This item was submitted to [Loughborough's Research Repository](#) by the author.
Items in Figshare are protected by copyright, with all rights reserved, unless otherwise indicated.

Environmental and human factors influencing thermal comfort of office occupants in hot-humid and hot-arid climates

PLEASE CITE THE PUBLISHED VERSION

PUBLISHER

© Taylor & Francis

LICENCE

CC BY-NC-ND 4.0

REPOSITORY RECORD

Erlandson, Tamara, Krzysztof Cena, Richard de Dear, and George Havenith. 2019. "Environmental and Human Factors Influencing Thermal Comfort of Office Occupants in Hot-humid and Hot-arid Climates". figshare. <https://hdl.handle.net/2134/2539>.

This item was submitted to Loughborough's Institutional Repository by the author and is made available under the following Creative Commons Licence conditions.

For the full text of this licence, please go to:
<http://creativecommons.org/licenses/by-nc-nd/2.5/>

**Environmental and human factors influencing thermal comfort
of office occupants in hot-humid and hot-arid climates**

TAMARA ERLANDSON and KRZYSZTOF CENA

Environmental Science, Murdoch University,
Perth WA 6150, Australia

RICHARD DE DEAR

Environmental and Life Sciences, Macquarie University,
Sydney NSW 2109, Australia

GEORGE HAVENITH

Human Sciences, Loughborough University,
Leicester LE11 3TU, UK

Keywords: Thermal comfort; Office occupants; Hot-arid; Hot-humid;
Human factors.

The effects of environmental and individual factors on thermal sensation in air-conditioned office environments were analysed for two large, fully compatible thermal comfort field studies in contrasting Australian climates. In the hot-humid location of Townsville, 836 office workers were surveyed; 935 workers participated in hot-arid Kalgoorlie-Boulder. Overall perceived work area temperature and measured indoor operative temperature correlated moderately with thermal sensation for Townsville (T) subjects but only perceived temperature correlated with Kalgoorlie-Boulder (KB) sensation. Multiple regression analyses confirmed that indoor climatic variables (including Predicted Mean Vote) contributed to actual thermal sensation vote (24% T; 15% KB), with operative temperature having more of an effect in T than in KB. Subsequent analyses of individual characteristics showed no linear contributions to thermal sensation. The remaining variances were significantly related to perceived work area temperature (7% additional explained variance in T; 12% in KB). Mann-Whitney

analyses (after correction for climatic variables) showed that T subjects with higher job satisfaction had thermal sensations closer to 'neutral'. Males, healthier subjects, non-smokers, respondents with earlier survey times and underweight occupants had lower median thermal sensations in KB. Townsville occupants appeared more adapted to their outdoor climatic conditions than Kalgoorlie-Boulder respondents, perhaps due to limited home air-conditioning. Further research into non-thermal impacts on gender-related thermal acceptability is suggested.

1. Introduction

The adaptive model of thermal comfort predicts that humans become adapted to the thermal environments to which they are most exposed (de Dear and Schiller Brager 1998). As air-conditioning in hot climates becomes more prevalent in the office, home and car, satisfying demanding occupants will lead to excessive energy consumption (Cena and de Dear 2001). Temperature settings for air-conditioned offices are often based on calculations of thermal neutralities by the Fanger (1970) comfort model which do not consider individual factors affecting thermal sensations in real settings. Recently, four benchmark studies sponsored by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) were conducted in San Francisco, USA (Schiller et al. 1988); Townsville, Australia (de Dear and Fountain 1994); Montreal, Canada (Donnini et al. 1997) and Kalgoorlie-Boulder, Australia (Cena and de Dear 1999). The two Australian studies of air-conditioned buildings in hot-humid Townsville and hot-arid Kalgoorlie-Boulder, given their full methodological compatibility, were chosen for comparison in the present paper.

Data from the Australian studies were analysed for the contributions of occupants' personal factors (gender or anthropometry, for example), as well as various cognitive variables, to their subjective thermal responses. In order to discriminate between these contributions and any indoor climatic effects, the data were first corrected for the climatic determinants and then the thermally unexplained residuals were analysed for individual effects. As these surveys were performed in hot outdoor climates, contrasting in humidity

levels, they also provided a unique opportunity to compare human factor effects on indoor thermal comfort in two distinct climatic contexts.

2. Methods

Thermal comfort field surveys of air-conditioned office buildings were conducted in the hot-humid climate of Townsville, in north-eastern Australia (de Dear and Fountain 1994) and hot-arid climate of Kalgoorlie-Boulder, south-western Australia (Cena and de Dear 1999). A high degree of compatibility was maintained between these ASHRAE studies for climatic and subjective data. Measurement protocols were the same for both locations and instrumentation also met prescriptions of ASHRAE 55-92 (ASHRAE 1992) and ISO 7726 (ISO 1985) Standards in both studies. Questionnaires routinely used by ASHRAE were replicated with minor climate-specific modifications. To further ensure compatibility, one of the principal investigators took part in both surveys and the two Australian locations were considered to be culturally comparable.

The tropical location of Townsville has a 'wet' summer season during which most of the annual rainfall occurs, and a 'dry' cooler season. Thermal comfort studies were performed in both seasons. The mean minimum and maximum daily outdoor temperatures for the dry season sample period were 14.0 and 24.0° C, respectively. Average minimum and maximum outdoor temperatures during the wet season sampling period were 24.8 and 29.3° C, respectively. Mean daily 6 a.m. outdoor relative humidity was 83% in the wet season. In contrast, Kalgoorlie-Boulder is situated in a desert region with minimal rainfall (258 mm typically falling on fewer than 65 days per annum). Data were collected during both summer and winter. Average minimum and maximum daily outdoor temperatures during the winter study period were 9.6 and 18.5° C. The summer survey had mean minimum and maximum outdoor temperatures of 16.7 and 30.7° C. The average daily 9 a.m. outdoor relative humidity was only 39% during summer.

The Townsville dry and wet season studies had sample sizes of 628 and 606 respectively, giving a total of 1,234 sets of data from 12 air-conditioned office buildings. A group of 836

individuals was surveyed and 398 occupants were interviewed in both seasons. Sample sizes of 640 and 589 were achieved in the Kalgoorlie-Boulder surveys during winter and summer, respectively, for a total of 1,229 sets of data. Twenty-two air-conditioned office buildings in Kalgoorlie-Boulder contributed 935 subjects, with 294 interviewed in both seasons. A summary of the subjects' characteristics is presented in table 1.

[Insert table 1 about here]

Fully compatible mobile measurement systems (de Dear and Fountain 1994, Cena and de Dear 1999) were used to collect data at each individual workstation of all Townsville and Kalgoorlie-Boulder subjects. Two standard questionnaires (used in all ASHRAE benchmark studies) were administered in both locations, identified as the 'Online' and 'Background' forms. The short 'Online' questionnaire was completed by subjects while their workstation's indoor climate was assessed. Simultaneous ratings of thermal acceptability, preference and thermal sensation on a semi-continuous ASHRAE seven-point scale ranging from 'cold' (-3) through 'neutral' (0) to 'hot' (+3) were recorded. The 'Online' form also included metabolic activity (office work) and clothing insulation checklists from ASHRAE Standard 55-92 (ASHRAE 1992). The comprehensive 'Background' questionnaire was generally completed at the same time as the 'Online' form, but addressed demographics and long-term opinions of personal work area satisfaction, job satisfaction, environmental control and health, using Likert or graduated scales with no 'neutral' mid-point.

In order to analyse the subjective thermal sensation vote for the possible effects of personal factors and perceptions, the data were first corrected for any variations in the actual indoor climate. The raw data were adjusted for indoor operative temperature, vapour pressure, air velocity, clothing insulation and metabolic activity by multiple regression, where these had significant effects, after which the residual variances in the data were tested for the impact of the personal characteristics and finally, overall perceived work area temperature. In an alternative approach, the raw data were corrected using the Predicted Mean Vote (*PMV*) index

(Fanger 1970) which integrates six key factors in the human heat balance. The *PMV* index is derived from air and mean radiant temperatures, vapour pressure, air velocity, clothing insulation and metabolic rate, and is expressed on a continuous version of the ASHRAE seven-point scale. To investigate an overall effect of the personal factors, as opposed to the linear effects explored in the regression analyses, the residuals after correction for *PMV* were split into groups of high and low values for each factor tested, and the 100 subjects with the highest values were contrasted with the 100 lowest subjects using Mann-Whitney tests on the parameter of interest (Havenith 2001).

3. Results

Significant correlations (Spearman Rank) were identified between thermal sensation and several physical and subjective thermal variables in Townsville and Kalgoorlie-Boulder (table 2). Thermal sensation showed moderate positive relationships with measured indoor operative temperature and overall ('on average') perceived work area temperature ($r_s = 0.44, 0.45$; $p < 0.001$) for Townsville subjects. A positive correlation between thermal sensation and concurrent work area air movement preference was also observed ($r_s = 0.31$; $p < 0.001$). In contrast, thermal sensation correlated moderately only with overall perceived work area temperature ($r_s = 0.49$; $p < 0.001$) for Kalgoorlie-Boulder occupants. Fair correlations between thermal sensation and air movement perceptions (concurrent work area acceptability and preference, general work area preference) were also observed in Kalgoorlie-Boulder ($r_s = -0.26, 0.37, -0.26$; $p < 0.001$). None of the experimental personal factors correlated significantly with thermal sensation.

[Insert table 2 about here]

Interactions between thermal sensation and several indoor climatic measurements, individual characteristics and cognitive variables were analysed by stepwise multiple regression for Townsville and Kalgoorlie-Boulder data. Season of survey did not significantly

affect thermal sensation so seasonal data were pooled for both survey locations. Indoor atmospheric variables, especially operative temperature (22% of prediction), accounted for 24% of variance (total adjusted coefficient of determination, r^2 , of 0.24) in Townsville thermal sensation. Kalgoorlie-Boulder regression analysis of thermal sensation had an initial r^2 of 0.15, predicted by several physical indoor factors (indoor operative temperature accounted for only 7% of variance in thermal sensation). Gender, age, body mass and surface area, pattern of smoking, drinking coffee or exercising, survey time, hours worked per week, work area and job satisfaction, health, and perceived environmental sensitivity all showed no linear impact on thermal sensation in either Townsville or Kalgoorlie-Boulder after correction for indoor climatic factors. When the same approach of linear regression was used with Predicted Mean Vote (*PMV*) as the initial predictor instead of the separate climatic variables, the explained variances in thermal sensation were 3% for Townsville and 6% for Kalgoorlie-Boulder data but the personal factors again showed no significant linear effect on thermal sensation. Overall perceived work area temperature was finally included in the regression analyses due to its moderate correlations with thermal sensation. It contributed an additional 7% to the variance in Townsville thermal sensation and an additional 12% to Kalgoorlie-Boulder variance.

Mann-Whitney analyses were used to compare median thermal sensation between obverse groups (generally the 100 highest and 100 lowest scoring subjects) of several individual characteristics. Seasonal data pooled for Townsville were first corrected for *PMV* to reduce variations in indoor climatic contexts of groups. There were no differences in median thermal sensation between Townsville males and females ($Z = -0.78$; $p > 0.05$), between young and old subjects ($Z = -0.96$; $p > 0.05$), between underweight (mean body mass index of 18.8 kg m^{-2}) and overweight (32.7 kg m^{-2}) respondents ($Z = -0.18$; $p > 0.05$), between participants with low and high body surface areas ($Z = -1.0$; $p > 0.05$), between subjects with low and high body surface to mass ratios ($Z = -0.48$; $p > 0.05$), between respondents on medication and those not ($Z = -0.74$; $p > 0.05$), between non-smokers and heavy (average 19 cigarettes per day) smokers ($Z = -0.18$; $p > 0.05$), between non-coffee-drinkers and heavy

coffee-drinkers ($Z = -1.3$; $p > 0.05$), nor between non-exercising and heavily exercising respondents ($Z = -0.61$; $p > 0.05$). Similarly, no differences in median thermal sensation were observed between early (median time 09:30) and late (16:00) survey times ($Z = -0.96$; $p > 0.05$), between subjects working short and long hours per week ($Z = -1.1$; $p > 0.05$), between occupants generally satisfied and dissatisfied with aspects of their work area ($Z = -0.15$; $p > 0.05$), between subjects self-reporting infrequent (mean score of 13 out of possible 50) and frequent (35 out of 50) ill-health symptoms ($Z = -0.54$; $p > 0.05$) nor between individuals perceiving themselves as environmentally insensitive and hypersensitive ($Z = -0.86$; $p > 0.05$). However, a significant difference in median thermal sensation was observed between Townsville respondents who were generally satisfied with various aspects of their job (average score of 86 out of possible 90) and those (49 out of 90) who were dissatisfied ($Z = -2.0$; $p < 0.05$). This may indicate that Townsville individuals with higher job satisfaction had a significantly lower median thermal sensation, but the lower thermal sensations of the satisfied group were closer to 'neutral' than those of the dissatisfied group (median of 0.0 compared to +0.3 on the ASHRAE seven-point scale).

Mann-Whitney analyses, corrected for *PMV*, using the Kalgoorlie-Boulder sample (two seasons pooled) also showed no significant differences in median thermal sensation between young and old occupants ($Z = -1.8$; $p > 0.05$), between respondents with low and high body surface areas ($Z = -1.4$; $p > 0.05$), between subjects with low and high body surface to mass ratios ($Z = -1.3$; $p > 0.05$), between participants on medication and those not ($Z = -0.18$; $p > 0.05$), between non-coffee-drinkers and heavy coffee-drinkers ($Z = -0.12$; $p > 0.05$), nor between non-exercising and heavily exercising respondents ($Z = -0.20$; $p > 0.05$). There were no differences in median thermal sensation between subjects working short and long hours per week ($Z = -1.0$; $p > 0.05$), between occupants generally satisfied (mean score of 82 out of possible 90) and dissatisfied (55 out of 90) with various aspects of their job ($Z = -0.57$; $p > 0.05$) or work area ($Z = -1.4$; $p > 0.05$), nor between individuals perceiving themselves as environmentally insensitive and hypersensitive ($Z = -1.6$; $p > 0.05$). However, there were significant differences in median thermal sensation between Kalgoorlie-Boulder males and

females ($Z = -4.8$; $p < 0.001$) and between subjects self-reporting infrequent (average score of 13 out of possible 50) and frequent (34 out of 50) ill-health symptoms ($Z = -2.7$; $p < 0.01$). Median thermal sensation also differed significantly between early (median time 09:00) and late (16:00) survey times ($Z = -2.7$; $p < 0.01$), between non-smokers and heavy (average 19 cigarettes per day) smokers ($Z = -2.4$; $p < 0.05$), and between underweight (average body mass index of 19.1 kg m^{-2}) and overweight (35.0 kg m^{-2}) subjects ($Z = -2.0$; $p < 0.05$). Kalgoorlie-Boulder males (median thermal sensation of -0.2 compared to $+0.1$), healthier subjects (-0.2 ; $+0.5$), early survey times (-0.2 ; $+0.5$), non-smokers (-0.2 ; $+0.1$), and underweight subjects (-0.2 ; $+0.3$) had significantly lower median thermal sensations after *PMV* correction.

Mean clothing insulation of Townsville subjects was 0.54 clo during the dry season and 0.44 clo for the wet season. Clothing level did not differ significantly between genders. Wet season standard deviation decreased to 0.13 clo from 0.19 clo in the dry season. Calculated chair insulation of 0.15 clo raised average insulation values to 0.69 and 0.59 clo for the dry and wet seasons, respectively. Kalgoorlie-Boulder subjects registered means of 0.69 clo in winter and 0.49 clo in summer. Females wore approximately 0.1 clo less than the males. Similarly, the standard deviation of Kalgoorlie-Boulder insulation decreased markedly from 0.23 clo in winter to 0.14 clo in summer indicating adaptive behaviour was restricted as level of clothing reached the socially acceptable minimum in both locations. Thermal insulation in Kalgoorlie-Boulder averaged 0.84 clo in winter and 0.64 clo in summer, including the chair increment. Mean metabolic activity was about 77 W m^{-2} (1.3 met) for males and females in both locations.

Indoor climatic data and thermal sensation on the ASHRAE seven-point scale for both Kalgoorlie-Boulder and Townsville subjects are presented in table 3. Townsville offices had mean indoor air and radiant temperatures (averaged across three heights of 0.1, 0.6 and 1.1 m above floor level) of around 23°C in the dry season and 24°C in the wet season. Average indoor relative humidity was 51% in the dry season and increased by about 5% in the wet season. Indoor air velocity close to 0.13 m s^{-1} (averaged across the three heights) did not differ significantly between seasons. Mean thermal sensation increased marginally from -0.4

in the dry season to around -0.3 in the wet season for both genders. Average indoor air and radiant temperatures in Kalgoorlie-Boulder (across three heights) were 22° C in winter and 24° C in summer. Mean indoor relative humidity decreased from 46% in winter to 41% in summer. Indoor air velocity (across three heights) rose from 0.13 in winter to 0.20 m s⁻¹ in summer. Kalgoorlie-Boulder females recorded slightly higher mean thermal sensation (+0.6) than males (+0.3) in winter but both genders voted +0.1 on average in summer. Full details of the above measurements are presented in the two key papers (de Dear and Fountain 1994, Cena and de Dear 1999).

[Insert table 3 about here]

4. Discussion

The methodological compatibility between the Kalgoorlie-Boulder and Townsville databases meant they were ideal for statistical comparison. The dependent variable, thermal sensation on the ASHRAE seven-point scale, registered a large variance (standard deviation >1.0, with a range of six sensation units between highest and lowest possible votes). The hot climatic conditions of Townsville and Kalgoorlie-Boulder differed mainly in terms of outdoor humidity levels. Anthropometric, social and cultural aspects, work logistics and dress codes were almost identical for the two large thermal comfort field experiments.

4.1. Thermal comfort variables

Occupants' thermal sensation at time of interview correlated strongly with their overall perceived work area temperature in both Townsville and Kalgoorlie-Boulder. Assuming that, for example, subjects thought their workspace warm on average, then they tended to vote warm when asked how they felt 'right now' or vice versa. This suggests that the survey instructions which prefaced the ASHRAE seven-point thermal sensation scale, and focused on personal (not environmental) thermal sensations, may have made a subtle distinction that was missed by the respondent. It is possible that ASHRAE thermal sensation and overall

perceived work area temperature questionnaire items were simply different ways of assessing the same underlying construct of subjective sensation, except that one used a continuous scale while the other relied on six adjectival descriptors. The fact that actual indoor climatic conditions were largely irrelevant to variations in thermal sensation was not unexpected given the typically static thermal surroundings of centrally air-conditioned buildings. In fact, for Kalgoorlie-Boulder respondents, overall perceived work area temperature appeared to be most strongly linked to thermal sensation as none of the climatic factors analysed had a significant relationship, suggesting that subjects were not successfully differentiating their instantaneous thermal sensations from longer-term, general thermal impressions of their workstations. In contrast, Townsville subjects' thermal sensation was observed to fluctuate with operative temperature. Their reaction to changes in indoor temperature suggested varying opinions of their workplace thermal conditions rather than just expectations. Preference for workspace air movement at the time of interview had fair positive correlations with thermal sensation (as thermal sensations increased so did requests for more air movement) for both locations and concurrent air movement acceptability had a fair negative correlation in Kalgoorlie-Boulder, indicating that air movement was rated as less acceptable, and more was desired, as subjects felt warmer. These data clearly did not support the principle of 'cool, dry air' underpinning contemporary HVAC comfort standards (ISO 1994, ASHRAE 1992). General preference for work area air movement (scale was reversed in 'Background' questionnaire hence opposite effect sign) had a fair negative correlation with thermal sensation only in Kalgoorlie-Boulder, highlighting the particular connection of longer-term, overall ratings and opinions with the instantaneous thermal responses of subjects at this location.

4.2. Non-thermal factors

As the data had previously been analysed for the basic thermal comfort variables, stepwise regression analyses were applied to see if there were any non-thermal or other subjective influences on thermal sensation after accounting for climatic factors. However, no linear

effect on subjects' sensation was observed for gender, age, body mass and surface area, pattern of smoking, drinking coffee or exercising, survey time, hours worked per week, work area and job satisfaction, health, or perceived environmental sensitivity. Townsville thermal sensation was predicted mainly by indoor operative temperature (explained 22% of variance in sensation) and overall perceived work area temperature (an additional 7% of variance). Kalgoorlie-Boulder analyses also showed that indoor operative temperature (responsible for 7% of variance in thermal sensation) and overall perceived work area temperature (an additional 12% of variance) were the main predictors of the actual thermal sensation. These results may suggest a difference between the two locations in the primary factor provoking thermal impressions, with Townsville subjects considering more the physical indoor conditions, and Kalgoorlie-Boulder participants referring more to general opinions and expectations, when casting votes on the ASHRAE seven-point scale. The coefficients of determination were low but this was expected based on the minor variations in temperature, and hence thermal sensation, found in air-conditioned buildings (de Dear and Schiller Brager 1998, Schiller Brager and de Dear 2000). As sample sizes were greater than 1000 subjects for both locations, these results were statistically significant. Predicted Mean Vote (*PMV*) which combines indoor air and mean radiant temperatures, vapour pressure, air velocity, clothing insulation and metabolic rate was used alternatively as the initial predictor. The explained variances in thermal sensation were 3% in Townsville and 6% in Kalgoorlie-Boulder using *PMV* and were lower than when the specific climatic variables were regressed. However, subsequent analyses of individual factor effects were not different between the two approaches. It is noted that air movement seemed to be more essential for thermal comfort in Kalgoorlie-Boulder than Townsville with the small but significant prediction of thermal sensation by indoor air velocity and also the correlations with concurrent air movement acceptability and general air movement preference.

Data were analysed using Mann-Whitney tests for significant differences in median thermal sensation between obverse (generally high and low) groups of several non-thermal variables after correction by *PMV* for climatic effects on thermal sensation. Townsville

subjects with higher job satisfaction recorded lower median sensations, closer to 'neutral', suggesting increased thermal comfort for these occupants. In Kalgoorlie-Boulder, males, healthier subjects, non-smokers, respondents with earlier survey times and underweight occupants had significantly lower median thermal sensations. The issue of non-thermal considerations affecting human thermal comfort therefore requires further investigation in office environments in various climates. Erlandson et al. (2002) recently observed that Kalgoorlie-Boulder female subjects, although in similar thermal environments to males, typically felt very warm and were thermally dissatisfied, particularly in winter. It was also found that the non-thermal aspect of job satisfaction correlated with thermal acceptability and it was thought that clothing insulation levels could have been adjusted more frequently by females to adapt to their work environment.

4.3. *Effects of clothing insulation*

Mean clothing insulation levels were comparable between Townsville and Kalgoorlie-Boulder for the respective wet (0.44 clo) and summer seasons (0.49 clo), although Kalgoorlie-Boulder females wore approximately 0.1 clo (about 1° C shift in *PMV* terms) less than the Kalgoorlie-Boulder males. The indoor thermal environments of these locations were also similar with mean effective temperatures (ET^*) of 23.9° C in the Townsville wet season and 23.5° C for Kalgoorlie-Boulder summer. Average indoor effective temperatures differed slightly, however, between Townsville dry (23.4° C) and Kalgoorlie-Boulder winter (22.1° C) seasons. This was accurately reflected in the clothing disparity between locations with Townsville subjects wearing 0.54 clo on average and Kalgoorlie-Boulder subjects wearing 0.69 clo (Kalgoorlie-Boulder females again wearing about 0.1 clo less than their male counterparts). Thermal sensation averaged negligibly cooler than neutral for Townsville males and females in the dry (-0.4) and wet seasons (-0.3). Both genders in Kalgoorlie-Boulder recorded nearly neutral mean sensations in summer (+0.1) which increased to marginally warmer than neutral in winter for males (+0.3) and females (+0.6). Clothing modification may provide an obvious and simple strategy for individual adaptation to the

indoor climate (Cena and Clark 1981, Brager and de Dear 1998, Morgan and de Dear 1999) and for reduction of energy costs due to office overcooling in hot climates. Clothing adjustments, however, are often restricted by social standards and office dress codes. In general, respondents in these two studies appeared to be dressing appropriately for their thermal conditions, although Kalgoorlie-Boulder females could perhaps have better utilised clothing adjustment to provide greater personal comfort during winter. Average metabolic rates of 1.3 met in both locations represented typical sedentary activities of office workers and did not suggest any major adaptive opportunity through change in behaviour in hot environments. There was no evidence that Townsville or Kalgoorlie-Boulder office workers were performing their duties with less effort and at lower metabolic rates than their counterparts in cold climates.

4.4. Gender considerations

Previous analyses showed no difference between Townsville males (24.2° C) and females (24.3° C) in the indoor operative temperature at which thermal sensation was most frequently 'neutral' (de Dear and Fountain 1994). However, despite similar thermal conditions for both genders, significantly more females than males were dissatisfied with the thermal environment at the time of survey. Other data analyses showed that significantly more Kalgoorlie-Boulder females than males under comparable conditions also found the concurrent thermal environment unacceptable (Cena and de Dear 2001). In winter, significantly more females than males perceived their work area as 'moderately' or 'very warm' on average (31% of females; 16% of males) and were dissatisfied with work area temperature in general (Erlandson et al. 2002). Previously, gender differences in the thermal response have been partially attributed to clothing insulation levels (Karyono 2000). However, clothing levels were approximately equivalent for Townsville males and females and Kalgoorlie-Boulder females wore about 0.1 clo less than males, so females could have felt slightly cooler than males under the same conditions. It is speculated that other non-

thermal workplace considerations (for example, job satisfaction) were affecting the thermal perceptions of females in both locations.

4.5. Thermal neutralities

Townsville thermal neutralities were 24.2° C and 24.6° C according to the ASHRAE thermal sensation scale (de Dear and Fountain 1994) in the dry and wet seasons, respectively, compared to 20.3° C in winter and 23.3° C in summer for Kalgoorlie-Boulder (Cena and de Dear 1999). Average thermal neutrality for all subjects was about 4° C higher in Townsville than Kalgoorlie-Boulder when comparing the dry and winter seasons. Townsville subjects were insulated about 0.15 clo less than Kalgoorlie-Boulder subjects on average so would have been able to tolerate temperatures approximately 1.5° C warmer. For wet and summer seasons, Townsville subjects had a neutral temperature around 1° C higher than their Kalgoorlie-Boulder counterparts, while the two locations had comparable mean clothing insulation levels. The higher neutralities of Townsville subjects perhaps indicated that they were somewhat acclimatised to their hot outdoor environment and this may have been aided by the relative lack of air-conditioning at home (85% of subjects reported not using or not having air-conditioning in their homes in wet season). The lower Kalgoorlie-Boulder neutralities implied that these respondents may have adapted to the cooler conditions of their indoor environment; nearly 50% of them were using air-conditioning at home in summer. It may also have been the case that Townsville subjects, because of their heightened thermal sensitivity, were using clothing adjustment more effectively than Kalgoorlie-Boulder participants to promote their thermal comfort and were hence able to tolerate higher temperatures. Saving energy by raising office temperatures might therefore be possible in hot environments and should be subject to further research..

5. Conclusions

- (1) The hot climatic conditions of Townsville and Kalgoorlie-Boulder differed mostly in terms of outdoor humidity levels; other factors were highly comparable for the two

large thermal comfort field experiments.

- (2) Townsville subjects wore less clothing on average in both seasons than Kalgoorlie-Boulder respondents, reflecting lower mean thermal sensations and higher neutral temperatures based on the ASHRAE thermal sensation scale. Clothing adjustment therefore presents an opportunity to reduce energy consumption due to excessive indoor cooling in hot climates.
- (3) Thermal sensation was predicted by indoor operative temperature and overall perceived work area temperature in Townsville and Kalgoorlie-Boulder. Townsville participants were slightly more sensitive to the physical thermal conditions at their individual workstations whereas Kalgoorlie-Boulder subjects' longer-term thermal opinions and expectations of their workstations were more connected to their concurrent thermal assessments.
- (4) After correction for the actual indoor climatic conditions (including *PMV*), no significant linear effects of personal characteristics on actual thermal sensation were observed in either Townsville or Kalgoorlie-Boulder.
- (5) Indoor air movement appeared particularly important for personal thermal comfort in the hot-arid climate of Kalgoorlie-Boulder, and the notion of draft held less meaning for office occupants in Townsville and Kalgoorlie-Boulder than suggested by current thermal comfort standards.
- (6) Higher job satisfaction was linked to lower median thermal sensation and possibly higher thermal comfort in Townsville. Males, healthier subjects, respondents with earlier survey times, non-smokers and underweight occupants had significantly lower median thermal sensations in Kalgoorlie-Boulder. Non-thermal factors (for example, job satisfaction or gender) not currently considered in thermal comfort standards require further investigation for effects on workplace thermal comfort.
- (7) Males and females responded differently to comparable indoor thermal environments in both hot-humid Townsville and hot-arid Kalgoorlie-Boulder. It is suggested that other non-thermal workplace considerations impacted on their thermal perceptions

and these need to be further investigated.

- (8) Townsville subjects appeared more acclimatised to the hot outdoor climatic conditions than Kalgoorlie-Boulder occupants, perhaps due to markedly less air-conditioning in hot-humid Townsville home environments. This indicates that saving energy by raising office temperatures might be possible in hot environments and that variable workplace thermal conditions may lead to greater acceptance by occupants.

Acknowledgments

The contribution by Marc Fountain to the Townsville project, ASHRAE RP-702, is acknowledged. Ed Arens, Gail Brager, Byron Jones and David Wyon are all thanked for their advice and support.

References

- ASHRAE 1992, *ANSI/ASHRAE Standard 55-1992, Thermal Environmental Conditions for Human Occupancy*, (Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers).
- BRAGER, G.S. and DE DEAR, R.J. 1998, Thermal adaptation in the built environment: a literature review, *Energy and Buildings*, **27**, 83-96.
- CENA, K. and CLARK, J.A. 1981, *Bioengineering, Thermal Physiology and Comfort*, (New York: Elsevier).
- CENA, K. and DE DEAR, R. 2001, Thermal comfort and behavioural strategies in office buildings located in a hot-arid climate, *Journal of Thermal Biology*, **26**, 409-414.
- CENA, K. and DE DEAR, R.J. 1999, Field study of occupant comfort and office thermal environments in a hot, arid climate, *ASHRAE Transactions*, **105**, 204-217.
- DE DEAR, R.J. and FOUNTAIN, M.E. 1994, Field experiments on occupant comfort and office thermal environments in a hot-humid climate, *ASHRAE Transactions*, **100**, 457-475.
- DE DEAR, R.J. and SCHILLER BRAGER, G. 1998, Developing an adaptive model of thermal comfort and preference, *ASHRAE Transactions*, **104**, 145-167.

- DONNINI, G., MOLINA, J., MARTELLO, C., LAI, D.H.C., LAI, H.K., CHANG, C.Y., LAFLAMME, M., NGUYEN, V.H. and HAGHIGHAT, F. 1997, Field study of occupant comfort and office thermal environments in a cold climate, *ASHRAE Transactions*, **103**, 205-220.
- ERLANDSON, T., CENA, K. and DE DEAR, R. 2002, Gender differences in thermal comfort and adaptive behaviour of office occupants in a hot-arid climate, *Proceedings of the 10th International Conference on Environmental Ergonomics*. (Fukuoka, Japan), **841-844**.
- FANGER, P.O. 1970, *Thermal Comfort*, (Copenhagen: Danish Technical Press).
- HAVENITH, G. 2001, Human surface to mass ratio and body core temperature in exercise heat stress – a concept revisited, *Journal of Thermal Biology*, **26**, 387-393.
- ISO 1985, *International Standard 7726, Thermal Environments – Specifications Relating to Appliances and Methods for Measuring Physical Characteristics of the Environment*, (Geneva: International Organization for Standardization).
- ISO 1994, *International Standard 7730, Moderate Thermal Environments – Determination of the PMV and PPD Indices and Specification of the Conditions of Thermal Comfort*, **2nd ed.** (Geneva: International Organization for Standardization).
- KARYONO, T.H. 2000, Report on thermal comfort and building energy studies in Jakarta – Indonesia, *Building and Environment*, **35**, 77-90.
- MORGAN, C.A. and DE DEAR, R.J. 1999, Office dress codes, thermal comfort and building energy conservation, in R.J. de Dear and J.C. Potter (eds), *Proceedings of the 15th International Congress of Biometeorology and International Conference on Urban Climatology*, (Sydney: Macquarie University), ICB23.2.1-6.
- SCHILLER, G.E., ARENS, E.A., BAUMAN, F.S., BENTON, C., FOUNTAIN, M. and DOHERTY, T. 1988, A field study of thermal environments and comfort in office buildings, *ASHRAE Transactions*, **94**, 280-308.
- SCHILLER BRAGER, G. and DE DEAR, R. 2000, A standard for natural ventilation, *ASHRAE Journal*, **42**, 21-27.

Table 1. Background information on Townsville and Kalgoorlie-Boulder office occupant samples.

	Location	Townsville		Kalgoorlie-Boulder	
	Season	Dry	Wet	Winter	Summer
	Sample Size	628	606	640	589
% of gender	Male	42.4	41.1	50.9	53.8
	Female	57.6	58.9	49.1	46.2
Age (years)	Mean	33.9	32.8	35.4	35.6
	Standard deviation	10.5	10.0	10.2	10.1
	Maximum	64.0	62.0	67.0	66.0
	Minimum	17.0	17.0	16.0	17.0
Height (cm)	Mean	170.2	169.9	170.2	171.6
	Standard deviation	9.8	9.9	10.0	10.3
	Maximum	198.0	198.0	204.0	207.0
	Minimum	148.7	130.0	150.0	150.0
Weight (kg)	Mean	69.5	69.2	74.8	75.7
	Standard deviation	14.8	14.7	16.6	16.4
	Maximum	126.0	145.0	135.0	168.0
	Minimum	37.0	40.0	40.0	42.0
Number of years in location	Mean	20.5	20.8	10.1	10.0
	Standard deviation	14.5	14.0	12.7	12.9
	Maximum	64.5	59.9	57.0	58.0
	Minimum	0.0	0.0	0.0	0.0
% at education level	High school	54.0	52.6	33.8	28.8
	Diploma/degree	39.6	41.2	52.5	55.6
	University postgrad	6.4	6.2	13.7	15.6
% with primary language	English	98.6	98.5	96.5	94.9
	Other	1.4	1.5	3.5	5.1
% using home air-conditioning 'at this time of year'	Yes	2.4	14.7	6.8	48.6
	No	62.9	48.1	88.6	46.9
	Not available	34.7	37.2	4.6	4.5

Table 2. Spearman rank correlation coefficients (*: $p < 0.001$, ^: $p < 0.05$ for significance levels) of Townsville and Kalgoorlie-Boulder subjects' thermal sensation on scale of -3 (cold) to +3 (hot) with physical thermal variables, subjects' characteristics and perceptions.

Location	Townsville	Kalgoorlie-Boulder
Sample Size	836	935
ASHRAE thermal sensation – rated by subjects on a scale of -3 (cold) to +3 (hot)		
Indoor operative temperature ($^{\circ}\text{C}$)	0.44*	0.16*
Indoor vapour pressure (kPa)	0.17*	-0.06^
Indoor air velocity (m s^{-1}) (average of 3 heights)	-0.03	-0.22*
Outdoor air temperature ($^{\circ}\text{C}$)	0.06^	-0.11*
Outdoor vapour pressure (kPa)	0.06^	-0.09^
Metabolism (met)	0.02	0.13*
Time of survey (24 h)	0.03	0.13*
Body mass index (kg m^{-2})	-0.01	0.06
Body surface area (m^2)	-0.04	-0.04
Clothing and chair insulation (clo)	-0.16*	0.01
Age (years)	-0.03	-0.03
Acceptability of work area air movement 'at the moment' (very unacceptable to very acceptable)	-0.15*	-0.26*
Preference for work area air movement 'at the moment' (less, no change, more)	0.31*	0.37*
Acceptability of work area air movement 'on average' (very unacceptable to very acceptable)	-0.06	-0.21*
Preference for work area air movement 'on average' (more, no change, less)	-0.16*	-0.26*
Perception of work area temperature 'on average' (very cool to very warm)	0.45*	0.49*
Perception of work area humidity 'on average' (very dry to very humid)	0.20*	0.17*
Health index (sum of 10 health symptom frequencies; never to very often)	-0.02	0.14*

Table 3. Summary of Townsville and Kalgoorlie-Boulder indoor atmospheric measurements, calculated thermal comfort indices and subjects' thermal sensation on scale of -3 (cold) to +3 (hot).

Location		Townsville		Kalgoorlie-Boulder	
Season		Dry	Wet	Winter	Summer
Sample Size		627	604	640	589
Air temperature (° C) (average of 3 heights)	Mean	23.3	23.6	22.0	23.4
	Standard deviation	0.9	1.0	1.4	1.4
	Maximum	25.7	27.6	24.5	30.5
	Minimum	20.1	21.3	16.0	19.1
Relative humidity (%)	Mean	50.8	56.3	46.1	41.5
	Standard deviation	8.7	6.3	6.6	8.8
	Maximum	69.0	71.0	69.8	66.1
	Minimum	34.0	44.0	31.6	24.5
Air velocity (m s ⁻¹) (average of 3 heights)	Mean	0.12	0.13	0.13	0.20
	Standard deviation	0.03	0.04	0.06	0.11
	Maximum	0.25	0.66	0.68	1.57
	Minimum	0.10	0.10	0.04	0.05
Operative temperature (° C)	Mean	23.4	23.8	22.1	23.7
	Standard deviation	0.9	1.0	1.3	1.4
	Maximum	25.7	27.7	24.5	31.7
	Minimum	19.8	21.2	16.6	19.8
Effective temperature (° C) (incl. chair insulation)	Mean	23.4	23.9	22.1	23.5
	Standard deviation	0.9	1.0	1.3	1.3
	Maximum	25.6	28.1	24.5	29.7
	Minimum	19.9	21.2	16.7	19.6
Predicted Mean Vote (incl. chair insulation)	Mean	0.1	0.0	-0.1	-0.2
	Standard deviation	0.5	0.5	0.5	0.6
	Maximum	1.2	1.5	1.0	1.9
	Minimum	-1.9	-1.6	-2.2	-3.0
ASHRAE thermal sensation – rated by subjects on a scale of -3 (cold) to +3 (hot)	Mean	-0.4	-0.3	0.4	0.1
	Standard deviation	1.1	1.1	1.0	1.1
	Maximum	3.0	3.0	3.0	3.0
	Minimum	-3.0	-3.0	-3.0	-3.0