCs, NO_2, and CO was measured and correlated to the outdoor conditions [125–127]. The subjective perception of air quality was correlated to the environmental conditions, which showed that the perceived environmental quality was highly correlated to parameters, such as air temperature and ventilation rates [6]. There is a need to understand the relationship between indoor air quality and thermal comfort perception, and to understand how to improve them without increasing energy consumption.

4.6. Indoor Envrionmental Quality

Indoor environmental quality (IEQ), which includes thermal comfort, air quality, visual, and acoustic quality, can affect students' health, comfort, and productivity. Indeed, research is increasingly focusing on multi-domain approaches to indoor environmental perception and behaviour [128,129], inspecting the various aspects of IEQ on people's comfort and satisfaction [130]. The evaluation of IEQ through objective and subjective measurements has been often carried out, while also considering the psychological and physiological impact on occupants' comfort [4,33], and pupils' performance [131] or symptomatology [132]. Indeed, the perception of the environment includes the four aspects of IEQ and can have an impact on students' health and learning abilities [41,70,131], but also on their wellbeing [6,32]. In some cases, the subjective assessment was performed through questionnaires to evaluate the perception, preferences, and needs regarding IEQ in classrooms [133], but also statistical surveys have been carried out [134]. Thermal comfort was frequently associated with lighting quality, considering different configurations of architectural characteristics [32,110] and the impact on energy consumption [105,108]. Since thermal perception is strongly related to acoustic, visual, and air quality, researchers should not focus on the evaluation of thermal comfort only, but on all the aspects of IEQ.

4.7. Architectural Features and Thermal Comfort

Thermal comfort in buildings is closely related to their architectural features, including dimensions, window-wall ratio, presence of shading systems, building orientation, articulation of classrooms, and the properties of the building envelope [17]. Most researchers considered classrooms as uniform spaces, however, due to solar radiation or to the position of ventilation systems, classrooms are usually non-uniform environments, and therefore thermal discomfort may occur locally. The influence of buildings' envelope on thermal comfort was evaluated [110], considering the effect of different types of insulated roofs (e.g., PCM, composite) on the possibility of overheating of classrooms [135]. In addition, dynamic characteristics of the envelope were evaluated and through the application of films that allow the control of solar radiation [136,137]. In some studies, researchers assessed the improved conditions of a renovation [138] or compared different types of school building constructions (light weight and medium weight) [60]. The relation between classroom characteristics and thermal comfort was also investigated [2,139], including the influence of a façade design to prevent overheating and improve daylight requirements [140], and the use of natural ventilation and ceiling fans to improve comfort [141]. The influence of shading systems and window configuration, including the glass ratio and glass properties, on occupants' comfort and energy demands were also assessed [97,142]. Additionally, studies were performed to allow building designers to choose the best configurations to improve comfort and reduce energy demands [108], in addition to considering the influence of the local climate on the architectural project [107]. Finally, the effect of building design on learning rate and perception was investigated in some works [143,144]. Despite its importance, studies on thermal comfort involving these aspects are not frequent and should be increased to provide guidance to building designers, aimed at improving indoor conditions and reducing consumptions.

4.8. Health and Productivity and Thermal Comfort

In the past, students' productivity has been inspected in regard to air quality [27] through the analysis of their performance in relation to different aspects of schoolwork (numerical or language-based) under different ventilation rates [145], or through providing them diverse tests measuring arithmetic concentration, performance speed, task performance accuracy, and visual memory [124]. Students' learning efficiency was also evaluated in relation to the characteristics of the shading systems [142] and increased classroom temperature [146]. Scholars' performance has been related to all the aspects of indoor environmental quality [41,131,147] and to the thermal environment only [148,149]. The influence of IEQ on health and productivity has been demonstrated as a function of Fanger's PMV and personal factors [25]. Researchers showed that students' health and productivity depend on buildings' features [2,143]. Thermal sensation as well as IEQ have been correlated to health-related issues that can occur as students pass a considerable amount of time in educational buildings [6,42,150]. It must be noted that the assessment of the influence of the thermal environment on health and productivity is not easy, as several variables can influence students' performance and wellbeing. Researchers have tried to determine students' performance through questionnaires, in which they were self-reporting their productivity [41], or through the measurement of speed errors [149]. Furthermore, the effect of the microclimate in classrooms was assessed through the measurement of cardiac autonomic control (ECG) and cognitive performances of the students [151]. This issue remains a very interesting and debated topic, as it still lacks a generally accepted scientific method to assess the influence of the thermal environment on students' health and productivity.

5. Conclusions and Directions for Future Research

The investigation of the current literature showed that researchers focused on different issues, adopting diverse models and indices to investigate thermal comfort in classrooms. However, to provide healthy and human-centred buildings, it is important to focus on students' individual needs and preferences, and not only on single dose-response relationships that have been established for the average adult. It is also clear that the focus should be on preventing negative effects as well as creating positive effects for human health. Indeed, even if the environmental conditions comply with guidelines, in several cases the prolonged stay indoors is not healthy [152]. An integrated approach that considers the positive and negative effects of indoor exposure is therefore needed, including the individual preferences and needs of the occupants [152]. To achieve this integrated approach, several aspects must be accounted for (Figure 9), while considering the individual differences that may be present in relation to the diverse educational stages, climate zone, model adopted, and operation mode.

From this analysis, it was possible to outline the current issues and delineate the directions for future research. However, it is important to note the limitations that the present study may have. The manual grouping of the confounding parameters, which was useful for the direct control of the information contained in the scientific literature, could be combined with statistic methods to test other possible classifications (e.g., country in which the study was carried out, period of investigation, year). Furthermore, the grouping per climate zone may present some limitations, as they include different countries that are characterised by diverse sociocultural backgrounds, and therefore the variability of comfort temperature can be very high. Even the different educational systems might affect the opportunities to adapt and therefore the comfort temperature. These considerations highlight that it is difficult to generalise indications regarding thermal comfort in educational buildings. On the contrary, from this review, it emerged the necessity of studies aiming at meeting the needs of the students, in order to provide human-centred buildings.

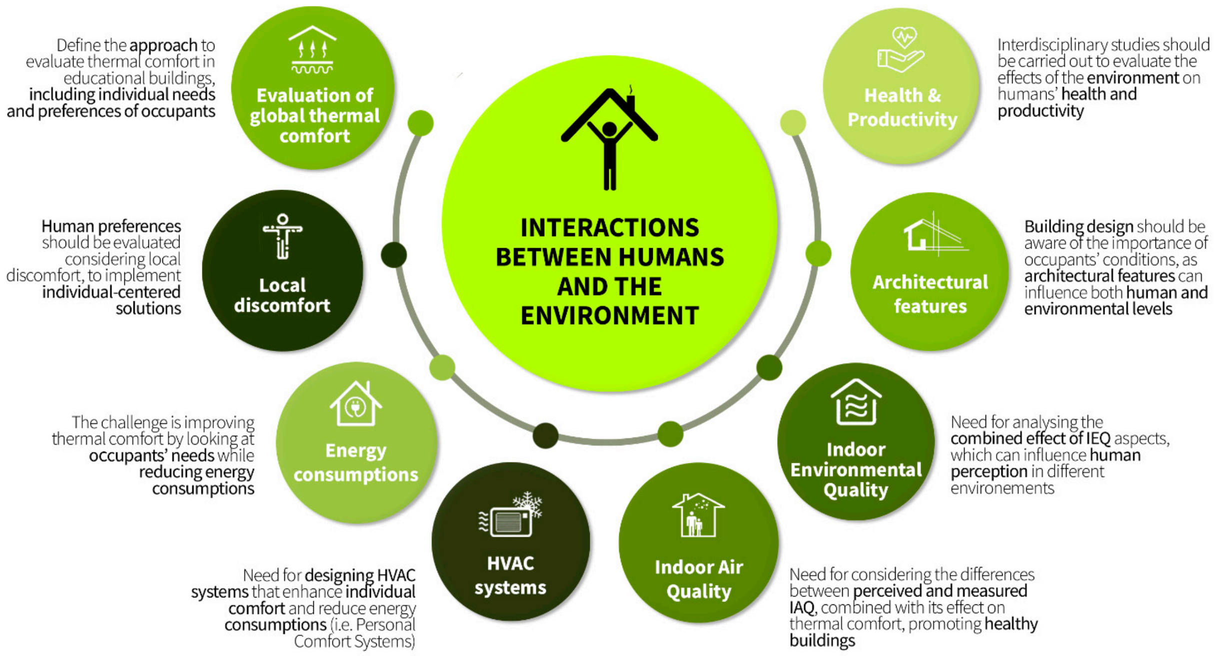


Figure 9. Directions for future research on thermal comfort in educational buildings.

The evaluation of global thermal comfort was carried out using different models and indices, but, in several cases, individual needs were not analysed. Given the variety of indices that have been used for comfort assessment, it is important to define a model for the evaluation of global thermal comfort in classrooms, which should take into account the individual needs and preferences of occupants.

The same concerns are related to local thermal discomfort, even if few studies were carried out on this topic. From this review it can be concluded that local discomfort is an important issue that should be assessed not only to inspect students' satisfaction but also to investigate the reasons for the higher productivity of students located in certain positions in the classrooms, to provide solutions that are more individual-centred.

Regarding energy demands, the literature showed that high consumptions are often connected to the characteristics of the building's envelope and to the improper control of HVAC systems. Students' dissatisfaction was often related to warm sensations during winter and cold sensations in summer, due to the extensive use of HVAC systems [47]. Since thermal comfort is also a function of the ventilation strategy, building designers need to consider the configurations that minimise consumptions and improve occupants' wellbeing. The aim is then to provide comfort in classrooms and reduce energy demands by looking at occupants' needs and preferences [153].

In this direction, HVAC systems can have a great impact on people's comfort and energy consumptions. Studies including different ventilation regimes are necessary. Moreover, in order to inspect people's needs, studies on personal comfort systems (PCS), which operate at the individual level are needed.

However, thermal comfort evaluation should not overlook the interaction with other environmental aspects since they all contribute to the human perception of the environment. The integration of IAQ in thermal comfort studies is necessary and should include objective and subjective measurements, working towards human-centred buildings. There is a need to consider the differences between perceived and measured IAQ, combined with its effect on thermal comfort.

Moreover, future studies should focus on the healing power of indoor environments that involve all the IEQ aspects, including thermal comfort, air, visual, and acoustic qualities. Indeed, people are subjected to a combination of them, and only through the analysis of their combined effect is it possible to understand humans' perception.

This review showed the need for research in order to understand the relation between thermal comfort and architectural features, to improve indoor environmental conditions and wellbeing in classrooms. This is necessary to guide building designers, which should be aware of the importance of occupants' conditions, as architectural features can influence the perception both at human (i.e., influence of personal control on perception) and environmental (i.e., providing uniform/non-uniform environments) levels.

Furthermore, as the indoor environment can affect students' health and productivity, it is fundamental to investigate it not as a single dose-response system only, but include interactions at both human and environmental levels to define a methodology for understanding the impact of the indoor environment on them.

All these issues showed that thermal comfort in educational buildings is still a very debated topic. In this way, there is the need to analyse them, considering their effect on individuals and their interactions with the environment. After the COVID-19 pandemic, the importance of ensuring healthy environments became even more evident, also due to the increasing amount of time that people spend indoors. Indeed, the pandemic period revealed the difficulties in providing sufficient indoor air quality, which should be enhanced without compromising thermal comfort and energy consumptions. There is the necessity to adapt educational buildings to the pandemic and post-pandemic periods, which should be considered together with climate change issues and needs identified before the pandemic.

This review, which critically analyses the studies according to different confounding parameters, highlighted the current issues and defined a way forward in research, represented a contribution in this direction, and will guide researchers and building designers towards a human-centred approach, which is currently lacking.

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Appendix A. Studies on Thermal Comfort in Educational Buildings

In this Appendix, the analysis of the 143 selected studies is reported. Table A1 shows the studies on thermal comfort in educational buildings extracted from the literature, including the relevant information necessary for the analysis:

- Author(s).
- Year of publication.
- Location of the study (country).
- Educational stage, which comprises kindergartens, primary, secondary schools, and universities.
- Climate zone, which is analysed according to the Köppen–Geiger classification (where A: tropical climates; B: dry (arid and semi-arid) hot and cold climates; C: temperate climates; D: continental climates; E: polar and arctic climates).
- Model adopted, which includes rational, adaptive, both (rational + adaptive), and others (where other indices or models were adopted, as described in Section 4).
- Operation mode, which consists of naturally ventilated (NV), air-conditioned (AC), and mixed-mode (MM) buildings.
- Period of the survey, which expresses the season of measurements.
- Reference.

Table A1. Studies on thermal comfort in educational buildings extracted from the literature.

Author(s)	Year	Location	Educational Stage	Climate Zone	Model Adopted	Operation Mode	Time of Survey	References
Auliciems A.	1969	UK	Secondary school	C	Others	AC	Autumn–Spring–Winter	[82]
Auliciems A.	1972	UK	Secondary school	C	Others	AC	Autumn–Spring–Winter	[148]
Auliciems	1973	UK	Secondary school	C	Others	NV	Spring–Summer	[66]
Humphreys	1973	UK	Secondary school	C	Others	NV	Spring–Summer	[62]
Auliciems	1975	Australia	Primary school	C	Others	AC	Autumn–Winter	[19]
Humphreys	1977	UK	Primary school	C	Others	NV	Summer	[154]
Kwok et al.	1998	USA	Secondary school	A	Both	MM	Autumn–Winter	[155]
Kwok et al.	2003	Japan	Secondary school	C	Adaptive	MM	Summer	[87]
Wong et al.	2003	Singapore	Secondary school	A	Rational	NV	Summer	[67]
Krüger et al.	2004	Brazil	University	C	Others	NV	Summer–Winter	[34]
Hu et al.	2006	China	University	C	Others	MM	Summer–Winter	[73]
Hwang et al.	2006	Taiwan	University	C	Rational	MM	Summer	[77]
Corgnati et al.	2007	Italy	University	C	Rational	AC	All seasons	[29]
Wargocki et al.	2007	Denmark	Secondary school	C	Others	NV	Summer	[145]
Wargocki et al.	2007	Denmark	Secondary school	C	Rational	NV	Summer	[146]
Zhang et al.	2007	China	University	C	Rational	NV	Spring	[92]
Cheng et al.	2008	Taiwan	University	C	Rational	MM	Autumn–Spring–Summer	[75]
Theodosiou et al.	2008	Greece	Primary school	C	Others	MM	Autumn–Spring–Winter	[103]
Al-Rashidi et al.	2009	Kuwait	Secondary school	B	Both	AC	-	[63]
Buratti et al.	2009	Italy	University	C	Both	AC	Spring–Winter	[99]
Corgnati et al.	2009	Italy	University	C	Both	NV	Autumn–Spring	[98]
Hwang et al.	2009	Taiwan	Primary + Secondary school	C	Both	NV	Autumn–Winter	[86]
Mumovic et al.	2009	UK	Secondary school	C	Rational	MM	Winter	[31]
Zeiler et al.	2009	Netherlands	Primary school	C	Rational	AC	Spring–Winter	[112]
Yao et al.,	2010	China	University	C	Both	NV	Spring	[24]
Cao et al.	2011	China	University	D	Rational	AC	Summer–Winter	[76]
Jung et al.	2011	South Korea	University	C	Both	MM	Autumn–Spring	[156]
Liu et al.	2011	Japan	University	C	Others	MM	Summer–Winter	[123]
Al-Rashidi et al.	2012	Kuwait	Primary school	B	Others	MM	Spring	[27]
Conceicao et al.	2012	Portugal	Kindergarten	C	Both	MM	Summer–Winter	[49]
De Giuli et al.	2012	Italy	Primary school	C	Adaptive	NV	Spring	[4]
Lee et al.	2012	China	University	C	Rational	AC	-	[70]
Liang et al.	2012	Taiwan	Primary +Secondary school	C	Adaptive	NV	Autumn–Winter	[97]

Table A1. *Cont.*

Author(s)	Year	Location	Educational Stage	Climate Zone	Model Adopted	Operation Mode	Time of Survey	References
Maki et al.	2012	Japan	University	C	Others	AC	Spring–Summer	[104]
Puteh et al.	2012	Malaysia	Secondary school	A	Others	NV	-	[150]
Teli et al.	2012	UK	Primary school	C	Both	NV	Spring–Summer	[53]
Barbhuiya et al.	2013	UK	University	C	Others	AC	Spring–Winter	[95]
Barrett et al.	2013	UK	Primary school	C	Others	MM	All seasons	[151]
D'Ambrosio et al.	2013	Italy	Primary + Secondary	C	Rational	NV	Summer–Winter	[21]
Fabbri et al.	2013	Italy	Kindergarten	C	Rational	-	Autumn	[50]
Pereira et al.	2013	Portugal	Secondary school	C	Rational	MM	Spring–Winter	[157]
Teli et al.	2013	UK	Primary school	C	Others	NV	Spring–Summer	[59]
Wargocki et al.	2013	Denmark	Secondary school	C	Rational	AC	Summer	[149]
Yang et al.	2013	USA	University	C	Others	AC	Winter	[144]
Baruah et al.	2014	India	University	C	Rational	NV	Spring–Winter	[91]
Choi et al.	2014	USA	University	C	Others	AC	-	[41]
De Giuli et al.	2014	Italy	Primary school	C	Both	MM	Spring–Summer–Winter	[33]
Gao et al.	2014	Denmark	Primary school	C	Adaptive	AC	All seasons	[42]
Katafygiotou et al.	2014	Cyprus	Secondary school	C	Others	-	-	[36]
Mishra et al.	2014	India	University	A	Both	NV	Spring–Winter	[72]
Mishra et al.	2014	India	University	A	Both	NV	Spring–Winter	[5]
Pereira et al.	2014	Portugal	Secondary school	C	Rational	NV	Spring	[158]
Serghides et al.	2014	Cyprus	University	C	Rational	AC	Summer–Winter	[105]
Teli et al.	2014	UK	Primary school	C	Both	NV	Summer	[60]
Turunen et al.	2014	Finland	Primary school	D	Others	AC	Spring–Summer	[6]
Wang et al.	2014	China	University	D	Adaptive	AC	Spring–Winter	[23]
Yun et al.	2014	Korea	Kindergarten	D	Both	NV	Spring–Summer	[48]
Almeida et al.	2015	Portugal	Secondary school	C	Others	MM	Spring–Summer–Winter	[68]
Almeida et al.	2015	Portugal	Secondary school	C	Adaptive	MM	Spring	[69]
Barrett et al.	2015	UK	Secondary school	C	Others	MM	All seasons	[147]
De Dear et al.	2015	Australia	Secondary school	C	Both	MM	Summer	[83]
Fong et al.	2015	China	University	C	Rational	AC	-	[106]
Huang et al.	2015	Taiwan	Primary school	C	Adaptive	NV	Autumn–Spring–Summer	[159]
Huang et al.	2015	Taiwan	Primary school	C	Adaptive	MM	Autumn–Spring	[114]
Mishra et al.	2015	India	University	A	Rational	MM	Autumn–Summer	[89]
Nam et al.	2015	Korea	Kindergarten	D	Both	AC	Spring–Summer	[51]

Table A1. *Cont.*

Author(s)	Year	Location	Educational Stage	Climate Zone	Model Adopted	Operation Mode	Time of Survey	References
Nico et al.	2015	Italy	University	C	Both	NV	-	[160]
Almeida et al.	2016	Portugal	Primary + Secondary + University	C	Both	NV	Spring	[101]
Liu et al.	2016	China	Secondary school	B	Rational	NV	Winter	[161]
Vittal et al.	2016	India	University	A	Both	NV	Winter	[90]
Castilla et al.	2017	Spain	University	C	Others	-	-	[139]
Hadad et al.	2017	Iran	Primary school	B	Both	MM	Autumn–Summer–Winter	[55]
Martinez-Molina et al.	2017	Spain	Primary school	C	Rational	MM	Autumn–Winter	[54]
Mishra et al.	2017	Netherlands	University	C	Adaptive	AC	Spring	[94]
Montazami et al.	2017	UK	Primary school	C	Adaptive	NV	Summer	[56]
Montazami et al.	2017	UK	Primary school	C	Adaptive	NV	Summer	[58]
Stazi et al.	2017	Italy	Primary school	C	Adaptive	AC	Spring–Winter	[162]
Teli et al.	2017	UK	Primary school	C	Adaptive	NV	All seasons	[61]
Trebilcock et al.	2017	Chile	Primary school	B	Adaptive	NV	Summer–Winter	[163]
Wang et al.	2017	China	University	D	Both	AC	Autumn–Spring–Winter	[164]
Zaki et al.	2017	Malaysia, Japan	University	A, C	Both	MM	Winter–Spring	[74]
Bajc et al.	2018	Serbia	University	C	Rational	MM	Winter	[25]
Bluyssen et al.	2018	Netherlands	Primary school	C	Others	MM	Spring	[2]
Fang et al.	2018	China	University	C	Both	AC	Autumn–Summer	[26]
Hamzah et al.	2018	Indonesia	Secondary school	A	Rational	NV	Summer	[65]
Kim et al.	2018	Australia	Secondary school	C	Both	MM	Autumn	[37]
Kumar et al.	2018	India	University	A	Both	NV	Spring–Summer	[71]
Singh et al.	2018	India	University	A	Both	NV	Spring–Summer	[38]
Aghniaey et al.	2019	USA	University	C	Both	AC	Summer	[113]
Ali et al.	2019	Jordan	Secondary school	B	Both	NV	-	[102]
Barbic et al.	2019	Italy	University	C	Others	AC	-	[151]
Bluyssen et al.	2019	Netherlands	Primary school	C	Others	MM	Spring	[165]
Branco et al.	2019	Portugal	Primary school	C	Others	MM	All seasons	[125]
Calama-González et al.	2019	Spain	Secondary school	C	Adaptive	NV	All seasons	[110]
Campano et al.	2019	Spain	Secondary school	C	Both	MM	Autumn–Summer–Winter	[166]
Chen et al.	2019	Taiwan	Primary school	C	Others	NV	Summer	[142]
Chen et al.	2019	Taiwan	University	C	Rational	MM	Spring	[167]
Chitaru et al.	2019	Romania	Secondary school	D	Rational	NV	Summer–Winter	[122]

Table A1. *Cont.*

Author(s)	Year	Location	Educational Stage	Climate Zone	Model Adopted	Operation Mode	Time of Survey	References
Colinart et al.	2019	France	Secondary school	C	Others	-	All seasons	[138]
Costa et al.	2019	Brazil	University	A	Others	MM	Summer	[107]
Fabozzi et al.	2019	Italy	University	C	Both	MM	Summer	[168]
Haddad et al.	2019	Iran	Primary school	B	Adaptive	NV	Autumn–Spring–Winter	[169]
Hamzah et al.	2019	Indonesia	University	A	Others	AC	Spring	[88]
Heracleous et al.	2019	Cyprus	University	B	Adaptive	MM	Winter	[170]
Huang et al.	2019	China	University	D	Others	AC	Spring	[171]
Jindal	2019	India	Secondary school	A	Adaptive	NV	All seasons	[96]
Jing et al.	2019	China	University	C	Rational	AC	Winter	[22]
Karyono et al.	2019	Indonesia	University	A	Others	AC	-	[81]
Korateng et al.	2019	Ghana	University	A	Adaptive	NV	Spring–Summer	[172]
Lawrence et al.	2019	UK	University	C	Rational	MM	Summer–Winter	[93]
Li et al.	2019	China	University	C	Others	AC	Summer	[116]
Liu et al.	2019	China	University	B	Rational	NV	Winter	[84]
Liu et al.	2019	China	University	C	Rational	NV	Winter	[173]
Monna et al.	2019	Palestina	Secondary school	C	Others	MM	All seasons	[174]
Ranjbar	2019	Turkey	University	D	Others	MM	Summer–Winter	[124]
Shen et al.	2019	China	University	C	Rational	NV	Summer–Winter	[175]
Shrestha et al.	2019	Nepal	Secondary school	D	Adaptive	NV	Autumn	[120]
Simanic et al.	2019	Sweden	Primary school	D	Others	MM	All seasons	[117]
Tian et al.	2019	China	University	C	Rational	AC	Summer	[115]
Toyinbo et al.	2019	Nigeria	Primary school	A	Others	NV	-	[127]
Vallarades et al.	2019	Taiwan	University	C	Rational	AC	Summer	[111]
Zhang et al.	2019	Netherlands	Primary school	C	Others	-	Spring	[14]
Zhang et al.	2019	Netherlands	Primary school	C	Others	-	Spring	[133]
Al-Khatri et al.	2020	Arabia	Secondary school	B	Both	AC	Summer	[176]
Barbosa et al.	2020	Portugal	Secondary school	C	Others	MM	Spring–Winter	[109]
Boutet et al.	2020	Argentina	Primary + Secondary school	C	Others	-	All seasons	[32]
Campano-Laborda et al.	2020	Spain	Secondary school	C	Others	MM	Spring–Winter	[132]
da Silva Júnior et al.	2020	Brazil	Secondary school	A	Rational	AC	Summer	[177]
Hamzah et al.	2020	Indonesia	Primary school	A	Both	NV	Spring	[178]
Heracleous et al.	2020	Cyprus	Secondary school	B	Adaptive	MM	Summer–Winter	[179]
Jiang et al.	2020	China	Secondary school	B	Both	MM	Winter	[119]

Table A1. *Cont.*

Author(s)	Year	Location	Educational Stage	Climate Zone	Model Adopted	Operation Mode	Time of Survey	References
Jowkar et al.	2020	UK	University	C	Others	MM	-	[78]
Jowkar et al.	2020	UK	University	C	Adaptive	MM	Autumn–Winter	[180]
Jowkar et al.	2020	UK	University	C	Others	AC	Autumn–Spring–Winter	[181]
Korsavi et al.	2020	UK	Primary school	C	Adaptive	MM	All seasons	[182]
Liu et al.	2020	China	University	B	Rational	NV	Autumn–Spring	[183]
Liu et al.	2020	China	University	D	Rational	MM	Autumn–Winter	[100]
Munonye et al.	2020	Nigeria	Primary school	A	Both	NV	Autumn–Spring	[184]
Papadopoulos et.	2020	Greece	University	C	Rational	AC	Winter	[126]
Pistore et al.	2020	Italy	Secondary school	C	Others	-	-	[134]
Talarosha et al.	2020	Indonesia	Primary school	A	Others	NV	Spring	[121]
Wang et al.	2020	China	Secondary school	C	Rational	AC	Summer	[131]
Zhang et al.	2020	China	University	C	Rational	-	-	[118]

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