Original Paper

Indoor and Built Environment

Indoor Built Environ 2008;0;0:1–14

Accepted: September 20, 2008

Implementation of a Multi-phase Approach for Investigating and Remedying a Thermal Comfort Problem in an Office Building

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Key Words
Thermal comfort problem · HVAC System · Office building

Abstract
This study presents the implementation of a multi-phase investigation and remedial approach aimed at solving a thermal comfort problem in an office building which was the subject of complaint. As part of the first phase to verify existence and extent of the problem, a simple and practical questionnaire survey was developed and utilized to try eliciting the occupants' perception of the thermal comfort quality of the space in question. Additionally, field measurements of space thermal parameters and the Heating, Ventilating and Air-Conditioning (HVAC) system parameters were conducted as part of the preliminary and detailed assessment stages. Analysis of assessment results has lead to the identification of short-term and long-term remedial measures to alleviate thermal comfort problems and improve the quality of thermal comfort in the office space.

Introduction

Thermal comfort, which is defined as "the state of mind that expresses satisfaction with the thermal environment" [1], is influenced by several environmental and personal parameters which determine body heat gains and losses. Air temperature, air humidity, air velocity, and mean radiant temperature (MRT) as well as human clothing and activity levels are factors that determine the heat balance of a human body in a given thermal environment. Several models are available relating the human sensation of comfort to those factors. In one basic form, as referred to by Hutchean and Handegord [2], the human body has been considered as "an inert object exchanging energy with its environment through radiation, convection and conduction and capable of losing heat by evaporation and of adapting to conditions through the body regulatory system." Prediction of thermal comfort has been of substantial interest to ASHRAE which developed the original comfort index based on effective temperature. A more elaborate prediction of thermal comfort at steady state conditions was carried out by Fanger [3,4]. He developed a comprehensive heat balance equation based on the various elements of energy exchange. The equation can be solved to predict comfort at any

Los Angeles, London, New Delhi and Singapore
DOI: 10.1177/1420326X08101531
Accessible online at http://ibe.sagepub.com

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combination of environmental conditions and variables of clothing and metabolic rates.

Charles [5] examined the accuracy of two commonly used thermal comfort models in predicting thermal comfort. The first, Fanger's Predicted Mean Vote (PMV) model, predicts the average thermal sensation of a group of people based on their combined influence on physical and personal parameters. The second, Fanger's Draught Model, predicts the percentage of occupants dissatisfied with local draught from three physical variables (i.e. air temperature, mean air velocity, and turbulence intensity). The PMV model was found to be a better predictor in air-conditioned buildings than in naturally ventilated ones. This is in agreement with the findings of Brager and de Dear [6] who concluded that the predicted neutral temperature in air-conditioned buildings was generally much closer to the actual neutral temperature, as compared to the predicted and actual temperatures in naturally ventilated buildings.

Charles [5] also reviewed other studies which suggest that occupants are more tolerant of a wider range of temperatures in naturally ventilated buildings, as compared to air-conditioned building occupants. Furthermore, at higher air temperatures, draughts might be perceived as pleasant air movement, rather than unwanted discomfort. He also found evidence to suggest that occupants were more tolerant of draughts if they had personal control over air delivery devices.

Pejtersen et al. [7] performed an intervention study in a mechanically ventilated office building in which there had been severe indoor environment complaints from the occupants. A new ventilation strategy was implemented and renovation of the HVAC system was undertaken, on the basis of laboratory experiments on a full-scale mock-up of a cellular office. The severity of occupants' environmental perceptions and symptoms was significantly reduced by the intervention.

Gan [8] demonstrated the importance of mean radiant temperature in relation to thermal comfort and building control for an office room. He concluded that the thermal discomfort due to radiant asymmetry in a room with a large cold or hot surface, such as a window, is influenced by the type and geometrical configuration of the window, and suggested specific measures to reduce its impact.

Richard and Marc [9] investigated the indoor climates and occupant comfort in 12 air-conditioned office buildings in Townsville, Australia. They compared the thermal environmental results with ASHRAE Standard 55-1992 prescriptions. Thermal neutrality, preference and acceptability results were compared with laboratory-based models and standards. They found that most of the thermal dissatisfaction expressed within the Standard 55 comfort zone was associated with requests for higher air velocity.

Newsham and Tiller [10] performed a field study of office thermal comfort using a questionnaire, which was found successful for getting good feedback. As predicted by the ANSI/ASHRAE Standard and the comfort theory, the number of thermal sensation votes indicating thermal acceptability was standard based. However, their results indicated a greater sensitivity to temperatures away from the neutral temperature that theory predicts. They found only 11% variance in the thermal sensation vote for indoor air temperature.

Thermal comfort considerations are usually paramount in most buildings occupied by people. In most modern buildings, mechanical means are utilized to maintain necessary comfort levels. It is likely, however, that thermal comfort problems would appear during the operational life of the building as a result of poor maintenance and operation. When such problems arise, it is essential to take immediate remedial measures to maintain occupants' morale and productivity. If not properly conducted, the process of rectifying thermal comfort problems can be time consuming and costly and may lead to fewer positive outcomes than desirable. Therefore, an approach that is efficient and cost effective is needed to identify and solve thermal comfort problems in office buildings.

The objective of this paper is to present the implementation of a multi-phase approach to investigate and remedy a thermal comfort problem in an office building. Utilizing the general procedure of a multi-phase assessment approach, a reported thermal comfort problem in a ten-story office building located in Dhahran, Saudi Arabia, a hot-humid climate zone, was considered for investigation. In order to obtain a comprehensive and a realistic picture about influencing environmental parameters and space characteristics, the investigation was limited to the floors where complaints were reported. The quality of the thermal comfort and the performance of the HVAC system serving the building were also assessed. Furthermore, specific and effective measures were recommended to alleviate the problem and to improve the thermal environment.

Investigation Methodology

A Multi-Phase Assessment Approach

Developing an investigative and remedial approach for thermal comfort problems requires special considerations aiming at solving such problems as quickly as possible

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with minimum inconvenience to occupants. A multi-phase oriented approach which involves people's participation, gradually commits resources and time and allows for inter-phase identification and implementation of remedial measures is the best approach. Recently, Budaiwi [11] introduced an approach through which thermal-comfort problems could be assessed, identified, and treated in a systematic way without utilizing unnecessary resources or time. Figure 1 shows the essential elements, actions and tools of a multi-phase investigation and a remedial approach for thermal comfort problems. It consists of three stages that is Phase I: Problem Verification and Mapping; Phase II: Preliminary Assessment; and, Phase III: Detailed Assessment.

In Phase I, the existence of the problem is verified and the magnitude of the problem is realized. Limited measurements as well as a review of the history of the building occupants' complaints would be sufficient for verifying the problem. When the problem is limited to a certain location in the building, the problem can be treated as isolated and the investigation of the problem should be focused on the identified location. However, when the problem is widespread, a more comprehensive assessment of space thermal conditions through questionnaire surveys and possibly interviews needs to be conducted to get a clearer description of the extent and seriousness of complaints and possible hints for solutions. Equipped with a good idea about the space thermal conditions, the investigator can move to the second phase (phase II) and conduct a closer assessment of space conditions by carrying out visual inspection and limited measurements of HVAC-space parameters. When the cause of the problem is clear, a quick-fix corrective measure is suggested and implemented. Otherwise, a temporary solution is employed and further investigation is required. A more comprehensive and closer evaluation of space thermal and physical conditions, as well as HVAC parameters is carried out in the third phase (phase III). Detailed assessment and measurement of space thermal comfort parameters, space thermal loads and physical alterations as well as HVAC performance parameters including coil, fan and air distribution parameters are carried out. Because this type of detailed investigation is costly and time consuming, the investigator should always be vigilant about the identification of potential remedial measures as he gradually goes about implementing various elaborate investigative steps. At any stage, when the cause and the remedial measure are identified, corrective measures should be immediately implemented and further investigation may be terminated or slowed down, or otherwise, if further investigation is seen as beneficial. During the implementation of all the above stages, building's occupants should be given great attention both as a valuable source of information about the building's thermal conditions and as tenants of the facility who should feel that they are cared about by responding to their concerns and exposing them to minimum inconvenience.

Implementation of the Investigation Approach

The occupants of a ten-storey office building located in the hot-humid area of Dhahran, Saudi Arabia complained about the thermal environment in their office spaces. The office building was constructed in 1978. Since then it has undergone a number of changes including modification of

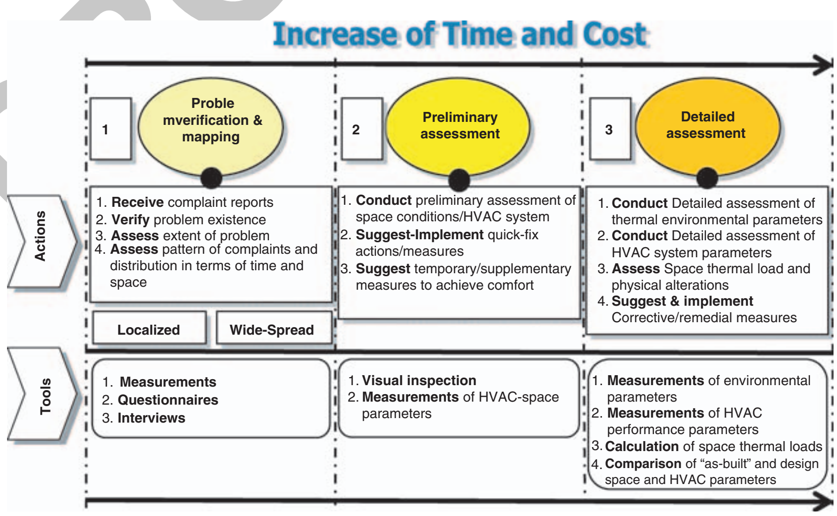

Fig. 1. A block diagram showing the Multi-phase approach, major actions and potential tools for investigating indoor-air quality problems leading to corrective and remedial measures.

its layout and a substantial increase in the number of people and heat generating equipment such as computers and photocopying machines. These changes have influenced the performance of the HVAC system and, therefore, the thermal environment of the office space. In an attempt to improve the thermal environment, certain remedial measures were taken including acidizing the coils and tinting the glass areas on the south facing side of the building. Some improvement in the thermal environment was achieved, yet complaints persisted. The multi-phase assessment approach was then utilized to assess the thermal comfort conditions, identify possible root causes, and suggest remedial measures to alleviate the problem.

Verification and Magnitude of the Problem

Past records of thermal comfort conditions in the office building indicated a repetitive and wide-spread pattern of thermal comfort related complaints on the 4th and 7th floors during the summer period. In an effort to further understand the nature of the problem and assess its extent, as well as the pattern and distribution of complaints in terms of time and space, the simple questionnaire survey illustrated in Appendix A was developed. The survey is not only important for obtaining a better picture about thermal comfort conditions, but also offers hints and remedy measures. Additionally, it offers an opportunity for those who are directly affected to express their feelings and share their experience in the assessment process.

It must be noted that the questionnaire survey is not very comprehensive and does not address the complicated psychological aspects influencing thermal comfort perception. However, the intention of the survey design and its components is to make it simple, practical and easy to implement considering the background of the building occupants. Furthermore, the results of the survey were not used as the sole tool for assessing the prevailing thermal comfort conditions as field measurement results were also utilized to indicate a more accurate and objective assessment of thermal comfort conditions.

In order to conduct a useful survey, it was important to appreciate all factors that influenced human thermal comfort. These factors can be classified as personal factors, which include: level of activity and amount of clothing and environmental factors, which include air temperature, air humidity, mean radiant temperature and air velocity. The questionnaire was prepared to include all parameters that influenced thermal comfort with the convenience of participants in mind to ensure optimal response. The purpose of the questionnaire was to reveal more about the role of these parameters in determining thermal comfort in the space concerned. The questionnaire was distributed to the occupants of the 4th and 7th floors and collected during the month of August. The total number of people targeted for the survey on both floors was 202 persons and the response was generally good, with 40% and 70% from the 4th and 7th floors respectively.

In the analysis of the survey, a person was considered thermally satisfied when his response was comfortable, slightly cool, or slightly warm. When a person is generally satisfied, it means that he is comfortable, slightly warm, or slightly cool most of the time, but he might be uncomfortable at other times. Figures 2(a) and (b) illustrate the thermal conditions on the 4th and 7th floors. About 69% of the 4th floor occupants were thermally satisfied, while approximately 31% were dissatisfied with their thermal environment. On the 7th floor, approximately 37% of occupants were thermally satisfied, while 63% were dissatisfied. Conditions on the 4th floor were judged to be relatively acceptable but with some improvement desirable. On the other hand, conditions on the 7th floor were generally characterized as unacceptable with major improvements required. Therefore, the 7th floor was chosen for further theoretical and experimental investigations.

It is thought that if people are exposed to certain environmental conditions for a long period of time, they become more tolerant, but not necessarily satisfied. Additionally, they will be more reliable in appreciating and evaluating their thermal environment in terms of comfort. Figure 3 shows the percentage of thermally satisfied and dissatisfied people who had been using the space for 10 months or less, and those who spent more than one summer in the same office space. In spite of the relatively small number of people who were new to the building, the general feeling was that conditions were not acceptable to both groups. The great majority of those who spent a longer period of time in the same office were not satisfied and preferred a change. It was a clear and credible claim that needed to be looked at and investigated further.

Effective diagnosis and treatment of thermal comfort problems in buildings require identification of the time period during which complaints are reported. This will isolate the problem within a specific time frame during which complaints are reported, hence allowing potential causes and remedies of the problem to be identified. Figures 4 and 5 illustrate the time periods of the year and summer seasons when generally dissatisfied or satisfied people feel uncomfortable with their environment. Furthermore, Figure 6 shows specifically the time of day during which thermal dissatisfaction occurred for the two groups. The majority of people (88%) were thermally

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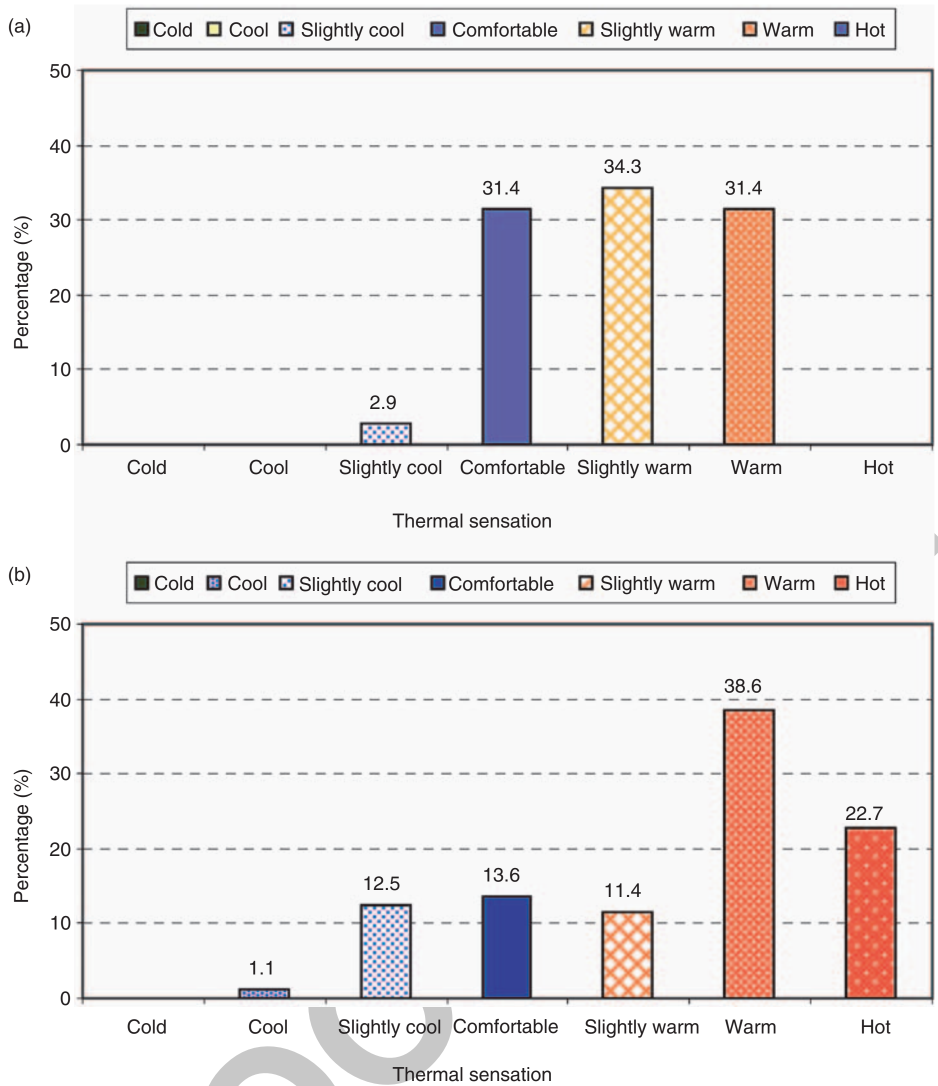

Fig. 2. Thermal comfort conditions on (a) the 4th floor and (b) the 7th floor.

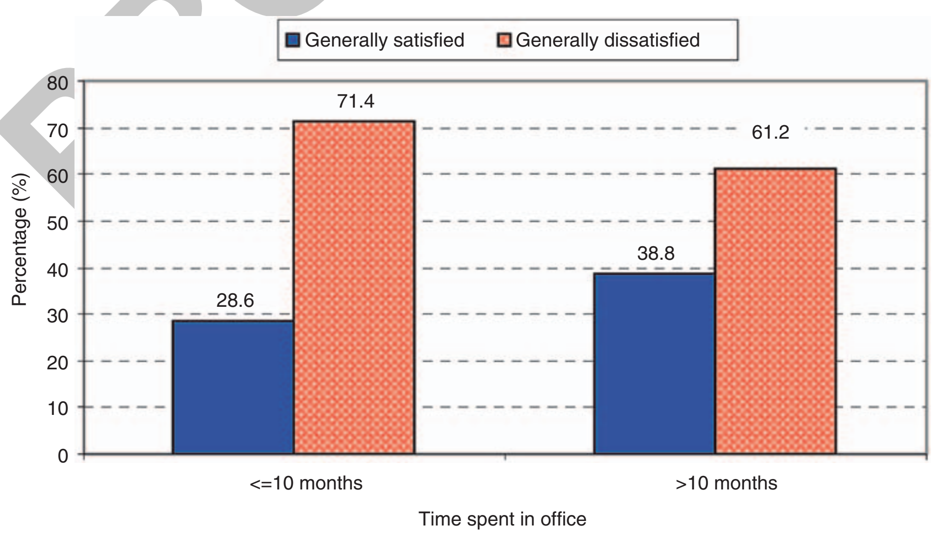

Fig. 3. Effect of time spent in office on status of thermal comfort.

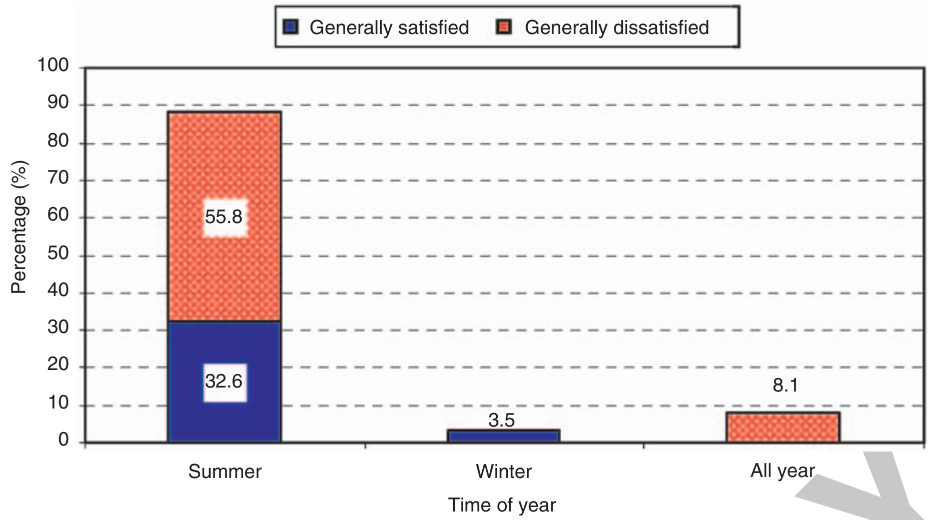

Fig. 4. Variation of thermal dissatisfaction over the year.

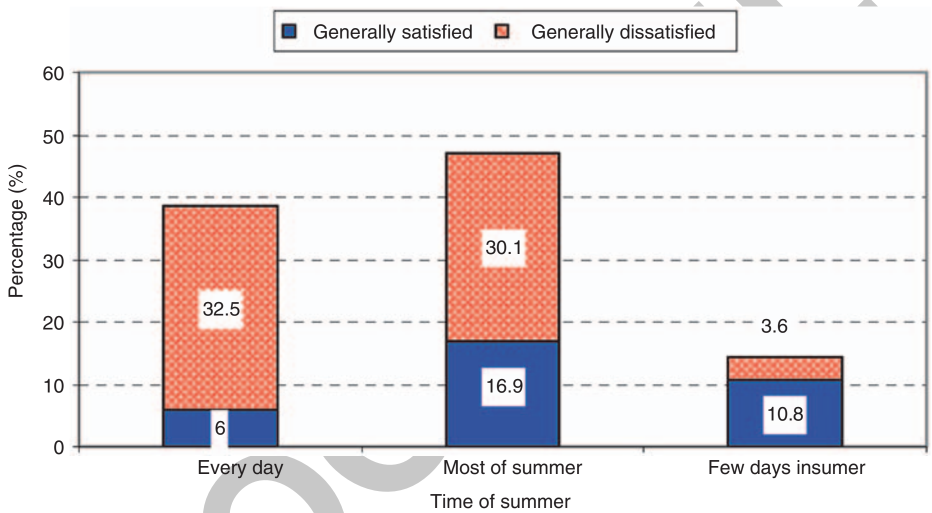

Fig. 5. Extent of thermal dissatisfaction during summer season.

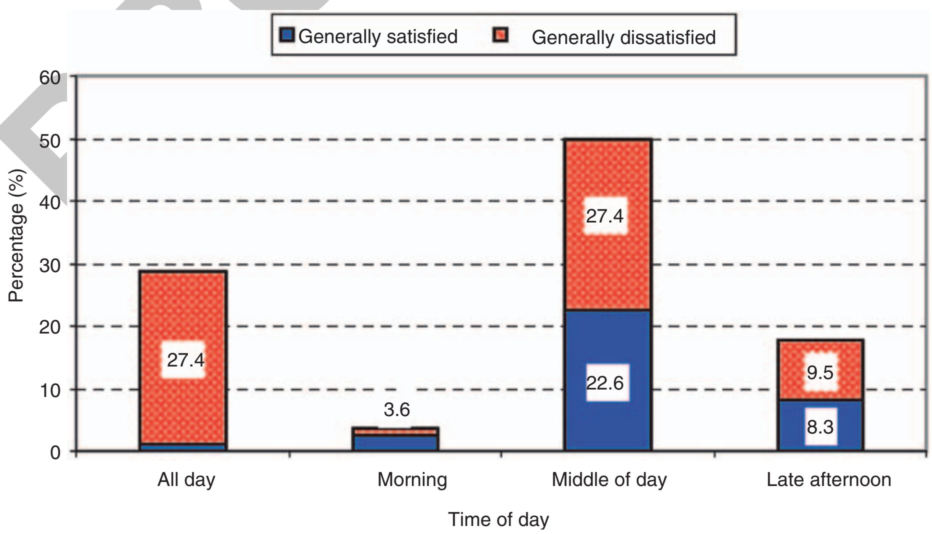

Fig. 6. Prevalence of thermal dissatisfaction during summer days.

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uncomfortable during summer and about 86% of those were uncomfortable every day during summer or most of the summer period. Discomfort was mostly experienced (about 50%) during the middle of the day (i.e. between 10:00 AM and 02:00 PM) while a large percentage (about 29%) experienced uncomfortable conditions all day. This means that about 79% were uncomfortable during the mid-day period. Subsequent, further investigation of the problem should then be carried out in the middle of the day during the summer season.

Office areas are located either in an open space, or a full-height partitioned space, resulting in a unique pattern of air velocity and distribution. Modifications in the space layout of the building can significantly impact the airflow patterns and distribution, hence changing the thermal environment. Figure 7 compares the thermal comfort conditions in closed and open office spaces. Although more occupants in the closed spaces (i.e. percentage wise) experience dissatisfaction, the level of discomfort in both cases is comparable with more than 60% dissatisfaction. This is an indication that the problem is commonly shared by occupants of both types of offices.

The presence of a window to the exterior can be a major source of heat, but at the same time can help enhancing the quality of the indoor environment. Absence of windows can lead to a sense of isolation which can be translated to a form of general dissatisfaction with the indoor environment. Figure 8 shows the relationship between thermal comfort and the absence/presence of windows. The level of dissatisfaction with the thermal environment is high with and without window to the exterior. However, more occupants were dissatisfied with the presence of windows.

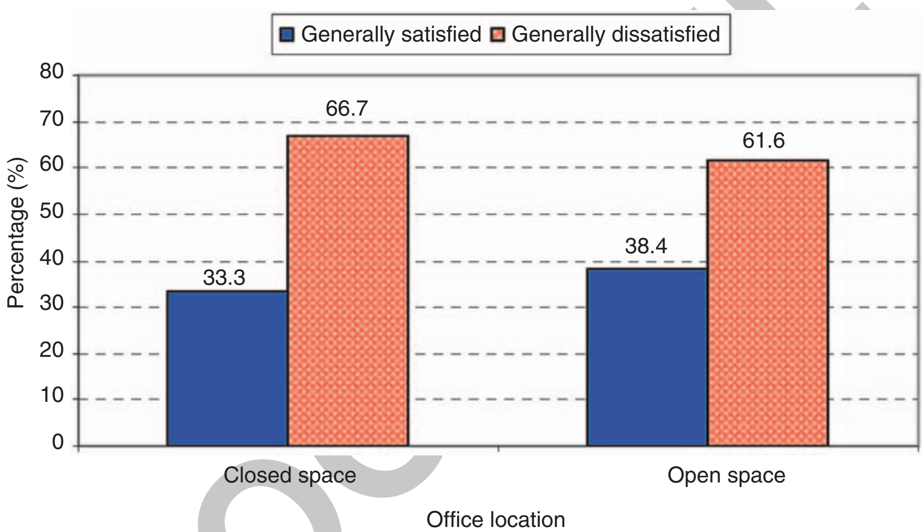

Fig. 7. Effect of office enclosure characteristics on thermal comfort.

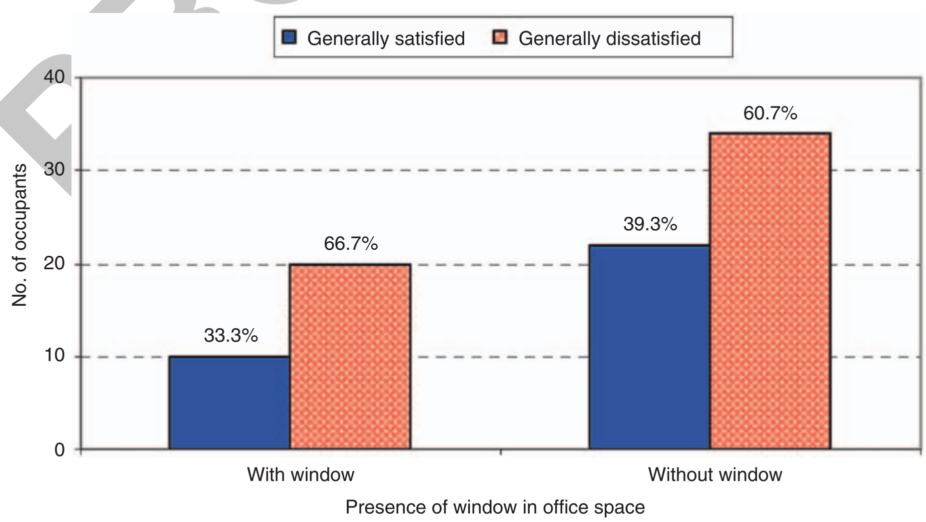

Fig. 8. Level of thermal comfort in the absence and presence of windows.

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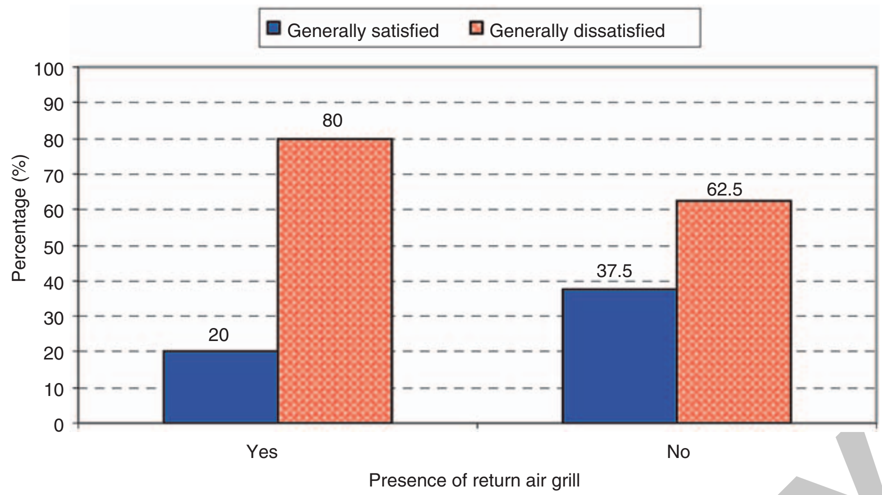

Fig. 9. Thermal comfort conditions in the absence and presence of return air grille in the enclosed office space.

This feeling is expected as windows represent a source of additional heat gain compared to being within an interior space or bounded by solid insulated walls. Generally, it can be said that discomfort conditions are common to both interior offices and perimeter offices with windows.

A return air grille may be arbitrarily located or may not exist in a full height partitioned office space if it was not initially designed to be enclosed. Air distribution and consequently comfort can either be enhanced or negatively affected by the presence of the return air grille depending on its location in the space relative to the supply air diffuser. Figure 9 shows occupants' evaluation of the thermal conditions of the enclosed spaces surveyed in the absence and presence of a return air grille. The general trend of occupants' responses reveals that fewer people are satisfied when there is a return air grille in the space while about twice as many people are thermally satisfied when return air grille is not available. In this case, the door opening will be the only escape route for the air supplied through the ceiling air diffusers. On the other hand, when the return air grille is available close to the supply diffuser, short circuiting of air flow may occur resulting in poor air circulation and distribution. This does not mean however, that not using the return air grille is better, but rather emphasizes the need for proper design and location of the return air grille to insure good air circulation within the space.

Understanding the relationship between the status of thermal comfort and personal and environmental parameters can help in identifying potential temporary measures that can be recommended to improve the thermal conditions when an extended period of time is required to rectify the problem. The clothing and the activity levels are important parameters in determining comfort, hence tangible enhancement of the comfort conditions can be achieved by their adjustment. At the same ambient temperature a person dressed in a business suit can feel thermally uncomfortable while another person wearing lighter clothing can be comfortable. Figure 10 illustrates the relationship between comfort and the level of clothing as obtained from the survey. People with different clothing levels reported similar levels of discomfort. Those with Saudi dress were being associated with a little higher, yet comparable, level at about 63%, compared to those lightly dressed at 60%. The level of discomfort in this case can consequently be judged as having only a moderate dependence on the clothing level.

More internal heat is generated in the human body as activity level increases. It is therefore expected that people at higher activity level need a lower temperature for comfort as more heat needs to be dissipated from the body. Consequently, it is expected that discomfort can be the result of unexpected activity level, higher than that normally assumed for seated people, when designing office buildings. Figure 11 shows the relationship between thermal comfort and the activity level. Results showed that thermal discomfort was not limited to those people who move around, but was also experienced by the majority of seated people as well. It is clear, in this case, that there was no strong association between thermal discomfort and the activity level.

When conditions are not favorable, thermal comfort can be significantly enhanced by increasing air movement within the space. When the HVAC system is not providing enough cooling or the air distribution is poor, a portable fan unit can help in achieving a temporary solution by providing the necessary air movement needed for comfort. Figures 12(a) and (b) show the pattern of fan use among satisfied and dissatisfied occupants and illustrate potential

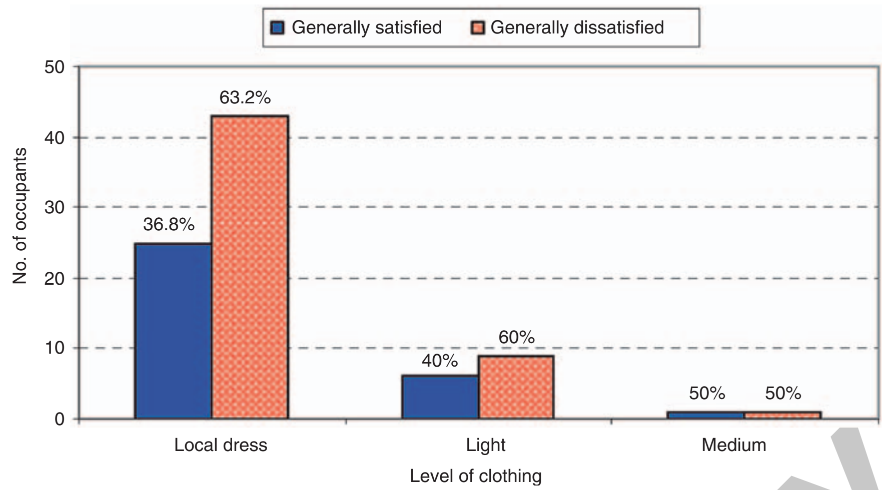

Fig. 10. The status of thermal comfort at different clothing levels.

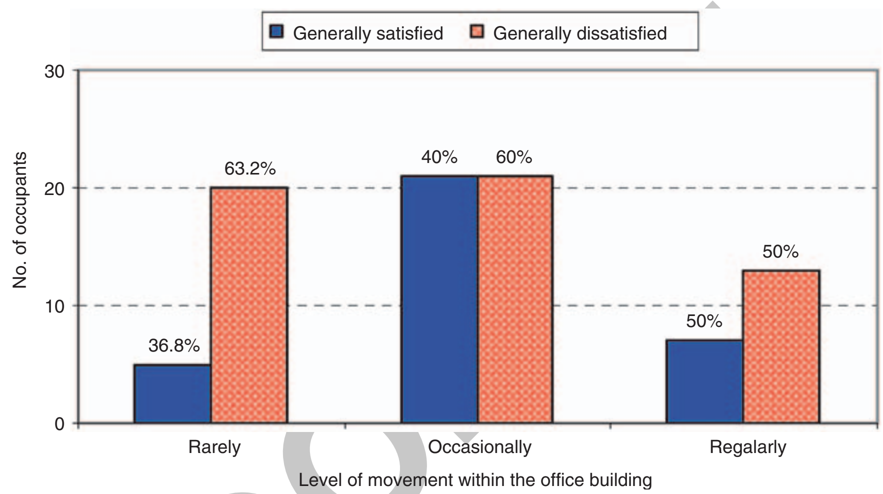

Fig. 11. Impact of activity level on thermal comfort conditions.

improvement when a fan is used. Results reveal that the majority of satisfied occupants (about 54%) did not need to use the fan which is expected behavior. However, the remaining satisfied occupants did use the fan continuously or on an occasional basis. This can be an indication of the occurrence of discomfort periods or a way to improve circulation of stagnant air within the space. Furthermore, it reveals that there was a considerable potential to use the fan since a large percentage of those dissatisfied (about 46%) were not using fans. For those who always used the fan but still felt uncomfortable, it was an indication of either intolerable conditions or improper use of fan. The majority of occupants (53%) who were generally satisfied but uncomfortable during a certain period in summer achieved comfort by using the fan. On the other hand, the vast majority of people who were generally dissatisfied experienced some improvement when using the fan but preferred cooler conditions as shown in Figure 12(b).

The survey conducted has confirmed the existence of the thermal comfort problem and revealed useful information about the status and level of occupant dissatisfaction. Furthermore, the relationship between comfort status and building physical parameters was established which will help in identifying remedial measures.

Preliminary Assessment

The purpose of this step is to inspect visually and conduct limited measurements within the occupied space to quickly identify possible causes of the problem and suggest quick-fix solutions if possible. Blockage of air diffusers or return air grilles, the presence of unusual heat-generating sources in the space, a substantially reduced diffuser airflow, abnormally elevated supply air temperature or increased outside airflow through the exterior envelope are possible causes that can lead to thermal comfort problems. The space was thoroughly inspected

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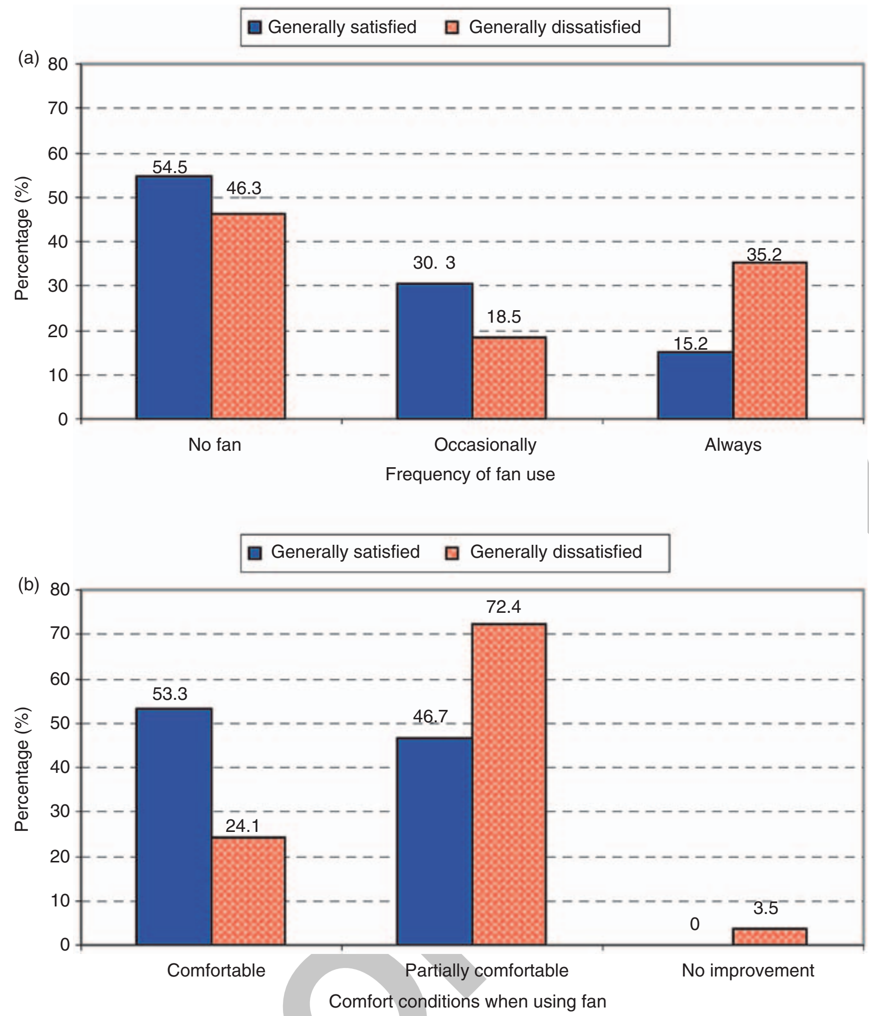

Fig. 12. (a) Frequency of fan use when thermal conditions are not favorable and (b) Level of improvement in thermal comfort when the fan is used for additional cooling.

however, no obvious cause of the problem could be visually identified and nothing seemed abnormal. As a second step, limited measurements of thermal comfort conditions in five different spaces located in the interior and the perimeter zones were conducted using the P&K Thermal Comfort Meter Type 1212. Measurements carried out late August during morning hours revealed that thermal conditions in interior and perimeter offices with north facing windows were acceptable, and those with south and east facing windows were slightly warm. Conditions were expected to be a lot less favorable for both cases during the afternoon period in the summer months. Furthermore, the supply air flow rate and temperature at several selected diffusers in the open space area were measured. The air flow rate ranged from 12.3 to 23.6 $L{\cdot}s^{-1}$ and the average air temperature was measured at 17.2°C. The major variations of airflow rate and the higher than normal supply air temperature are indicative of potential problems in the HVAC system performance and operation. Up to this point, no clear definite cause and remedy for the problem has been identified as further detailed investigations of building and HVAC system performance are necessary. As a temporary solution, the following measures were recommended to improve the thermal environment:

1. Ask those people with east, south or west windows to use venetian blinds most of the time. This will reduce heat gain and the effect of thermal radiation on comfort.
2. Turn off heat-generating equipment when not in use as it represents a major source of heat gain in office spaces.
3. Turn off unnecessary lighting during unoccupied periods. Proper modification to lighting controls may be needed.
4. Advise occupants to wear lighter clothing.

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5. A small portable fan should be issued to the thermally dissatisfied individuals to be used during uncomfortable periods till more detailed investigations and proper actions are carried out.

Detailed Assessment

Prior to conducting further on-site investigations, detailed information about the building's physical characteristics and HVAC system component design and schedules were collected. Subsequently, several site investigations were performed on the space thermal conditions and the components of the HVAC system serving the space. Parameters that affect thermal comfort, which include air temperature, air velocity, relative humidity and operative temperature were measured using the P&K Indoor Climate Analyzer Type 1213, a sling psychrometer, and the P&K Thermal Comfort Meter Type 1212. The air temperature was found to be about 24°C in the interior spaces and ranged from 22.9°C to 25.8°C in perimeter spaces, while the relative humidity was around 50% in all spaces. The operative temperature, which takes into account both convective and radiative heat exchange, was found to be about 1°C higher than ambient air for perimeter spaces and interior spaces with heat generating equipment (e.g. computers). The perimeter spaces are characterized by having better air movement with air velocity around $0.13\,m{\cdot}s^{-1}$ while air in the interior space is relatively stagnant with a velocity around $0.09\,m{\cdot}s^{-1}$.

Comparison of the existing space configurations and the original design revealed major alteration in space layout and separations. Most of the exterior perimeter zones which were originally designed as open space are separated by full-height partitions without any consideration of the impact on air circulation and distribution. Because of these major modifications carried out in office layout and partitioning, there was unbalanced air distribution due to installation of additional air supply lines to feed enclosed spaces at the expense of other air outlets in the interior zones. The additional air supply lines were not properly designed to accommodate the new thermal conditions of the newly created spaces, hence, problems were experienced.

In order to assess the deficiency of the cooling capacity and distribution of the supply air, the thermal load of a selected enclosed office space on the 7th floor where thermal conditions were unacceptable was calculated and compared with the cooling capacity of the supply air delivered to the space. To carry out these calculations, wall and window surface temperatures as well as ambient and supply air temperature were measured at around 9:30 AM on a day in September. In addition, the supply air flow rate for the same space was measured. The impact of solar heat gain was neglected in the calculation since it would not significantly affect the results. The simple space load calculations indicated that air supply should be increased by about 40% in some of the interior spaces. A practical solution requires a combined modification of the flow rate and the temperature of the supply air.

Calculation of the space cooling load (based on design conditions) for the whole south wing floor gave a more comprehensive idea about the required cooling capacity of the system and better quantification of the problem. Based on the collected data on the building, rough calculations of space cooling load due to a number of components were performed. These components included: solar (glass), conduction (wall and glass), infiltration, lighting, people and equipment. Based on the existing physical and operational characteristics of the building, the space cooling load calculations for the south wing of the 7th floor of the building revealed a total space cooling load of 78,534 Watts with the required air supply quantity to be $6552\,L{\cdot}s^{-1}$ based on a supply air temperature of 12°C.

The performance of the AHU on the 7th floor of the office building was assessed by measuring the mixing air temperature, supply air temperature, return air temperature, fresh air temperature, inlet chilled water temperature and outlet chilled water temperature. The first set of measurements was performed in one morning in September. The measured supply air temperature was 15.8°C and the return air temperature ranged from 24.2°C to 25.0°C. The corresponding chilled water temperature entering the coil was 8.1°C and the leaving water temperature was 14.4°C. The temperature of the pre-cooled fresh air was measured at 16.7°C. A second set of measurements was carried out the next day and it was noted that there were noticeable differences from the previous measurements. These differences were thought to be due to a change in weather conditions and in particular to outdoor ambient air humidity. The supply air temperature had increased by 1.0°C and the pre-cooled fresh air temperature was measured at 17.8°C. A total of 2040 GPM was pumped to the building at a temperature of 5.6°C. The return water temperature was at 11.7°C.

Suggested Remedial Measures

Based on the above findings and measurement results, the following recommendations were formulated to remedy the problem. These recommendations were to be

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carried out in a logical and systematic way taking into account the level and urgency of the problem and the time and cost of implementation.

1. Return air temperature in the south wing of the 7th floor of the building was unreasonably low (around 24.0°C) considering the additional load picked up from plenum and lighting. Therefore, air leakage from supply ducts should be checked particularly at joints and newly installed flexible ducts. It is possible that a good portion of conditioned air is leaking to the plenum and does not reach the occupied space.
2. Rough calculations of the required amount of air for the office space show that the design fan capacity ($6372\,L{\cdot}s^{-1}$) is still acceptable provided the air is supplied at 15.0°C. Measured air flow rates at most supply air diffusers in interior spaces are significantly lower than design values. The total air supplied by fan needs to be checked and adjusted to the design value.
3. Because of the major changes that have occurred in space configuration and interior thermal loads, it was necessary to perform detailed calculations of the cooling load for the interior zone and all newly created enclosed spaces. Detailed calculations should be performed to determine the amount of air required for each space as well as the total air requirement, and to check if the available fan capacity is sufficient.
4. The right amount of air should be provided to each space through the proper duct design for the whole floor. Required ducting modifications could be scheduled for a holiday period to avoid interruption to operation of the office spaces.
5. Measured cooling coil outlet air temperature is 1.7–2.2°C higher than the design value (13.9°C). If the actual airflow rate is around the design value, then there are three possible reasons for such deficiency:
6. Decreased cooling coil efficiency. This is evident because the measured temperature rise is around 6.5°C which is 2.0°C less than the design value. This means that a considerable amount of heat is not being removed from the air stream.
7. The amount of chilled water delivered to the coil is less than the design value. Although the actual water flow through the coil was not measured, comparisons between the total chilled water supply to the building (about 2,040 GPM) and the design supply (about 2292 GPM) would indicate a deficiency of 10% in the amount of water supplied to each coil.
8. Chilled water is supplied to the coil at a higher temperature. Measured inlet water temperature is 0.8°C higher (~about 8.0°C) than the design value (7.2°C) in spite of the fact that water leaves the plant at 5.6°C.

To overcome the above problem, it is recommended that steps be taken to measure water flow through each individual coil, compare this with design values and consequently modify if there exists any deviation. When more chilled water is needed an additional chiller can be put into operation to match the original design and the increased load at the coil resulting from higher efficiency. When chilled water temperature rising across the cooling coil is less than 8.0°C at the design air flow rate, the coil needs to be replaced with a more efficient one. Such action can be justified considering the age of the current coil (more than 15 years) and the availability of a more efficient and improved cooling coils at the present time.

Conclusion

A multi-phase approach for investigating and remedying thermal comfort problems in building was employed for a multi-story office building which was a subject of complaint. The suggested approach is solution-oriented which involves occupants' participation and is based on a gradual commitment of resources. As part of this assessment approach, a practical questionnaire survey was conducted to verify and define the extent of the problems. The next step included visual inspection and limited measurement of space thermal parameters and HVAC parameters, which resulted in preliminary identification of causes and recommending quick-fix measures to reduce level discomfort. Further detailed assessment was carried out to identify root causes and recommend radical solutions of the problem. The assessment procedure included detailed measurement of thermal comfort parameters, cooling load calculation and measurement of performance parameters of HVAC system components. Based on the analysis of findings from the different phases of investigation, temporary and major remedial measures including modification of space and HVAC parameters were suggested for improving building thermal comfort conditions considering occupant convenience, time and cost as major factors in the process. The methodology of the proposed multi-phase assessment approach used in this study has been successfully implemented for assessing and suggesting appropriate remedial measures for the problem at hand as described. However, certain adjustments may need to be introduced when applied for solving other specific thermal comfort problems in buildings.

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Acknowledgment

The authors would like to thank King Fahd University of Petroleum and Minerals for the support that made this research possible.

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Appendix A

"Thermal Comfort" Survey Form: Phase I

Part I: General Information			
1. Location:	Building:	Floor No.:	Room No.:
2. Job title:			
3. Period of use for current office space:		Years:	Months:
4. Your office space is:	☐	An enclosedspace withfloor to ceiling partitions	
	☐	Located in an openspace withpartitions less than 2 m (6.5 feet) high	
5. Does your office have a supply air outlet?		☐ **Yes**	
		☐ **No**	
6. Does your office have a return air grille (an opening, normally located in the ceiling, through which air is removed from space)**?**		☐ **Yes**	
		☐ **No**	
7. Does your office have a separate control for the air-conditioning system?		☐ **Yes**	
		☐ **No**	
8. If you have any heat generating equipment in your office, please indicate and mention the number of each equipment.		Equipment	Number
	☐	**Computer**	
	☐	**Printer**	
	☐	**Coffee maker**	
	☐	**Paper shredder**	
________ ←	☐	**Other** (Specify)	

Part II: Thermal Comfort		
1. How do you generally feel during office hours?	☐	**Cold** (intolerable conditions)
	☐	**Cool** (prefer warmer conditions)
	☐	**Slightly cool** (can live with it)
	☐	**Comfortable** (not feeling cool or warm)
	☐	**Slightly warm** (can live with it)
	☐	**Warm** (prefer cooler conditions)
	☐	**Hot** (intolerable conditions)
2. Do you experience any local discomfort in your body due to draft?	☐	**Yes**
	☐	**No**
3. What time of the year you are thermally uncomfortable (feeling warm or cool)?	☐	**All year**
	☐	**Summer**
	☐	**Winter**
4. If you are thermally uncomfortable duringsummer, how often does this occur?	☐	**Every day during summer**
	☐	**Most of the summer period**
	☐	**A few days insummer**
5. What time of the day you are thermally uncomfortable?	☐	**All day**
	☐	**Early morning** (before 10 AM)
	☐	**Middle of the day** (10 AM - 2 PM)
	☐	**Late afternoon** (after 2 PM)
6. Level of clothing normally worn indoors is:	☐	**Typical local dress**
	☐	**Light** (light-weight trousers, short sleeves shirt)
	☐	**Medium** (typical business suit)
________ ←	☐	**Other** (Specify) ________
7. Does your work involve a lot of movement within the building?	☐	**Rarely** (mainly seated)
	☐	**Occasionally**
	☐	**Regularly**
8. Do you have a window in your office space? If yes, please indicate the approximate area and direction (e.g. south, north, etc.)	☐	**No**
	☐	**Yes** — Area (m^2) = ; Direction:
8.a Are windows in your office openable?	☐	**Yes**
	☐	**No**
8.b Do you have controllable shading devices on windows (i.e. curtains, venetian blinds, etc.)	☐	**Yes**
	☐	**No**
9. Do you use a fan for additional cooling when you are uncomfortable?	☐	**No**
	☐	**Occasionally**
	☐	**Always**
10. If you use a fan in your office, how do you feel when it is on?	☐	**Comfortable**
	☐	**Partially satisfied** (e.g. some improvement but still feeling warm)
	☐	**No improvement**

11. Please add below any comments or concerns about your office environment.

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