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Literature survey on how different factors influence human comfort in indoor environments

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ABSTRACT

The present paper shows the results of a literature survey aimed at exploring how the indoor environment in buildings affects human comfort. The survey was made to gather data that can be useful when new concepts of controlling the indoor environment are developed. The following indoor environmental conditions influencing comfort in the built environment were surveyed: thermal, visual and acoustic, as well as air quality. The literature was surveyed to determine which of these conditions were ranked by building users as being the most important determinants of comfort. The survey also examined the extent to which other factors unrelated to the indoor environment, such as individual characteristics of building occupants, building-related factors and outdoor climate including seasonal changes, influence whether the indoor environment is evaluated as comfortable or not. The results suggest that when developing systems for controlling the indoor environment, the type of building and outdoor climate, including season, should be taken into account. Providing occupants with the possibility to control the indoor environment improves thermal and visual comfort as well as satisfaction with the air quality. Thermal comfort is ranked by building occupants to be of greater importance compared with visual and acoustic comfort and good air quality. It also seems to influence to a higher degree the overall satisfaction with indoor environmental quality compared with the impact of other indoor environmental conditions.

1. Introduction

In developed countries people spend more than 90% of their time indoors. Indoor conditions have therefore far-reaching implications for their health, general well-being and performance. Numerous studies have explored how building users perceive the indoor environment and which conditions are considered to be comfortable. In indoor environments, a number of physical and chemical parameters have been identified that influence the comfort of building occupants. Standards dealing with indoor environmental quality have been developed to define the acceptable ranges of these parameters. Even though the requirements of these standards are met, not all building occupants are satisfied with the indoor environment. In addition, the same indoor conditions may lead to different subjective responses. One obvious reason is that people differ and therefore not all are satisfied by the same conditions. Another reason could be that not only physical conditions influence satisfaction with indoor environments. There may also be other factors, unrelated to environmental quality, that influence whether indoor environments are considered to be comfortable or not; these factors are usually not regulated by the standards.

Previous literature reviews examining the issue of comfort of building occupants in indoor environments were focused mostly on the effects of single environmental conditions on humans. For example, reviews were made investigating which conditions lead to satisfaction with the visual environment [1] or with the acoustic environment [2]. Some reviews examined which factors not related to the indoor environment may influence preference for indoor environmental conditions. These reviews again focused on satisfaction with a single environmental condition, e.g. the visual environment [3] or the thermal environment [4,5]. No review has been carried out summarizing the possible influence of different non-environmental factors on whether overall indoor environmental quality, being an interaction of thermal, visual and acoustic conditions as well as indoor air quality, is evaluated as comfortable or not. The present literature survey was performed to gather more information on this matter.

The objective of the present literature survey was to investigate what constitutes comfort for building occupants. This knowledge is

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Table 1
Summary of studies investigating the importance of environmental conditions on overall satisfaction with IEQ.

Study	Place of experiment	Population	Procedure	Data analysis	Results	Concluding remarks
[14]	Climate chambers	Untrained panel of subjects ($n = 48$)	Participants evaluated conditions in the chamber in the context of being exposed to those conditions all day at work; then the analyses were performed to compare the ranges of change of operative temperature, pollution level and noise level, which would correspond to equal change in % dissatisfied	Logistic regression analysis	A 1 °C change in operative temperature was found to correspond to a change of 3.8 dB(A) in sound pressure level or a change of perceived air quality by 7 decipol (measured at 26 °C) (Spearman rank–order correlation coefficient: 0.9)	The relationship was based on an average of 5 assessments made by each subject during their 30-min presence in the chamber. The study did not rank the environmental conditions, but quantitatively compared their impact on dissatisfaction
[15]	Secondary school in Italy, some of the classrooms were acoustically renovated	Students ($n = 852$, RR = 85%)	Participants filled out the questionnaires about their satisfaction with thermal, visual, acoustic conditions, air quality and overall environmental quality with reference to a typical, cold and sunny winter day; the analyses were then performed to find the correlation between each environmental condition with the overall satisfaction with IEQ	Analysis of consistency: Kolmogorov–Smirnov normality test and Mahalanobis and Cook distances; correlation: Pearson coefficient	In the acoustically renovated classrooms the highest correlation was found between the overall satisfaction with IEQ and thermal conditions (Pearson coefficient: 0.50), followed by acoustic conditions (0.39), air quality (0.32) and visual conditions (0.29). In non-renovated classrooms overall satisfaction with IEQ was highly correlated with acoustic conditions (0.50) and much lower correlations were observed with indoor air quality (0.31), thermal (0.28) and visual conditions (0.25)	Relative importance of environmental conditions on overall satisfaction with IEQ was not constant. The environmental conditions were ranked differently depending on acoustical properties of the classrooms. The ranking of conditions did not depend on satisfaction level with a particular condition – the lower level of satisfaction did not cause the condition to be considered more important
[16]	29 office buildings in the USA	Building occupants ($n = 492$, RR unknown)	Participants filled out questionnaires to rate their satisfaction with indoor air quality, thermal, acoustic and visual environment and overall satisfaction with IEQ; the analyses were then performed to find the correlation between satisfaction with each environmental condition and the overall satisfaction with IEQ	Two sample *t*-test; Pearson correlation coefficient	The highest correlation was found between the overall satisfaction with IEQ and satisfaction with air quality (Pearson coefficient: 0.52), followed by satisfaction with thermal (0.51), visual (0.45) and acoustic (0.43) conditions (all p-values <0.000)	The ranking of environmental conditions slightly differed between females and males, and between perimeter and interior zones. Women valued lighting higher than acoustics compared to men, who valued acoustics more than lighting. Those sitting in the interior zone ranked lighting higher than thermal conditions compared with those sitting in the perimeter zone, who ranked thermal conditions higher than lighting. The importance of conditions did not depend on the satisfaction level with a particular condition – the lower level of satisfaction did not cause the condition to be considered more important
[17]	Climate chambers	Untrained panel of subjects ($n = 16$)	Participants evaluated conditions in the chambers in the context of being exposed to these conditions in their daily work; the analyses were then performed to compare the range of changes of operative temperature, perceived air quality and noise level, which would cause equal change in % dissatisfied	Probit analysis and linear regression analysis	A 1 °C change in operative temperature caused the same % dissatisfied as a change in perceived air quality of 2.4 decipol (at 23.1 °C) or a change in sound pressure level of 3.9 dB(A)	The relationships were based on assessment after 1-min exposure in the chamber. The study did not rank the environmental conditions, but quantitatively compared their impact on dissatisfaction
[18]	26 office buildings in 5 European countries	Building occupants ($n = 4655$*, RR unknown)	Participants judged the environment quality using the preference scales (for warmth, air movement, humidity, light and noise), air quality scale and overall environmental satisfaction scale;	Multiple regression analysis	Contribution to overall satisfaction with IEQ was the highest for satisfaction with temperature (coefficient: 0.39) and air quality (0.36), followed by satisfaction	Participants were not asked directly about their satisfaction with environmental conditions, but the level of satisfaction was estimated based on the assessments indicating the extent to which people

(*continued on next page*)

Table 1 (*continued*)

Study	Place of experiment	Population	Procedure	Data analysis	Results	Concluding remarks
			their votes were converted into satisfaction levels to estimate how much satisfaction with individual environmental conditions contributed to overall satisfaction with IEQ		with air movement (0.16), humidity (0.12), noise (0.13) and light (0.05) (R^2 of the model = 0.26)	preferred other conditions compared with the conditions to which they were exposed. It can be one of the reasons that R^2 is so low. Different results were observed in different countries. Thermal conditions and air quality consistently had the highest contribution to overall satisfaction with IEQ while visual conditions had the lowest
[19]	32 typical residential apartments in Hong Kong	Residents of the buildings (n = 125, RR unknown)	Participants judged the satisfaction with air quality, thermal, visual and acoustic environment and overall satisfaction with IEQ using the dichotomous acceptability scales	Multivariate logistic regression analysis	The acceptability of thermal and acoustical conditions was found to contribute most to overall satisfaction with IEQ, followed by acceptability of visual environment. The acceptability of air quality had the lowest contribution (sample correlation coefficient: 0.9999)	If a particular environmental condition was judged to be more unacceptable, it was considered to have higher importance. Most people judged their environment as acceptable and there were only a few votes expressing unacceptability with the environmental conditions
[20]	Typical commercial buildings in Hong Kong	Office workers and visitors (n = 548, RR unknown; the usable sample fulfilling consistency requirements was 22% of all votes of participants)	Participants rated the relative importance of pairs of 4 environmental conditions (thermal comfort, air cleanliness, odour and noise) but it was not stated in relation to which context the votes should be made	Analytical hierarchy process (AHP); only those votes fulfilling the requirement for a consistency ratio of 9% were included in the analysis	Odour was perceived as the most important (AHP weight: 0.42) in contrast to thermal conditions, which were assessed as least important (0.11). Air cleanliness and noise were of comparable importance (0.23)	Perceived importance of environmental conditions depended slightly on the occupants' gender, purpose of stay in the building (worker/visitor) and duration of working in the building. Odour was always ranked as having the highest importance and thermal conditions as having the lowest. Votes provided by 78% of respondents were disregarded in the analyses as they did not fulfil the limit for consistency, suggesting that the majority of people had problems making consistent judgments
[21]	Private and public high-rise residential buildings in Hong Kong	Residents and visitors (n = 563, RR unknown; the usable sample fulfilling consistency requirements was 33% of all participants' votes)	Participants rated the relative importance of pairs of 4 environmental conditions (thermal comfort, air cleanliness, odour and noise) but it was not stated in relation to which context the votes should be made	Analytical hierarchy process (AHP); only those votes fulfilling the requirement for a consistency ratio of 9% were included in the analysis	Thermal comfort was valued the highest (AHP weight: 0.34), and odour the lowest (0.20). Air cleanliness and noise were rated similarly (0.23)	Importance of environmental conditions varied between private and public buildings, purpose of stay in a building (resident/visitor) and duration of living in the building. Thermal environment was always considered to have the highest importance. Votes provided by 67% of respondents were disregarded in the analyses as they did not fulfil the limit for consistency, indicating that the majority of people had problems making consistent judgments
[22]	Typical air-conditioned office buildings in Hong Kong	Building occupants (n = 293, RR unknown)	Participants judged satisfaction with air quality, thermal, visual and acoustic conditions and overall satisfaction with IEQ using the dichotomous acceptability scales; the contribution of satisfaction with single environmental conditions to the overall satisfaction with IEQ was estimated	Multivariate logistic regression analysis and χ^2-test	Satisfaction with the thermal environment was found to be the most important for overall satisfaction with IEQ, followed by satisfaction with air quality, noise and illumination (sample correlation coefficient: 0.99)	If a particular environmental condition was judged to be more unacceptable, it contributed to a larger extent to overall satisfaction with IEQ

* number of interviews or filled out questionnaires; in some buildings occupants responded more than once; RR – response rate.

important when solutions for controlling the indoor environment that maximize the comfort of building users need to be devised. After summarizing briefly how comfort is currently described in the literature, the paper discusses whether all environmental conditions contribute equally to achieving comfort, or whether they are ranked differently by building users. The article also attempts to identify which factors unrelated to the indoor environment influence whether indoor environmental quality is evaluated by building users to be comfortable. These factors include, for instance, individual characteristics of building occupants (occupants' gender, age, country of origin etc.), building-related factors (room interior, type of building and control over the indoor environment), and the outdoor climate (including seasonal changes).

The present paper attempts to examine the following hypotheses:

- hypothesis 1: the evaluation of whether overall indoor environmental quality is comfortable or not depends strongly on the indoor environmental conditions that are ranked by people to have high importance for achieving comfort,
- hypothesis 2: there are factors unrelated to the indoor environment that strongly influence whether indoor environmental quality is assessed as comfortable. This hypothesis is composed of 3 sub-hypotheses, each related to impact of a different group of factors: individual characteristics of building occupants (hypothesis 2.1), building-related factors (hypothesis 2.2) and outdoor climate (hypothesis 2.3).

2. Indoor environmental quality

There follows a short summary of how thermal, visual and acoustic comfort as well as good indoor air quality are currently defined in the literature and the requirements that exist in the standards regarding these parameters. This information provides a background for further discussion in the present paper.

2.1. Thermal comfort

Thermal comfort is "that condition of mind which expresses satisfaction with the thermal environment" [6]. When thermally comfortable, a building user will wish to feel neither warmer nor cooler, if asked about thermal state and preference. The definition applies to the thermal comfort of an individual. In buildings, however, a person usually shares the built environment with other occupants. Standard ISO 7730 [7] provides the indices predicted mean vote (PMV) and predicted percentage dissatisfied (PPD), which make it possible to predict the mean thermal sensation and mean satisfaction with thermal conditions of a group of people. The standard defines the thermal environment as a function of four physical variables (air temperature, mean radiant temperature, relative air velocity and air humidity) and two variables related to people (activity level and clothing). Additionally, requirements for thermal comfort can only be met if no local discomfort exists, i.e. if building users are not disturbed by draught, too high radiant temperature asymmetry, too low or too high internal surface temperatures, or too high vertical air temperature difference. While the above approach to the evaluation of thermal conditions is based on the heat exchange between a human body and the surrounding environment, an adaptive approach has since been proposed [8]. It assumes that people are able to adapt to the thermal environment by means of behavioural adjustments (e.g. by changing the insulation value of their clothing), relaxation of expectations and acclimatization to the conditions to which they are exposed. Building users are then able to feel comfortable in a wider range of conditions than the conditions prescribed by applying the PMV index.

2.2. Visual comfort

Visual comfort is defined as "a subjective condition of visual well-being induced by the visual environment" [9]. Although the definition implies that there is a psychological dimension of comfort, a number of physical properties of the visual environment are defined and used to evaluate its quality in an objective way. Visual conditions are characterized by such parameters as luminance distribution, illuminance and its uniformity, glare, colour of light, colour rendering, flicker rate and amount of daylight [10].

2.3. Acoustic comfort

Navai and Veitch [2] defined acoustic comfort as "a state of contentment with acoustic conditions". However, the term acoustic comfort is not commonly used and providing a good acoustic environment is mainly associated with preventing the occurrence of discomfort (annoyance). The quality of the sound environment is linked to numerous physical parameters, which include both the physical properties of sound itself and the physical properties of a room. Sound is characterized by the sound pressure level in a short-term and long-term period and by sound frequency. The acoustic environment is influenced by such physical room properties as sound insulation, absorption and reverberation time [11].

2.4. Good indoor air quality

The term comfort is not commonly used in relation to indoor air quality and it is mainly linked with the lack of discomfort due to odour and sensory irritation. Acceptable air quality is defined as "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction" [12]. Consequently most of the standards providing the requirements for indoor air quality define the conditions by providing the minimum percentage of persons dissatisfied with air quality. They are mainly based on the discomfort and annoyance caused for visitors to indoor spaces. Recently, some standards also deal with the requirements for occupants.

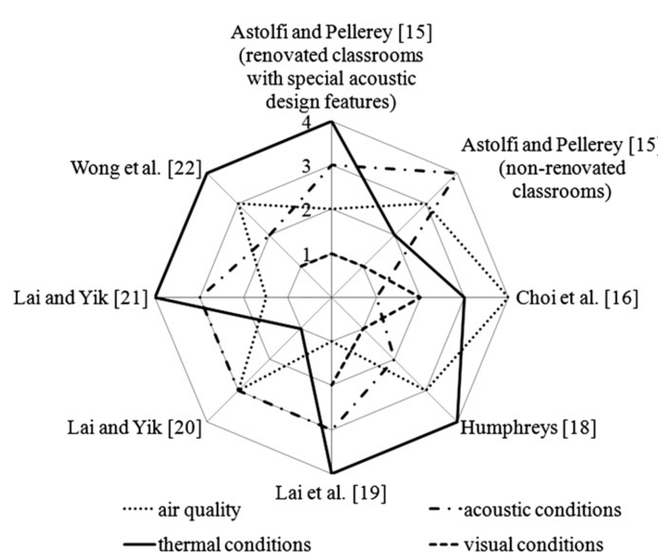

Fig. 1. Ranking of the importance of different environmental conditions for overall satisfaction with IEQ; the higher number indicates higher ranking (importance).

Table 2
Summary of studies examining the effects of individual characteristics of building occupants on satisfaction with IEQ.

Study	Place of experiment	Population	Data analysis	Results	Comments
[23]	11 residential multi-storey buildings	Building occupants ($n = 394^*$, RR unknown)	It was verified that there was no correlation between the personal variables and measured indoor conditions	No statistically significant differences in thermal sensation were observed between residents having different gender, age or length of residence in Israel	Study considered to have strong design
[16]	29 office buildings in USA	Building occupants ($n = 492$, RR unknown)	Two sample *t*-tests to verify that the differences in subjective responses were not caused by exposure to different indoor conditions; Pearson correlation coefficient to find correlation between environmental conditions and overall satisfaction with IEQ	Males expressed significantly higher satisfaction with the thermal environment ($p = 0.001$) and air quality ($p = 0.018$) than females. No differences between genders were found in satisfaction with acoustic ($p = 0.38$), visual ($p = 0.73$) and overall environmental conditions ($p = 0.39$). For both genders air quality and thermal environment were ranked highest. The ranking of acoustic and visual conditions differed slightly between genders. Women ranked visual conditions higher than acoustic conditions, compared to men, who ranked acoustic conditions slightly higher than visual conditions	Study considered to have strong design. It was verified that both genders were exposed to the same conditions
[24]	13 office buildings with lighting systems typical of lighting practice at the time the study was conducted	Building occupants ($n = 912$, RR unknown)	No statistical analysis to verify whether the differences in subjective responses were caused by exposure to different indoor conditions	Older occupants, males, managers or professionals and those with a larger workstation floor area were more satisfied with the lighting than younger occupants, females, those holding secretarial or clerical positions and workers with a smaller workplace area even though the former did not have noticeably higher task illuminance	Study considered to have weak design
[25]	34 air-conditioned office buildings in Australia	Building occupants ($n = 2463^*$, RR unknown)	Correlation of subjective responses to variations in indoor environmental conditions; multiple regression analysis	Gender, age, height and weight, health, pattern of smoking, coffee drinking or exercising, job satisfaction, hours worked per week and self-estimated environmental sensitivity had no significant effect on thermal sensation	Study considered to have strong design
[13]	Climate chamber	Danish college-age students ($n = 128$), elderly Danes ($n = 128$) and data from 720 college-age Americans [26]	Linear regression analysis	No significant differences in thermal comfort responses were found between people of different gender, age, body build or country of origin. Menstrual cycle had no influence on the thermal comfort responses	Study considered to have strong design
[27]	56 buildings in 9 European countries	Building occupants (n and RR unknown)	Correlation of perception of indoor conditions with measured physical conditions; multiple logistic regression analysis	Women and those performing secretarial work reported more adverse environmental perceptions than others. Nationality was a significant factor for the perception of the indoor environment. Individuals who worked many hours at a VDU perceived the air as more stuffy and the surroundings as noisier than the others (all observations: $p < 0.05$)	Study considered to have strong design

[28]	12 mechanically ventilated buildings	Building occupants ($n = 877^*$, RR unknown)	Pearson correlation coefficient	Job satisfaction correlated with satisfaction with air quality, thermal sensation, and acceptability of air movement. Correlation coefficients were very low, but significant ($r < 0.2$; $p < 0.003$). The weekly length of fitness had no significant impact on any evaluations	Study considered to have medium design. It was not checked whether the differences occurred due to variations in the indoor environment
[29]	10 office buildings with displacement ventilation	Building occupants ($n = 227$, RR unknown)	Results tested for statistical significance	Gender, fitness and age did not have a significant effect on the acceptability of the thermal environment ($p > 0.05$)	Study considered to have medium design. It was not verified whether the differences occurred due to variations of the indoor environment
			No statistical analysis to verify whether the differences in subjective responses were caused by different indoor conditions	Satisfaction with job and relationship with superiors and colleagues had a positive correlation with the acceptability of the thermal environment. Office workers subjected to time pressure in their job experienced higher discomfort due to draft than others exposed to similar velocities	Study considered to have weak design
[30]	Air-conditioned office building in Japan	Building occupants ($n = 406^*$, RR unknown)	Correlation of subjective responses with variations of the indoor environmental conditions; weighted linear regression analysis	Significant differences in neutral temperature between Japanese males and non-Japanese males ($p < 0.01$), Japanese females and non-Japanese males ($p < 0.01$), Japanese females and Japanese males ($p < 0.05$); the biggest difference between Japanese females and non-Japanese males	Study considered to have strong design. The data were correlated with mean seasonal operative temperature prior to statistical analysis
[31]	Open-plan office building in USA	Building occupants ($n = 86$, RR unknown)	It was verified that there was no correlation between the personal variables and measured indoor conditions; bivariate correlations between responses describing satisfaction	No significant influence of satisfaction with management, job satisfaction and job stress on satisfaction with lighting. Overall satisfaction with IEQ was correlated with job satisfaction ($r = 0.26$; $p < 0.01$) and satisfaction with management ($r = 0.33$; $p < 0.01$), but not with job stress	Study considered to have strong design
[32]	6 primary schools in Sweden	Teachers and other school employees ($n = 97$, RR = 91%)	Multiple linear regression analysis	Gender and age did not affect the perception of room temperature, air dryness and dustiness of air ($p > 0.05$). Work stress influenced the perception of air dryness ($p < 0.05$) and dustiness ($p < 0.01$) but not perceived room temperature ($p > 0.05$)	Study considered to have medium design. It is not known whether the environmental conditions were uniform
[33]	Climate chamber	Young persons ($n = 108$)	Analysis of variance	Men chose less noisy environments, while women decided to stay closer to thermally neutral (but noisier) conditions compared with men ($p < 0.01$)	Study considered to have strong design. The same experimental procedure was used for males and females
[34]	38 schools in Sweden	Teachers and other school employees ($n = 1303$, RR = 85%)	Multiple logistic regression analysis	The air quality was perceived to be worse by younger school employees and by those dissatisfied with the psychosocial atmosphere at work. No significant differences in subjectively assessed air quality between males and females and those with different smoking habits	Study considered to have medium design. It is not known whether the environmental conditions were uniform

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Table 2 (*continued*)

Study	Place of experiment	Population	Data analysis	Results	Comments
[35]	Office building in U.K. and office building in Pakistan	Building occupants ($n < 32$ in U.K., $n = 15$ in Pakistan, RR unknown)	No statistical analysis to study whether differences in subjective responses are caused by exposure to different indoor conditions	The number of U.K. workers dissatisfied with externally generated noise was higher than the number of Pakistani workers disturbed by externally generated noise, even though the sound level was lower in the U.K.	Study considered to have weak design. Small number of people participated
[36]	13 air-conditioned buildings in Thailand	Building occupants ($n = 1520$, RR unknown)	Linear regression analysis	The neutral temperature of males, workers with higher education and those using air conditioners at home was slightly lower than the neutral temperature of females, workers with lower education and those without air conditioners at home	Study considered to have weak design

* number of interviews or filled out questionnaires; some of the building occupants gave their response more than once; RR – response rate; Studies considered to have strong design are those in which the impact of changes in indoor environmental conditions on the effects of individual characteristics are controlled, and in addition provided testing for statistical significance of the observed effects. The studies considered to have medium design are those which provided only testing for statistical significance of the observed results; all other studies are considered to have weak design.

3. Methods

A literature search was undertaken for articles presenting the results of studies on how thermal, acoustic and visual comfort, as well as indoor air quality, are ranked by building users in connection with overall satisfaction with indoor environmental quality (IEQ) and its impact on human comfort, and whether factors unrelated to indoor environment play a role in this relationship. Throughout the article, comfort is defined as satisfaction with purely IEQ and does not include satisfaction with other aspects of the building such as furniture, colours, etc. The search was limited to the studies that were performed in non-industrial buildings (homes, offices and schools) or in the climate chambers in which environmental conditions resembled non-industrial buildings. Relevant articles were searched electronically in the databases of Science Direct, Compendex and Web of Science, and manually in the proceedings of Indoor Air and Healthy Buildings conferences. Besides the papers found during the literature survey, a “Thermal Comfort” book [13] was included as it comprehensively describes all the aspects related to the effects of the thermal environment on man that are relevant for the current survey. No other books were included.

The literature discussing how thermal, acoustic and visual comfort, as well as indoor air quality, are ranked by building users was searched using keywords that are related to the indoor environment and that describe such terms as contribution, prioritization, ranking and importance. The literature was searched to confirm or reject the following hypotheses: (1) Thermal, acoustic and visual comfort and indoor air quality do not equally contribute to whether overall IEQ is assessed to be comfortable or not; (2) This contribution of thermal, acoustic and visual comfort and air quality can be influenced by individual characteristics of the building users and the conditions in a building; (3) Building users can not make consistent judgment of how important the indoor environmental conditions are for their comfort. More than 10 articles were found that presented information relevant to at least one of the above hypotheses. From among these articles, only nine covering the period from 1993 to 2009 were included in the present survey. These articles discussed the importance of at least three environmental conditions for overall human comfort. The studies that discussed the importance of only two environmental conditions were considered to simply compare rather than rank the conditions; although they provide some valuable information, it was decided not to include them in the present survey.

The literature providing information on factors which are unrelated to the indoor environment but which may influence whether IEQ is comfortable or not was searched using keywords describing occupant perception, subjective response, human/personal factors and building factors. No articles reporting the influence of factors on health (including sick building syndrome (SBS) symptoms) or performance were included, even though they may contribute to comfort. The literature was first screened to identify the potential factors. More than 50 studies were found indicating the following factors: personal characteristics (occupants’ gender, age, country of origin etc.), building-related factors (room interior, type of building and control over the indoor environment) and the outdoor climate (including seasonal changes). For the final analysis, only the data from 33 studies were included in which it was controlled that the differences in whether IEQ was evaluated to be comfortable or not were not actually caused by the variations in indoor environmental conditions. Articles reproducing the same data published elsewhere were excluded. The selected studies cover the period between 1977 and 2009.

Table 3
Summary of studies presented in Table 2 investigating how individual characteristics influence satisfaction with IEQ.

Study	Study design	Influencing factor (on the right) and influenced aspect (below)	Gender	Age	Country of origin	Height and weight	Fitness	Health	Self-estimated environmental sensitivity	Menstruation cycle	Pattern of smoking	Pattern of coffee drinking	Education level	Type of job	Job satisfaction	Relationship with superiors and colleagues	Psychosocial atmosphere at work	Job stress	Time pressure	Hours worked per week
		Impact on thermal conditions																		
[23]	S	Thermal sensation	O	O																
[16]	S	Satisfaction with temperature	+																	
[25]	S	Thermal sensation	O	O		O	O	O	O		O	O			O					O
[13]	S	Thermal comfort	O	O	O	O				O										
[28]	M	Acceptability of thermal environment					O								+					
[29]	M	Acceptability of thermal environment	O	O			O													
[29]	W	Acceptability of thermal environment													+	+			+	
[30]	S	Neutral temperature	+		+															
[32]	M	Perception of temperature	O	O														O		
[36]	W	Neutral temperature	+										+							
		Impact on perception of air quality																		
[16]	S	Satisfaction with air quality	+																	
[32]	M	Perception of air quality	O	O														+		
[34]	M	Subjective air quality	O	+							O						+			
		Impact on visual conditions																		
[16]	S	Satisfaction with visual environment	O																	
[24]	W	Visual satisfaction	+	+										+						
[31]	S	Satisfaction with lighting													O	O		O		
		Impact on acoustic conditions																		
[16]	S	Satisfaction with acoustic environment	O																	
[35]	W	Acoustic dissatisfaction and disturbance			+															
		Impact on other environmental aspects																		
[16]	S	Ranking of conditions	+																	
[27]	S	Adverse perception	+		+									+						
[31]	S	Overall satisfaction with environment													+	+		O		
[33]	S	Preference for conditions	+																	
		Number of O	9	6	1	2	3	1	1	1	2	1			2	1		3		1
		Number of +	8	2	3								1	2	3	2	1	1	1	
		Summary	?	O	+	OO	OO	OO	OO	OO	OO	OO	++	++	?	?	++	O	++	OO

Studies considered to have strong design (S) are those in which the impact of changes in indoor environmental conditions on the effects of individual characteristics are controlled, and in which there was statistical analysis of the results. The studies considered to have medium design (M) are those which provided only testing for statistical significance of the observed results; all other studies are considered to have weak design (W). O: no influence found; +: influence found; in the summary the studies considered to be (1) consistent indicate that all studies show the same result (++ or OO), (2) mostly consistent indicate that 70% of studies show the same result (+ or O), (3) inconsistent as less than 70% of studies show the same result (?).

4. Results

4.1. Hypothesis 1: the importance of different environmental conditions for comfort

Nine studies were examined. Four studies were performed in offices, two in residential buildings and climate chambers, and one in a school building. Their details are given in Table 1.

In two studies the impact of overall IEQ on comfort was modelled, based on the effects of single environmental conditions on comfort [14,17]. This was done to learn about physical conditions of the thermal and acoustic environments and air quality which lead to the same levels of overall satisfaction with IEQ and to estimate how much a change of each condition affects overall comfort. The results show that the change in thermal and acoustic conditions and air quality should be different in order to obtain the same change of the overall satisfaction with IEQ.

The other seven studies explored the importance of environmental conditions only in terms of the subjective evaluations of building users [15,16,18–22]. They examined the importance of indoor environmental conditions for comfort by asking the building users to rank the conditions according to their importance, or to fill out the questionnaires indicating their satisfaction with different environmental conditions or overall satisfaction with IEQ; these responses were used to estimate the contribution of satisfaction with each parameter to overall satisfaction with IEQ. The results of these studies show that thermal comfort was ranked to have slightly higher importance than acoustic comfort and satisfaction with air quality, and considerably higher importance compared with visual comfort (Fig. 1).

Women and men ranked the environmental conditions differently. Ranking depended also on whether the indoor environment was the workplace or home, whether a person was a visitor or occupant, whether a workstation was closer or further from the window, and on the duration of working or living in the building. Ranking was different in different countries, and depended on whether the building was private or public. No general conclusions regarding the influence of the above factors on ranking could, however, be formulated because these impacts were not systematic.

In two studies it was observed that the satisfaction level influenced how the condition was ranked - when people were more dissatisfied with a condition, this condition was considered to have higher importance [19,22]. These results could not, however, be confirmed by the results of two other studies [15,16].

In two studies the majority of people could not consistently rank which indoor environmental conditions are important for comfort [20,21]. In these studies participants chose the condition they perceived as the most important from among the pairs of 4 environmental conditions. Their responses were then analysed to create a final ranking of conditions for each person separately. The analysis showed that the responses of most people were not consistent enough to make the creation of such a ranking possible; these responses were disregarded and are not included in Fig. 1.

4.2. Hypothesis 2.1: impact of individual characteristics of building occupants on satisfaction with IEQ

Table 2 summarizes 15 studies providing information on the impact of individual characteristics of building occupants on thermal, visual and acoustic comfort and satisfaction with air quality and on overall satisfaction with IEQ. These studies were performed mainly in office buildings; two were performed in schools and climate chambers, and one in residential buildings.

The results of these studies presented in Table 3 show that thermal comfort was influenced by the level of education, the relationship with superiors and colleagues and time pressure, but not by gender, age, body build, fitness, health, self-estimated environmental sensitivity, menstruation cycle, pattern of smoking and coffee drinking, job stress or hours worked per week. Perception of air quality was influenced by the psychosocial atmosphere at work and job stress, but not by the pattern of smoking. Visual comfort was affected by occupants' age and type of job, but not by job satisfaction, relationship with superiors and colleagues or job stress. Acoustic comfort was affected by country of origin, but not by occupants' gender.

Table 3 shows also that age, body build, fitness, health, self-estimated environmental sensitivity, menstruation cycle, pattern of smoking and coffee drinking, job stress and hours worked per week had no influence on whether overall IEQ is assessed to be comfortable or not. It shows that country of origin, level of education, type of job, psychosocial atmosphere at work and time pressure do influence overall satisfaction with IEQ. Gender, job satisfaction and relationship with superiors and colleagues in some studies were shown to have an influence and in some studies to have no effect on whether overall IEQ was comfortable or not. The results are slightly different if only studies are selected which can be considered to have a strong design, i.e. in which the potential impact of indoor environmental conditions on the observed results was controlled and in which the results were tested using statistical methods. These studies show that most individual characteristics (occupants' age, body build, fitness, health, self-estimated environmental sensitivity, menstruation cycle, pattern of smoking and coffee drinking, job stress and number of hours worked per week) do not influence overall satisfaction with IEQ.

4.3. Hypothesis 2.2: impact of building-related factors on satisfaction with IEQ

Table 4 summarizes 18 studies examining the impact of building-related factors on human comfort in indoor environments.

Two studies performed in climate chambers examined the effect of room interior on thermal comfort. They found a very slight influence of colour of light on thermal comfort [37] and no effect of room decoration on thermal comfort [38].

The type of building was shown to have an impact on thermal comfort. People felt warmer at home and colder in the office in relation to the sensation predicted by PMV [42]; neutral temperatures were also different in homes and in offices [41]. Thermal sensation and comfort were different in naturally ventilated (NV) and air-conditioned (AC) buildings. In countries with warm climates such as Israel, Thailand, Singapore and the southern part of China, the comfort temperatures and neutral temperatures in warm periods were observed to be higher in NV buildings compared with AC buildings, both in homes and in offices. The difference was about 3 °C in Israel [23] and Thailand [39] and 0.6 °C in China [45]. In Singapore the difference in comfort temperature between NV residential buildings and AC office buildings was 4.3 °C [40]. In dwellings in Israel, residents felt much warmer in AC homes and slightly warmer in NV homes compared with the prediction made with PMV [44]. Opposite findings were observed in U.K., where neutral temperatures in the summer were lower in AC buildings compared with NV buildings [43]. In winter the comfort temperatures and neutral temperatures were higher in heated dwellings compared with non-heated dwellings, by 2 °C [23] and in NV offices compared with AC offices, by 1.4 °C [43]. People in AC buildings were observed to be more sensitive to temperature deviations away from the optimum compared to those staying in NV buildings. The range of acceptable temperatures was wider in NV buildings

Table 4
Summary of studies examining the effect of building-related factors on satisfaction with IEQ.

Study	Place of experiment	Population	Data analysis	Results	Concluding remarks
Room interior					
[37]	Climate chamber	College-age students ($n = 16$)	Analysis of variance	0.4 °C difference in preferred temperature between experiments when extreme blue and extreme red artificial lighting was provided in the chamber ($p < 0.05$)	Colour of light had small influence on thermal conditions which were judged by subjects as comfortable. The difference was so small that it is of no practical significance
[38]	Climate chambers (standard chamber and modified chamber with enriched room decoration)	College students ($n = 48$)	Results tested for statistical significance	Subjects felt significantly warmer when wood panels, pictures on the walls, red carpet and an indirect light were added, and furniture in the chamber was changed compared to thermal sensation in standard chamber ($p < 0.05$). There were no significant differences in thermal comfort	Even though the room decor had an effect on thermal sensation of subjects, the subjects felt equally comfortable in standard chamber and chamber with enriched room decoration. Thermal comfort can not be modified by changing the room decoration
Type of building					
[23]	189 heated and non-heated dwellings and 205 AC and NV dwellings in Israel	Habitants of the dwellings ($n = 394$*, RR unknown)	Results tested for statistical significance	No significant difference in thermal comfort votes between heated and non-heated dwellings in winter even though the operative temperature and the thermal sensation were significantly lower in non-heated dwellings. The estimated comfort temperature was 2 °C higher in heated than in non-heated dwellings. In summer, comfort temperature was 3 °C higher in NV than in AC homes	Even though the thermal sensation of occupants differed in heated and non-heated dwellings, the occupants felt equally comfortable. People who experience a different thermal sensation can feel equally comfortable. The comfort temperature was higher in heated and NV dwellings than in non-heated and AC dwellings
[39]	4 AC and NV office buildings in Thailand	Building occupants ($n = 1146$*, RR unknown)	Linear regression analysis	In warm seasons neutral effective temperature was higher in NV (27.4 °C) than in AC (24.7°) buildings	Occupants in NV buildings accepted higher temperatures than in AC buildings
[8]	160 buildings in 9 countries around the world	Building occupants (n ∼ 21000, RR unknown)	Weighted linear regression analysis	The occupants of centralized HVAC buildings were significantly more sensitive to temperature deviations away from optimum compared to the occupants of NV buildings ($p < 0.001$), in which the range of acceptable operative temperatures was almost twice as great as in buildings with centralized HVAC	Occupants in NV buildings accepted wider temperature ranges than in AC buildings
[40]	NV residential buildings and AC office buildings in Singapore	Building occupants ($n = 818$, RR unknown)	Probit regression technique	In summer neutral operative temperature in NV residential buildings was 28.5 °C and was 4.3 °C higher than in AC office buildings	The neutral temperature was higher in NV than in AC buildings and it was higher in homes than in offices
[41]	NV homes and office buildings in Iran	Building occupants (short-term study at homes: $n = 891$; long-term study in offices: $n = 3819$*, RR unknown)	Linear regression analysis	In summer the neutral temperature was 1.7 °C higher in homes than in offices. In winter the difference was very small (0.4 °C) and the neutral temperature was higher in offices	The study showed that the difference in neutral temperature occurred between home and office environment

(*continued on next page*)

Table 4 (*continued*)

Study	Place of experiment	Population	Data analysis	Results	Concluding remarks
[42]	Office building and homes of the office workers in U.K.	Employees of one institution ($n = 30$, chosen among 39 applicants)	Results tested for statistical significance	People felt warmer in homes and colder in offices in relation to the sensation predicted by PMV ($p < 0.05$)	Thermal sensation differed between home and office environment. It was not explored whether the comfort level was different for the two environments
[43]	4 NV and 4 AC office buildings in U.K.	Building occupants (winter: $n = 6050$*, RR = 63%; summer: $n = 5037$*, RR unknown)	Regression and probit analysis	Neutral temperature was lower in NV offices than in AC offices by 1.4 °C in winter and 2.2 °C in summer. The range of thermal acceptability was wider in NV offices than in AC offices in winter, while it was of a similar size in summer	In winter slightly more occupants in NV offices judged the conditions as acceptable and preferred no change compared with AC offices. In summer more occupants in AC offices perceived the conditions as acceptable compared with occupants in NV offices
[44]	117 AC and NV dwellings in Israel	Habitants of the dwellings (number and RR unknown)	Results tested for statistical significance	In summer residents felt much warmer in AC homes and slightly warmer in NV homes than predicted by PMV. All of the residents in AC dwellings and 92% of occupants of NV dwellings rated their thermal sensation within slightly cool and slightly warm even though the operative temperature in AC homes was significantly lower than in NV homes. More people felt comfortable in AC than in NV dwellings	Occupants in NV dwellings relaxed their expectations regarding their thermal sensation compared to the thermal sensation of occupants in AC dwellings. Most of them still preferred to feel cooler and the comfort level was significantly lower in NV than in AC dwellings
[45]	65 NV and 46 AC dwellings and office buildings in China	Building occupants ($n = 229$, RR unknown)	Linear regression analysis	In summer the neutral temperature was 0.6 °C higher in NV than in AC buildings. The range of acceptable temperature was slightly wider in NV than in AC buildings but the temperature ranges in NV and AC buildings overlapped to a large extent	The difference in neutral temperature between AC and NV buildings was rather small
Control of the indoor environment					
[24]	13 office buildings with lighting systems typical of lighting practice at the time the study was conducted	Building occupants ($n = 912$, RR unknown)	No statistical analysis	The possibility to control the lighting improved satisfaction with lighting quality. Occupants with task lighting expressed generally higher satisfaction than those without any task lighting	Providing occupants with possibility to control the environment improved satisfaction with indoor environment
[28]	12 mechanically ventilated buildings	Building occupants ($n = 877$*, RR unknown)	Pearson correlation coefficient	Providing users with a higher degree of control over their thermal environment improved satisfaction ratings with work area temperature and air quality and overall satisfaction with IEQ (p-value<0.0001)	Providing occupants with the possibility to control the environment improved satisfaction with the indoor environment. The beneficial effect of control on comfort was quite small
[29]	10 office buildings with displacement ventilation	Building occupants ($n = 227$, RR unknown)	Results tested for statistical significance	Possibility to control the environmental conditions had no significant effect on acceptability with the thermal environment	Providing occupants with the possibility to control the environment did not improve satisfaction with the indoor environment

[46]	Test room	Participants ($n = 120$, data from 94 participants analysed, the rest of participant excluded from analysis mainly due to insufficient English language skills)	Multivariate analysis of variance (MANOVA)	There was no significant difference in satisfaction with lighting between participants who could set the lighting at the beginning of the experiment and those who had no influence on lighting conditions and were exposed to the conditions chosen by their experimental partner, even though the perceived degree of control of the participants in the former group was much higher	Providing occupants with possibility to control the environment did not improve satisfaction with the indoor environment
[47]	Test rooms	People working in the building where the test rooms were built ($n = 14$)	No statistical analysis	More people assessed the lighting as confortable when they were offered manual control or a combination of manual and automatic control of the visual environment	Providing occupants with the possibility to partially control the environment improved satisfaction with the indoor environment
[48]	Office buildings in England	Building occupants ($n = 497$, RR unknown)	No statistical analysis	People expressed higher satisfaction when they perceived that they had more control of the environment	The occupants were more satisfied with the environment when they perceived that they had control of environmental conditions
[49]	Building in USA	Building occupants ($n > 1000$*, RR ~ 40%)	Results tested for statistical significance	In winter people with a higher degree of control reported higher satisfaction with temperature, air movement, air quality and sound than those with a lower degree of control ($p < 0.05$)	The occupants were more satisfied with the environment when they perceived that they had control of environmental conditions

* number of interviews or filled out questionnaires; some of the building occupants gave their response more than once; RR – response rate; AC – air-conditioned building; NV – naturally ventilated building.

compared with AC buildings either in all seasons [8] or only in summer [45] or in winter [43]; in one study the size of the acceptable temperature range in summer was actually similar in NV and AC buildings [43].

Five studies performed in office buildings and two studies carried out in a laboratory setting in test rooms examined how control of indoor environmental conditions influence satisfaction with IEQ. Providing people with control led to an increased satisfaction level with thermal, visual and acoustic environment as well as air quality [24,28,47–49] but only in two studies [28,49] was a formal statistical analysis made of the observed results. Two studies showed that access to control did not influence thermal [29] and visual comfort [46].

4.4. Hypothesis 2.3: impact of outdoor climate and season on satisfaction with IEQ

Table 5 summarizes 10 studies examining whether outdoor climate and season influence thermal comfort. No study was found that examined whether they affect satisfaction with other indoor environmental conditions or overall IEQ.

People staying indoors felt warmer in winter than in summer even though the indoor temperature was lower [54]. It was consistently observed that neutral and comfort indoor temperatures increased with increasing outdoor temperatures [8, 52, 53]. Comfort and neutral temperatures were higher in warmer climates compared with temperatures in colder climates [25]. They were higher in summer than in winter [23,41,50]. In three studies there was, however, almost no difference in neutral temperatures between winter and summer [43, 51, 55].

5. Discussion

The present literature survey is a part of a larger research programme on user-driven innovation aiming to develop control solutions for indoor environments that maximize the comfort of building occupants and enhance their quality of life. The present literature survey intended to collect information relevant to this aim. In particular, it was intended to learn whether comfort is predominantly controlled by any of the four environmental conditions related to thermal, visual and acoustic comfort, as well as satisfaction with air quality. It was also intended to find out which factors unrelated to the indoor environment should be taken into account where comfort is concerned. The focus was only on those factors that were considered by the authors to be important when developing innovative solutions for controlling the indoor environment in non-industrial buildings.

The studies surveyed used quantitative models and qualitative assessments to examine the importance of different environmental conditions for overall satisfaction with IEQ. Qualitative assessments provided ranking only of those environmental parameters considered by building users to be important. The quantitative models provided more information because they indicated the extent to which the environmental conditions should be changed in order to create a change in comfort. Further studies examining the quantitative models would be beneficial, as only a few studies have used this approach so far. This information would be useful when overall IEQ in buildings is classified according to satisfaction with the individual indoor environmental conditions, as recommended by standard EN15251 [56]. It would also be quite useful when remedial measures are taken regarding improvement of IEQ, indicating which of the indoor environmental parameters should be tackled first.

The studies surveyed showed that building users consider thermal comfort to be the most important parameter influencing

Table 5
Summary of studies on how outdoor climate and season affect satisfaction with IEQ.

Study	Place of experiment	Population	Data analysis	Results	Comments
[23]	394 dwellings in Israel	Habitants of the dwellings ($n = 394$*, RR unknown)	Linear regression analysis	Comfort temperature was 6.5 °C higher in summer than in winter in the dwellings without cooling and heating. The difference in comfort temperature was smaller (1.5 °C) in the case of dwellings with cooling in summer and heating in winter	Occupants in dwellings without cooling and heating accepted bigger variations of indoor temperature throughout the year than the occupants of dwellings with heating and cooling
[50]	22 AC office buildings in Australia	Building occupants ($n = 1229$*, RR unknown)	Probit analysis	The neutral operative temperature was 3 °C higher in summer than in winter	Building occupants accepted higher indoor temperatures when outdoor temperatures were higher
[8]	160 buildings in 9 countries around the world	Building occupants (n $\sim$ 21000, RR unknown)	Linear regression analysis	An increase in neutral temperature with increasing mean outdoor daily effective temperature was observed ($p = 0.0001$). It was higher for buildings with NV than for buildings with centralized HVAC	Neutral temperature was not the same all around the world. It depended on outdoor climate. The neutral temperature in NV buildings followed closer the changes in outdoor temperature than in buildings with centralized HVAC
[51]	12 AC office buildings in Australia	Building occupants ($n = 1234$*, RR unknown)	Probit analysis	Neutral operative temperature was 0.4 °C higher in wet (warmer) than dry (cooler) season	The difference in neutral temperatures between seasons was very small
[25]	34 AC office buildings in Australia	Building occupants ($n = 2463$*, RR unknown)	Probit analysis	Neutral temperature was higher in buildings in a warmer climate than in a colder climate	The neutral temperature was not the same for different climatic zones
[41]	NV homes and office buildings in Iran	Building occupants (short-term study: $n = 891$; long-term study: $n = 3819$*, RR unknown)	Linear regression analysis	Neutral temperature increased with increasing mean monthly outdoor temperature. The difference in neutral temperature between hot and cool season was 7.6 °C for homes and 5.5 °C for offices	Neutral temperature was not constant throughout the year – it was higher in the warmer than in the cooler season
[52]	34 mostly free-running or heated buildings in Pakistan	Building occupants ($n = 7112$*, RR unknown)	Regression analysis	Comfort temperature increased with increasing (daily and monthly) mean outdoor temperature	Comfort temperature followed the changes in outdoor temperature
[53]	26 office buildings in 5 European countries, both free-running and with heated/cooled mode	Building occupants (number and RR unknown)	Regression analysis	Comfort temperature increased with increasing mean outdoor temperature, to a greater extent in free-running than in heated and cooled buildings	Strong influence of outdoor temperature on comfort temperature
[54]	Homes in U.K.	Building occupants (winter: $n = 515$, RR = 56%; summer: $n = 293$, RR = 71%)	Results tested for statistical significance	Thermal sensation votes of residents were higher in winter than in summer even though the indoor temperature was lower in winter ($p < 0.001$)	Thermal sensation of occupants was influenced not only by the indoor temperature but also because they judged their thermal sensation in relation to the outdoor temperature. Thus they felt warmer in winter than in summer
[43]	8 office buildings in U.K.	Building occupants (winter: $n = 6050$*, RR = 63%; summer: $n = 5037$*, RR unknown)	Regression and probit analysis	In AC buildings the neutral temperature was almost the same in summer and winter, while in NV buildings it was about 1 °C lower in summer than in winter	The difference in neutral temperature between summer and winter in NV buildings was inconsistent with expectations
[55]	16 office buildings in Germany	Building occupants (n$\sim$1300*, RR~80%)	No statistical analysis	The neutral temperature was higher by 0.5 °C in summer than in winter	The differences in neutral temperature between summer and winter were very small

* number of interviews or filled out questionnaires; some of the building occupants gave their response more than once; RR – response rate; AC – air-conditioned building; NV – naturally ventilated building.

overall satisfaction with IEQ. Consequently, when control solutions for the indoor environment are developed, providing thermal comfort should be given the highest priority. Account should also be taken of other factors unrelated to IEQ, such as gender or position of workstation, as they can also affect whether thermal comfort, acoustic comfort, visual comfort or satisfaction with air quality have a dominant impact on satisfaction with IEQ. A general recommendation should be that controlling indoor environmental conditions needs a case-by-case approach and it may be difficult to adopt universal solutions that match all.

Surveyed studies do not provide clear answer to whether the importance of environmental parameters is influenced by their satisfaction level. Two studies implied that as the satisfaction with physical environment changes, the importance of the environmental parameters will change as well. This was not confirmed by two other studies discussing this topic. Too limited data collected through the present survey do not allow careful analysis of this aspect. Future studies should further examine this dynamic character of human response.

Thermal comfort was influenced by building type (homes and offices, NV and AC buildings) and climate including seasonal changes. It was not affected by room decoration or light colour. The occupants of NV buildings had a more forgiving attitude in relation to indoor thermal conditions compared with the occupants of AC buildings. They accepted higher indoor temperatures in summer and lower temperatures in winter, and they also accepted wider temperature ranges. These observations are in line with the adaptive model of thermal comfort proposed by de Dear and Brager [8]. This is another argument indicating that designing the systems for achieving comfort, in this case thermal comfort, requires a case-by-case approach, depending on the building type.

Local outdoor climate should also be considered. Differences in neutral temperature between seasons were observed, suggesting that the temperature indoors should follow the change in outdoor temperature rather than be kept constant for the entire year. The differences between seasons were greater in hot and warm climates than in cold and moderate climates. It should be noted that the differences in neutral temperatures between seasons were observed in areas with warm winters and hot summers, while in areas with cold winters and warm summers almost no differences between seasons were seen. This was probably because outdoor temperatures in the summer were not very high, causing small differences in neutral temperatures between summer and winter. Consequently, these results indicate that the decision as to what extent indoor temperature should follow seasonal change, should be made with due consideration to local climate conditions.

The surveyed literature showed that the neutral temperature depended on the building type (homes and offices, NV and AC buildings), climate and season. The observed differences in neutral temperature can also be partially explained by differences in other environmental parameters which influence neutral temperature (air velocity, clothing insulation, activity level and humidity). The extent to which other parameters may influence the observed differences in neutral temperature is unknown as it was not discussed in the surveyed articles. Lack of consideration of influence of other environmental parameters on neutral temperature causes that the conclusions about the influence of building type and climate on thermal comfort are less firm.

Even though thermal sensation (feeling warm/cold) differed among building users, the results of the studies surveyed showed that at the same time the building users felt equally comfortable. This observation implies that the systems for controlling the thermal environment should take into account thermal satisfaction votes and not only the thermal sensation votes.

Room decoration and colour of light were shown to have no significant effect on the perception of thermal comfort. These studies were performed in climate chambers. But it seems reasonable to assume that the same results would be observed in real buildings.

The studies found in the present survey focused exclusively on the impact of building type, climate and season as well as room interior on thermal comfort. Nothing is known on the potential influence of these factors on visual and acoustic comfort as well as on the satisfaction with air quality. Studies on these aspects are required.

Based on the results of the present survey, it is reasonable to suggest that when the systems for controlling the indoor environment are designed, the possibility of customizing environmental conditions should be offered to building users in order to reflect their preferences. This recommendation is made considering that the results of the studies surveyed were not consistent as regards the impact of individual characteristics of building users on comfort. Some showed that gender, job satisfaction, relationship with superiors and colleagues do influence comfort and some that they do not. Delegating customization of environmental conditions to building users is further supported by the studies showing that providing personal control over the environment to building users has a strong beneficial effect on the satisfaction with IEQ.

It is difficult to judge from the present data which individual characteristics of building users play the most important role for comfort. Many of the studies discussing this issue do not have a proper design and sufficient analysis of results. There are also too few studies on this issue. The available studies examine mainly the impact of gender, age, country of origin, physical fitness and job satisfaction. Further investigations on whether individual characteristics influence satisfaction with IEQ are required with more detailed analysis of the results than in past studies.

The results of the studies surveyed in the present paper seem to be consistent with previous literature reviews. This is particularly true as regards the impact on thermal comfort of outdoor climate and season [5] and of building type [4]. The positive impact of the possibility to control indoor environment vis-à-vis comfort seems also to give a reasonable result. On the other hand, it was surprising to observe that individual characteristics of building users did not influence comfort as expected, especially as regards the impact of gender and age on thermal comfort. In the case of gender, it was expected to find that women preferred a warmer environment, but no such differences in thermal sensation were observed in the studies surveyed. The reason could be the definition of keywords when searching for the studies in the databases, resulting in some omissions. Lack of the effect of age was probably due to the fact that most of the studies surveyed were carried out in offices where different age groups in general were not well represented.

In the present survey, relatively few studies were found that examined the influence of factors unrelated to the indoor environment as regards comfort, compared for example with the number of studies discussing the same issue in relation to SBS symptoms. It is expected that there are many more studies that provide information on this issue. They were not identified in the present survey, probably because this influence was not reported as a main result and therefore could have been omitted when searching the databases and screening the results using abstracts.

6. Conclusions

- Creating a comfortable thermal environment is often considered to be the most important factor for achieving overall satisfaction with IEQ.

- The type of building, outdoor climate and season influence thermal comfort. Compared with air-conditioned buildings, the neutral temperatures are generally higher in naturally ventilated buildings and they increase with outdoor temperature.
- The number of studies identified in the surveyed literature was too few to provide convincing evidence regarding the impact of personal characteristics on comfort implying that further work on this aspect is essential. Even so it is prudent to say that the literature included in the survey suggests that (1) the thermal comfort is influenced by the relationship with superiors and colleagues, level of education of building users, and time pressure, and not influenced by room interior or by colour of light; (2) that the perception of air quality is affected by the psychosocial atmosphere at work and by job stress; (3) that the visual comfort is influenced by age and type of job; and (4) that the acoustic comfort is affected by the country of origin.
- Providing people with the possibility to control the indoor environment improves thermal and visual comfort and overall satisfaction with IEQ as well as satisfaction with indoor air quality.
- Little information is available on modelling how individual environmental conditions related to thermal, acoustic and visual comfort, as well as satisfaction with indoor air quality influence the overall satisfaction with IEQ. This information would be important especially when remedial measures are implemented indoors.
- As a minimum, the solutions for controlling the indoor environment should include control of the thermal environment, the possibility of delegating control to occupants, and adjustments based on outdoor conditions, as well as the possibility of customizing the control. Control solutions may be different in naturally and air-conditioned buildings and should always be made on a case-by-case basis.

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References

[1] Galasiu AD, Veitch JA. Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. Energy Build 2006;38(7):728–42.
[2] Navai M, Veitch JA. Acoustic satisfaction in open-plan offices: review and recommendations. Research Report RR-151. Ottawa, Canada: Institute for Research in Construction, National Research Council Canada. Available at, http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr151/rr151.pdf; 2003.
[3] Veitch JA. Psychological processes influencing lighting quality. J Illum Eng Soc 2001;30(1):124–40.
[4] Brager GS, de Dear RJ. Thermal adaptation in the built environment: a literature review. Energy Build 1998;27(1):83–96.
[5] Nicol JF, Humphreys MA. Adaptive thermal comfort and sustainable thermal standards for buildings. Energy Build 2002;34(6):563–72.
[6] ASHRAE Standard 55-2004. Thermal environmental conditions for human occupancy. Atlanta: American society of heating, refrigerating, and air-conditioning engineers; 2004.
[7] ISO 7730. Moderate thermal environments – determination of the PMV and PPD indices and specification of the conditions for thermal comfort. Geneva: International organization for standardization; 1993.
[8] de Dear R, Brager GS. Developing an adaptive model of thermal comfort and preference. ASHRAE Trans 1998;104(1):145–67.
[9] EN 12665. Light and lighting – basic terms and criteria for specifying lighting requirements. Brussels: European committee for standardization; 2002.
[10] EN 12464-1. Light and lighting - lighting of work places - part 1: indoor work places. Brussels: European committee for standardization; 2002.
[11] Cowan JP. Handbook of environmental acoustics. New York: Van Nostrand Reinhold; 1994.
[12] ASHRAE Standard 62.1. Ventilation for acceptable indoor air quality. Atlanta: American society of heating, refrigerating, and air conditioning engineers; 2007.
[13] Fanger PO. Thermal comfort: analysis and applications in environmental engineering. Copenhagen: Danish Technical Press; 1970.
[14] Alm O, Witterseh T, Clausen G, Toftum J, Fanger PO. The impact of human perception of simultaneous exposure to thermal load, low-frequency ventilation noise and indoor air pollution. Proceedings of the 8th International Conference on Indoor Air Quality and Climate, Edinburgh, Scotland 1999; 5: 270–5.
[15] Astolfi A, Pellerey F. Subjective and objective assessment of acoustical and overall environmental quality in secondary school classrooms. J Acoust Soc Am 2008;123(1):163–73.
[16] Choi JH, Aziz A, Loftness V. Decision support for improving occupant environmental satisfaction in office buildings: The relationship between sub-set of IEQ satisfaction and overall environmental satisfaction. Proceedings of the 9th International Conference Healthy Buildings, Syracuse, NY USA 2009: paper 747.
[17] Clausen G, Carrick L, Fanger PO, Kim SW, Poulsen T, Rindel JH. A comparative study of discomfort caused by indoor air pollution, thermal load and noise. Indoor Air 1993;3(4):255–62.
[18] Humphreys MA. Quantifying occupant comfort: are combined indices of the indoor environment practicable? Build Res Inf 2005;33(4):317–25.
[19] Lai ACK, Mui KW, Wong LT, Law LY. An evaluation model for indoor environmental quality (IEQ) acceptance in residential buildings. Energy Build 2009;41(9):930–6.
[20] Lai JHK, Yik FWH. Perceived importance of the quality of the indoor environment in commercial buildings. Indoor Built Environ 2007;16(4):311–21.
[21] Lai JHK, Yik FWH. Perception of importance and performance of the indoor environmental quality of high-rise residential buildings. Build Environ 2009;44(2):352–60.
[22] Wong LT, Mui KW, Hui PS. A multivariate-logistic model for acceptance of indoor environmental quality (IEQ) in offices. Build Environ 2008;43(1):1–6.
[23] Becker R, Paciuk M. Thermal comfort in residential buildings–Failure to predict by standard model. Build Environ 2009;44(5):948–60.
[24] Collins BL, Fisher W, Gillette G, Marans RW. Second level post-occupancy evaluation analysis. J Illum Eng Soc 1990;19(2):21–44.
[25] Erlandson T, Cena K, De Dear R, Havenith G. Environmental and human factors influencing thermal comfort of office occupants in hot-humid and hot-arid climates. Ergonomics 2003;46(6):616–28.
[26] Nevins RG, Rohles FH, Springer W, Feyerherm AM. A temperature-humidity chart for thermal comfort of seated persons. ASHRAE Trans 1966;72 (1):283–91.
[27] Groes L, Pejtersen J, Valbjørn O. Perceptions and symptoms as a function of indoor environmental factors, personal factors and building characteristics in office buildings. Proceedings of the 7th International Conference on Indoor Air Quality and Climate, Nagoya, Japan 1996; 4: 237–42.
[28] Haghighat F, Donnini G. Impact of psycho-social factors on perception of the indoor air environment studies in 12 office buildings. Build Environ 1999;34 (4):479–503.
[29] Melikov A, Pitchurov G, Naydenov K, Langkilde G. Field study on occupant comfort and the office thermal environment in rooms with displacement ventilation. Indoor Air 2005;15(3):205–14.
[30] Nakano J, Tanabe S, Kimura K. Differences in perception of indoor environment between Japanese and non-Japanese workers. Energy Build 2002;34 (6):615–21.
[31] Newsham G, Brand J, Donnelly C, Veitch J, Aries M, Charles K. Linking indoor environment conditions to job satisfaction: a field study. Build Res Inf 2009;37 (2):129–47.
[32] Norbäck D. Subjective indoor air quality in schools- the influence of high room temperature, carpeting, fleecy wall materials and volatile organic compounds (VOC). Indoor Air 1995;5(4):237–46.
[33] Pellerin N, Candas V. Combined effects of temperature and noise on human discomfort. Physiol Behav 2003;78(1):99–106.
[34] Smedje G, Norbäck D, Edling C. Subjective indoor air quality in schools in relation to exposure. Indoor Air 1997;7(2):143–50.
[35] Wilson M, Nicol JF. Tolerated noise levels in the U.K. and Pakistan and simultaneous thermal comfort. Renew Energy 1994;5(2):1006–8.
[36] Yamtraipat N, Khedari J, Hirunlabh J. Thermal comfort standards for air conditioned buildings in hot and humid Thailand considering additional factors of acclimatization and education level. Sol Energy 2005;78(4):504–17.
[37] Fanger PO, Breum NO, Jerking E. Can colour and noise influence man's thermal comfort? Ergonomics 1977;20(1):11–8.
[38] Rohles FH, Wells WV. The role of environmental antecedents on subsequent thermal comfort. ASHRAE Trans 1977;83(2):21–9.
[39] Busch JF. A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in Thailand. Energy Build 1992;18(3–4): 235–49.
[40] De Dear RJ, Leow KG, Foo SC. Thermal comfort in the humid tropics: field experiments in air conditioned and naturally ventilated buildings in Singapore. Int J Biometeorol 1991;34(4):259–65.
[41] Heidari S, Sharples S. A comparative analysis of short-term and long-term thermal comfort surveys in Iran. Energy Build 2002;34(6):607–14.

[42] Oseland NA. Predicted and reported thermal sensation in climate chambers, offices and homes. Energy Build 1995;23(2):105–15.
[43] Oseland NA. Thermal comfort in naturally ventilated versus air-conditioned offices. Proceedings of the 7th International Conference on Indoor Air Quality and Climate, Nagoya, Japan 1996; 1: 215–20.
[44] Paciuk M, Becker R. Predicted vs. recorded summer thermal responses in air-conditioned and naturally ventilated dwellings in Israel. Proceedings of the 9th International Conference on Indoor Air Quality and Climate, Monterey, USA 2002; 5: 104–9.
[45] Yang W, Zhang G. Thermal comfort in naturally ventilated and air-conditioned buildings in humid subtropical climate zone in China. Int J Biometeorol 2008;52(5):385–98.
[46] Veitch JA, Newsham GR. Exercised control, lighting choices, and energy use: an office simulation experiment. J Environ Psychol 2000;20(3):219–37.
[47] Vine E, Lee ES, Clear R, DiBartolomeo D, Selkowitz S. Office worker response to an automated venetian blind and electric lighting system: a pilot study. Energy Build 1998;28(2):205–18.
[48] Williams RN. Field investigation of thermal comfort, environmental satisfaction and perceived control levels in UK office buildings. Proceedings of the 4th International Conference Healthy Buildings, Milan, Italy 1995: 1181–6.
[49] Zagreus L, Huizenga C, Arens E, Lehrer D. Listening to the occupants: a web-based indoor environmental quality survey. Indoor Air 2004;14(8):65–74.
[50] Cena K, de Dear RJ. Field study of occupant comfort and office thermal environments in a hot, arid climate. ASHRAE Trans 1999;105(2):204–17.
[51] de Dear RJ, Fountain ME. Field experiments on occupant comfort and office thermal environments in a hot-humid climate. ASHRAE Trans 1994;100(2):457–74.
[52] Nicol JF, Raja IA, Allaudin A, Jamy GN. Climatic variations in comfortable temperatures: the Pakistan projects. Energy Build 1999;30(3):261–79.
[53] Nicol F, Humphreys M. Maximum temperatures in European office buildings to avoid heat discomfort. Sol Energy 2007;81(3):295–304.
[54] Oseland NA. A comparison of the predicted and reported thermal sensation vote in homes during winter and summer. Energy Build 1994;21(1):45–54.
[55] Wagner A, Gossauer E, Moosmann C, Gropp T, Leonhart R. Thermal comfort and workplace occupant satisfaction—Results of field studies in German low energy office buildings. Energy Build 2007;39(7):758–69.
[56] EN15251. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Brussels: European committee for standardization; 2007.