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Thermal comfort in chilled ceiling and displacement ventilation environments: vertical radiant temperature asymmetry effects

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Abstract

The paper presents some of the findings from a broader investigation aimed at determining thermal comfort design conditions for combined chilled ceiling/displacement ventilation environments. A typical chilled ceiling/displacement ventilation office has been created within a laboratory test room, in which the ceiling temperature can be varied over a range of typical operating values; the thermal comfort of eight female test subjects was then measured in the test room over the range of ceiling temperatures. Vertical radiant temperature asymmetry was found to have an insignificant effect on the overall thermal comfort of the seated occupants for the typical range of ceiling temperatures that would be encountered in practice in such combination environments. There was a slight trend for the reported sensation of 'freshness' to increase as ceiling temperature was reduced though this requires further study. It is concluded that existing guidance regarding toleration of radiant asymmetry is valid for thermal comfort design of chilled ceiling/displacement ventilation environments. © 1998 Elsevier Science S.A.

Keywords: Chilled ceiling; Displacement ventilation; Radiant asymmetry

1. Introduction

Energy consumption in buildings is responsible for about 50% of the United Kingdom's total carbon dioxide emissions, with a similar situation prevailing in other industrialised countries. In many industrial and commercial buildings, the provision of comfortable space conditions has often been achieved through the use of air-conditioning, widely recognised as being an energy-intensive solution. Interest has therefore been kindled into the adoption of low energy techniques for the conditioning of office environments. One such technique is that of displacement ventilation. This has arrived in the UK from mainland Europe, and consists of the provision of a full fresh air supply to a space at low level, low velocity and at a temperature lower than that of the desired zone air temperature. Density differences cause the fresh air to form a layer over the floor; the air then rises as it is warmed by heat sources in the zone, and the convective plumes generated by these sources remove heat and contaminants which are extracted at ceiling level. The system is able to provide an environment of improved air quality as compared with the mixing of air which occurs in conventional heating, ventilating and air conditioning (HVAC) systems (for the same air flow rate conditions); also, the same heat loads can be removed for a supply air temperature of typically 19°C as compared with one of 13°C in HVAC systems, thereby saving energy. As a result of thermal comfort limitations, namely that the vertical air temperature gradient should be less than 3°C per metre (BS EN ISO 7730, 1995), a displacement ventilation system is limited to removing a convective load of up to 25 Wm^{-2} of floor area (Sandberg and Blomquist, 1989). However, the heating loads encountered in many offices are frequently greater than this figure, and so it becomes necessary to install an additional cooling mechanism, such as a chilled ceiling.

In a chilled ceiling system, cold water flows through pipework which is bonded to ceiling tiles, producing a typical ceiling tile surface temperature in the range 16–19°C. Chilled ceilings can remove heat loads of up to 100 Wm^{-2} of floor area mainly by radiation, and are considered to enhance the thermal comfort sensation of occupants in a manner analo-

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gous to being outdoors and beneath the open sky. When combined with displacement ventilation, the advantages offered by each system separately (improved air quality, enhanced thermal comfort) are claimed to be retained for the combined arrangement, but is this actually the case?

A 3-year research project, funded by the UK Engineering and Physical Sciences Research Council (EPSRC), has been set up to answer this question. The aim of the research is to determine the design conditions necessary for occupant thermal comfort in such combination environments. Part of the study involved the investigation of the effects of vertical radiant asymmetry on the thermal comfort of sedentary occupants. Work conducted by Fanger et al. (1985) has shown that vertical radiant asymmetries of up to 14°C could be tolerated without adversely affecting comfort; however, it is necessary to determine whether this finding remains valid within the relatively more sophisticated environment of a chilled ceiling/displacement ventilation system. This was investigated experimentally and the results are reported here.

2. Method

2.1. The test environment

A test room was set up to represent an office environment, comprising a chilled ceiling and a displacement ventilation system. The room can be considered as 'light weight' in terms of its thermal response, and is cuboidal in shape, being 5.4 m long, 3 m wide and 2.8 m high. Its four walls were clad with Frenger panels, offering control of wall surface temperatures, while the chilled ceiling and displacement ventilation system were comprised of commercially available units. The chilled ceiling has a 90% active area, consisting of six individual circuits connected in parallel; each circuit, in turn, is comprised of four or five chilled panels connected in series, and the area of each circuit is approximately 2.5 m^2. The circuits could be activated either individually or collectively. Displacement ventilation was provided by a semi-cylindrical wall-mounted diffuser fitted at one end of the room; this supplied the room with 100% fresh air, which could be tempered and humidified, as required, prior to entry into the test environment.

The room was equipped with a window to overlook the external environment, so as to preserve the impression of a normal office. However, the window consisted of seven layers of glass, providing insulation from the external environment, and thus minimising temperature differences between wall and glass surfaces; this temperature difference was further minimised by extending the Frenger water flow network to include the window itself, with piping disguised as framework. Direct solar gain to the room was eliminated by a fitted blind.

The following environmental parameters within the room were controllable; supply air flow rate, supply air temperature, relative humidity, mean radiant temperature and the surface temperature of the chilled ceiling.

The test room was carpeted and furnished to a normal office standard. Four thermal dummies (to represent human heat sources) were placed in the room prior to the commencement of a test to ensure that conditions of thermal equilibrium were reached and that air flow patterns typical for chilled ceiling/displacement ventilation environments were established.

All surface temperatures in the room were measured to a resolution of ± 0.2°C using Type T copper/constantan thermocouples, and the vertical air temperature profile in the centre of the room was recorded using eight radiation-shielded thermocouples (Type T) mounted on a column. Plane radiant temperatures in six directions, and the mean air velocity, were measured at three heights (0.1 m, 0.6 m, and 1.1 m) above the floor using a Bruel and Kjaer Type 1213 Indoor Climate Analyser. All environmental parameters were logged every 5 s and average values were calculated every 5 min.

2.2. Experimental design

The purpose of the experiment was to determine the effect of ceiling temperatures on the vertical radiant temperature asymmetry within a chilled ceiling/displacement ventilation office environment and its effect on the thermal comfort of sedentary office workers. Four ceiling temperatures were selected for investigation: 22, 18, 14 and 12.5°C, exceeding the range of chilled ceiling temperatures that would be encountered in practice. The supply air mass flow rate of the displacement ventilation system was set at 3 air changes/h (ach) and a temperature of 19°C (typical design conditions) for all four ceiling temperatures. Eight female subjects took part in the study; female subjects were chosen because, from our earlier series of investigations, it was found that the female subjects were more thermally sensitive to their environment than were the male subjects in this study. Each subject was tested individually, being exposed to all four test conditions in series; each undertook a repeated measures experiment in which she carried out office work while seated within the experimental office. Throughout each experiment, and for each test condition, the environment was maintained at thermally neutral (PMV = 0), as calculated from BS EN ISO 7730 (1995). It was important that the subject felt thermally neutral throughout the experiment in order that any departure from thermal neutrality which she experienced could be attributed to vertical radiant temperature asymmetry alone, and not to any other cause. Each subject completed a total of 22 sensation questionnaires issued during the experiment, and was asked to give details about her current thermal condition, about how she would prefer to feel, about whether she felt any local discomfort and about the freshness of the air in the test room.

2.3. Experimental procedure

The experiments were conducted during the afternoon and early evening. Each subject reported at least 30 min prior to the commencement of the experiment, to allow sufficient time for completion of the consent and health declaration forms, and to have physical measurements taken (height and weight). A summary of these measurements is presented in Table 1.

Each subject wore the same ensemble of typical office clothing, of a size suitable for each person, and supplied by the experimenters; this ensemble consisted of the following: a long sleeve white cotton shirt buttoned to the neck; a dark, mixed fibre, (65% polyester, 35% viscose, with 100% nylon lining) knee length skirt approximately 600 mm in length; a pair of 15 denier nylon tights. The subjects wore their own shoes, specified by the experimenters to be of a formal 'office type' (no sandals or training shoes), and their own underwear (bra and cotton pants). The clo value of the ensemble was estimated to be 0.75 clo. The duration of the experiment was 3 h, each subject being asked to undertake sedentary office based tasks, such as typing, studying or reading, at a work station which consisted of some desk space, a lamp and a personal computer. Throughout the test, the thermal load to be removed by the chilled ceiling/displacement ventilation system was constant at 62 W/m^2 of floor area, two thermal dummies being employed to represent other office workers. Immediately prior to the subject and the experimenter entering the test environment, two other thermal dummies (for preconditioning purposes) were removed, to be replaced by the test subject and the experimenter.

The subject sat at a table facing the diffuser, at a distance of approximately 2.5 m separating the subject and the diffuser. The experimenter sat in the room at point X, as illustrated in Fig. 1.

The subjects were not allowed to move about inside the room, thus maintaining the metabolic rate to the estimated value of 70 W/m^2 (1.2 met). The subject completed a sensation questionnaire at various stages throughout the experiment.

Questionnaires were completed prior to entering the test environment, immediately upon being seated in the room, and subsequently in sets of five questionnaires for each of the four ceiling temperatures (see Table 2). The times when no questionnaires were completed corresponded to transitions between steady ceiling temperatures.

Table 1
Anthropometric measurements of subjects

	Age (years)	Weight (kg)	Height (mm)
Mean	31	65	1627
Range	21–48	49–114	1524–1715

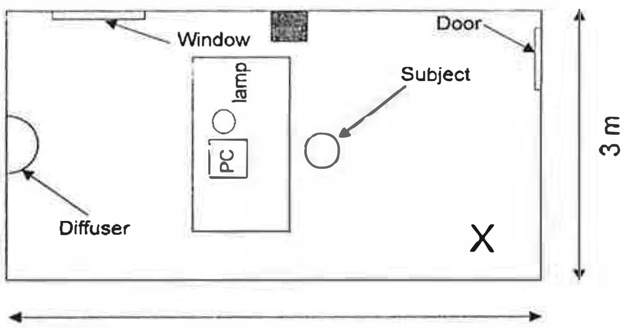

Fig. 1. Plan of the experimental room.

3. Results

3.1. Confirmation of test conditions and thermal neutrality

Firstly, it was important to confirm that the thermal conditions that were required during the experiment were actually achieved. The variable in this experiment was the ceiling temperature and Fig. 2 shows the ceiling temperature as a function of time for all eight subjects, ($N=8$).

Control of the ceiling temperature in the test environment was accurate to within ±0.5°C for the temperatures 22°C, 18°C, and 14°C. However, there was some difficulty in achieving the set value of 12°C, a mean temperature of 12.5°C instead being the lowest that was achievable; this is still lower

Table 2
Summary of times when subjects had to complete questionnaires

Ceiling temp.	Time (min)	Questionnaire completed	Ceiling temp.	Time	Questionnaire completed	Ceiling temp.	Time	Questionnaire completed
N/A	Before	YES	22°C	60	YES	14°C	125	YES
22°C	0	YES	18°C	65	NO	14°C	130	YES
22°C	5	NO	18°C	70	NO	14°C	135	YES
22°C	10	NO	18°C	75	NO	14°C	140	YES
22°C	15	NO	18°C	80	YES	12.5°C	145	NO
22°C	20	NO	18°C	85	YES	12.5°C	150	NO
22°C	25	NO	18°C	90	YES	12.5°C	155	NO
22°C	30	NO	18°C	95	YES	12.5°C	160	YES
22°C	35	NO	18°C	100	YES	12.5°C	165	YES
22°C	40	YES	14°C	105	NO	12.5°C	170	YES
22°C	45	YES	14°C	110	NO	12.5°C	175	YES
22°C	50	YES	14°C	115	NO	12.5°C	180	YES
22°C	55	YES	14°C	120	YES			

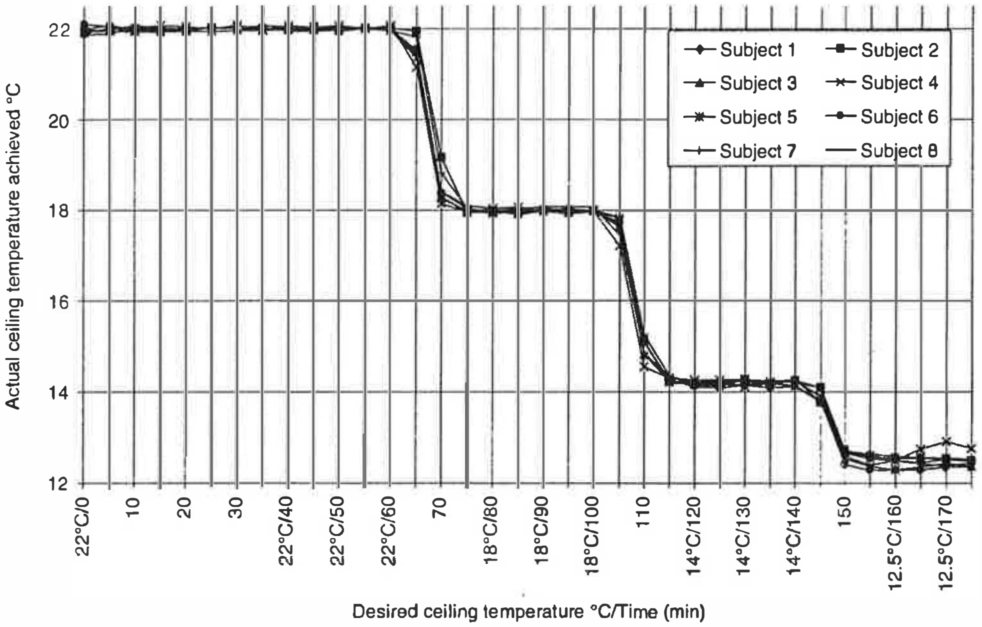

Fig. 2. Profile of the four ceiling temperatures, $N=8$.

than the chilled ceiling temperatures that would be found in practice (lowest ceiling temperature being maintained above dewpoint temperature).

Since the experiment required the overall thermal sensation of the subject to be maintained as neutral (PMV = 0), the PMV was calculated for each experimental condition, based on the values of the parameters measured during the experiments. The calculated PMV values were then plotted against the actual votes of the subjects, using the seven point sensation scale (BS EN ISO 7730, 1995): these are shown in Fig. 3. Here, the values for the actual vote used in the plots were taken from the final questionnaires completed by the subject at the end of each of the four test conditions.

Inspection of Fig. 3 shows that, in general, thermal neutrality was maintained for each subject throughout the experiment. The individual subject's votes were combined to give the Actual Mean Vote (AMV) which was then compared with the Predicted Mean Vote (PMV) (Table 3). It can be seen that both are closely matched, with the exception of the 22°C ceiling temperature which did show a significant difference from the predicted value at the $P<0.02$ level.

Fig. 4 is a histogram showing the thermal preference of the subjects in terms of how they would prefer to feel at that particular time (warmer, cooler or no change); the results are shown as a function of ceiling temperature.

Throughout the experiment the majority of the subjects preferred 'no change' to their thermal environment indicating that in general they remained thermally neutral throughout.

3.2. *Effect of vertical radiant asymmetry*

Fig. 5 shows the comparison between the subjects' actual votes and the vertical radiant temperature asymmetry, in °C. It can be seen that as the vertical radiant temperature asymmetry between the chilled ceiling and the floor increases, this has an insignificant effect on overall thermal comfort as reported by each subject. This is in agreement with the findings of Fanger et al. (1985) who showed that, for a cooled ceiling, a radiant temperature asymmetry of up to 14°C could be tolerated. The implication of these results is that for the range of chilled ceiling temperatures likely to be encountered in practice in a chilled ceiling/displacement ventilation environment, vertical radiant temperature asymmetry between the cooled ceiling and the floor is likely to have no adverse effect on the overall thermal comfort of the occupants.

In addition to the effect of vertical radiant temperature asymmetry on overall thermal sensation, the subjects were also asked to report their local thermal sensations, on various body parts.

Table 4 summarises the results, where the sensations are classified as being on either the 'cool' or 'warm' side of neutral. It can be seen that no particular pattern regarding thermal sensation on body parts emerges from this set of data, showing no significant local discomfort patterns. This was also confirmed by results from a study involving a larger sample of subjects, 184 in total (Loveday et al., 1997).

3.3. *Sensation of 'freshness'*

One of the benefits claimed for a chilled ceiling system is that it enhances the feeling of 'freshness' among the occupants in a manner similar to that of being outdoors under the open sky. In order to test this claim, the subjects were asked to report their sensation of 'freshness' on a five point scale ranging from 'very stuffy' to 'very fresh'. The results are plotted in Fig. 6, where they are compared respectively with the level of radiant asymmetry in °C, and mean actual votes, across the range of ceiling temperatures tested.

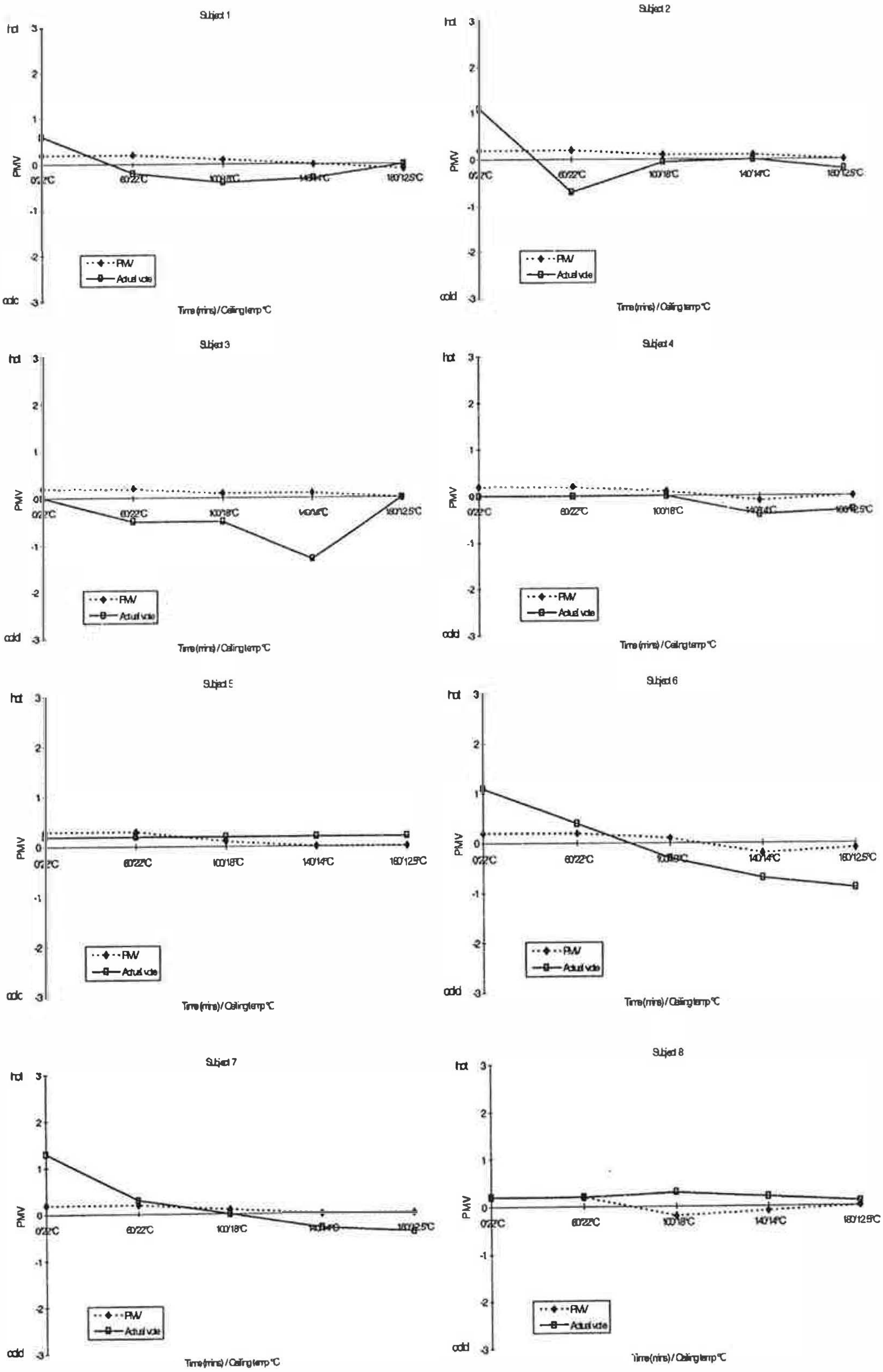

Fig. 3. Actual votes compared with the predicted vote for each experimental condition.

It can be seen that there is a trend for the sensation of 'freshness' to increase with increasing radiant asymmetry down to a ceiling temperature of between 18 and 14°C, but then to level off. While radiant asymmetry might be the sole cause of the increasing freshness sensation, it should be remembered that the increased movement of cool downward

Table 3
Summary of actual mean votes and comparison with predicted mean votes for each ceiling temperature

Ceiling temp.	Predicted mean vote	Standard deviation	Actual mean vote	Standard deviation	95% Confidence interval	*t*-value	Significance
22°C	0.21	0.035	−0.094	0.283	0.08, 0.53	3.20	$P<0.02$
18°C	0.06	0.106	−0.037	0.396	−0.22, 0.46	0.65	[a]
14°C	−0.025	0.104	−0.32	0.501	−0.13, 0.74	1.63	[a]
12.5°C	−0.025	0.046	−0.18	0.352	−0.12, 0.44	1.38	[a]
Overall mean	0.056		−0.16				

[a]Not significant.

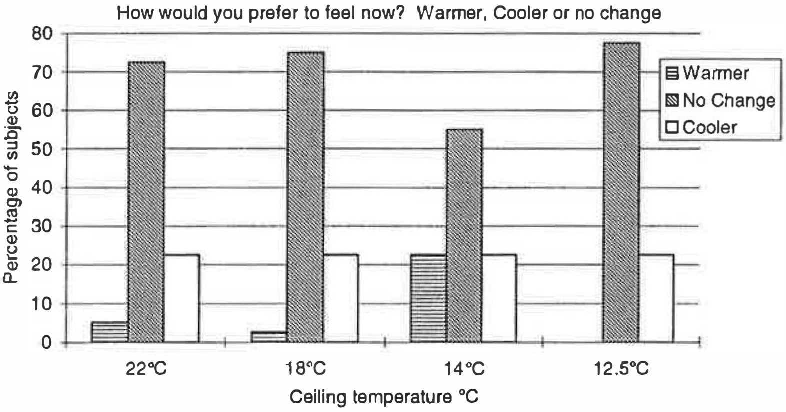

Fig. 4. How would you prefer to feel now? Warmer, cooler or no change.

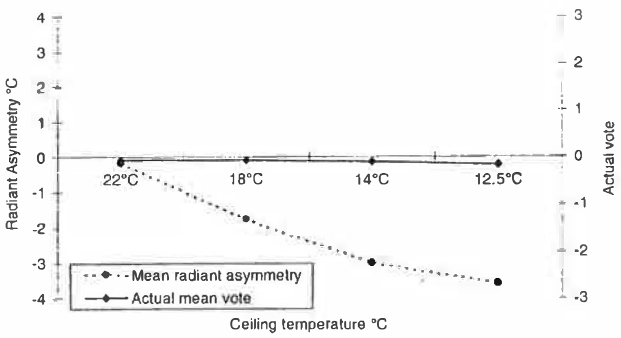

Fig. 5. Comparison of actual mean vote with mean radiant asymmetry.

air currents at the lower ceiling temperatures (as reported by Taki et al., 1996) may also affect the freshness sensation. Both radiant asymmetry and mean air velocity at a height of 1.1 m varied during the experiment, and so attributing any change in 'freshness' sensation to one particular cause cannot be made here. It is also worth noting that the sensation of 'freshness' is known to be related to the temperature of the air at the nose/mouth level (Chrenko, 1974; Fanger, personal communication, 1997). Throughout the experiment reported here, the temperature of the air at respiration height varied little, and so the observed effects on freshness are likely to be due either to radiant asymmetry or to air movement or to both. Further investigations are recommended to separately quantify the effects of the above influences on 'freshness' sensation from the point of view of designing chilled ceiling/displacement ventilation environments.

4. Discussion

The experimental conditions necessary for maintaining each of the test subjects at thermal neutrality (PMV = 0) were achieved. This was verified by the close agreement between the actual subject votes and the predicted votes. This, in turn, demonstrates the validity of BS EN ISO 7730 (1995) for predicting thermal comfort in chilled ceiling/displacement ventilation environments.

For the levels of radiant asymmetry tested in the experiment, there is an insignificant effect on the overall thermal comfort as reported by the subjects when carrying out sedentary office work. This confirms the findings of Fanger et al. (1985), which established that a vertical radiant temperature asymmetry of up to 14°C could be tolerated, and shows that in relation to radiant asymmetry, existing guidance is adequate when designing for comfort in chilled ceiling/displacement ventilation environments.

There also appears to be a relationship between radiant asymmetry and/or air velocity and the reported sensations of freshness. As both the radiant asymmetry and the air velocity at a height of 0.1 and 1.1 m increase, so does the perceived freshness; it is unclear whether this is caused by a combination of both factors or by the effect of only one of them. Further study is recommended, with a view to informing future design guidance.

5. Conclusions

The work reported here forms part of a broader investigation into the factors influencing the thermal comfort of sed-

Table 4
Summary of subjects local thermal sensations reported by subjects (number of subjects reporting sensation shown)

Ceiling Temperature °C	22°C		18°C		14°C		12.5°C	
Sensations	Cool	Warm	Cool	Warm	Cool	Warm	Cool	Warm
head	1		1	1	1			
shoulders		1	1		2			
trunk					1		1	
arms	1							
hands		1	1			1	1	
above knee	1							
below knee	1		2		1	1	1	
feet	1			1		1	2	

■ = No thermal sensation felt by any subject
N = 8

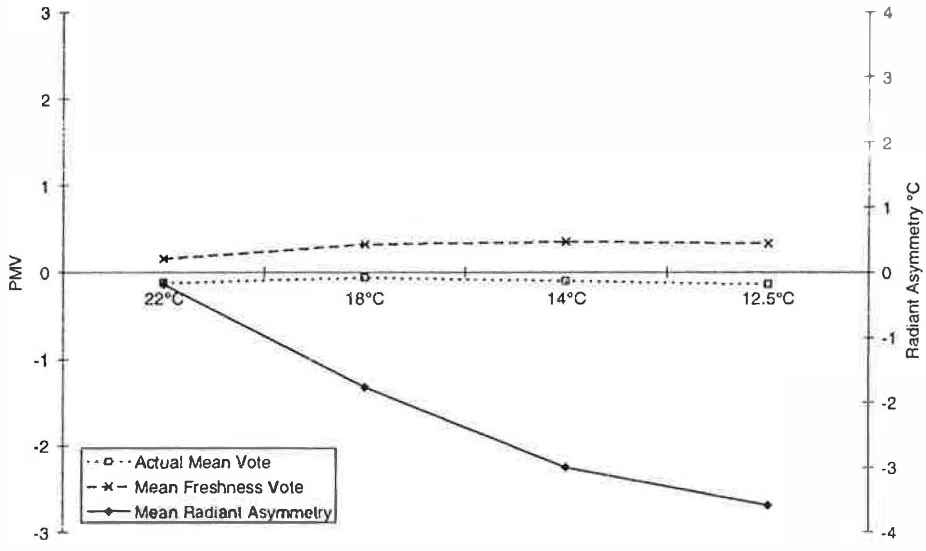

Fig. 6. Comparison of freshness with AMV and vertical radiant asymmetry ($N=8$).

entary office workers in chilled ceiling/displacement ventilation environments. The following conclusions can be drawn.

i) The vertical radiant temperature asymmetry experienced within a typical chilled ceiling/displacement ventilation environment does not significantly affect the thermal comfort of the desk-seated occupant. Existing guidance (Fanger et al., 1985) is valid, without modification, for thermal comfort design in such environments.

ii) The sensation of 'freshness' appears to be correlated with increasing vertical radiant temperature asymmetry. It may also be related to an increased downward movement of cool air which occurs at lower ceiling temperatures; the respective influences of each of these effects remains to be determined.

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