RESEARCH

THE RELATIONSHIP BETWEEN COMFORT PERCEPTIONS AND ACADEMIC PERFORMANCE IN UNIVERSITY CLASSROOM BUILDINGS

Simi Hoque[1] and Ben Weil[2]

ABSTRACT

This paper presents preliminary data on a series of building comfort experiments conducted in the field. We performed physical in-situ measurements and solicited responses from 409 (184 female; 225 male) university students in six different classrooms at the University of Massachusetts-Amherst during three seasons (fall, winter and spring). Our questions focused on student perception of comfort in varied environmental (temperature and humidity, and air speed) conditions. We collected records of student academic performance in the classes, correlating their comfort perceptions to their test scores. Statistical analysis of classroom environmental variables, thermal satisfaction, and student scores suggest that by enhancing thermal comfort, we can improve academic performance.

KEYWORDS

thermal comfort, student performance, university classrooms, energy conservation

1. INTRODUCTION AND BACKGROUND

Indoor Environment Quality (IEQ) impacts occupant productivity [1]. Occupant performance is correlated to healthy indoor air, as well as acoustic, thermal and visual comfort [2-4]. Despite this, building engineers and managers design and operate buildings with the perspective that IEQ is maintained through a constant and uniform environment. Static models set fixed parameters for temperature, humidity, and air flow regardless of outdoor climate, occupant preference, and context. This approach leads to an increased reliance on mechanical controls and potentially energy intensive systems for thermal conditioning. These impacts have an additional academic penalty when the building serves an educational purpose. Though numerous studies suggest poor indoor air quality (IAQ) affects student performance [5-7], air quality and ventilation rates are not the whole story [8, 9]. The hypothesis of this research was that student performance suffers when students feel discomfort and increasing thermal satisfaction in university classrooms should translate into improved academic achievement among students.

1. Dept. of Environmental Conservation, University of Massachusetts-Amherst, simih@eco.umass.edu.

2. Dept. of Environmental Conservation, University of Massachusetts-Amherst, bweil@eco.umass.edu.

Research on human thermal comfort began in the 1960s [10] and has been the basis for a number of comfort models and standards [11] that drive the design and operation of indoor environmental systems. These models are based on the idea that despite different climates, living conditions, and cultures, the temperature range people find comfortable under similar conditions of clothing, activity, humidity, and air movement are equivocal [12-14]. Quantifying the thermal comfort of a body in an environment involves measuring independent environmental parameters like air temperature, mean radiant temperature, relative humidity, and relative air velocity as well as independent personal variables such as metabolic activity and clothing. These parameters are modeled in aggregate to analyze the relationship between the environmental and physiological factors. The model is then used to produce a thermal sensation scale known as the PMV (Predicted Mean Vote) [10].

An understanding of occupant needs is important for the building and operations process--from designers, engineers, and developers to facility managers. Research has demonstrated that IEQ has considerable impact on human health, stress, productivity and wellbeing [15-18]. This has largely been driven by the awareness that IEQ issues impact office-based workforces and sick building syndrome [1]. Much of the existing scholarship is focused on quantifying the relationship between occupant comfort and thermal conditions (temperature and relative humidity), acoustic quality, IAQ, and visual access, based on the adaptive comfort model. The adaptive comfort model, in contrast to heat balance models, suggests comfort is a variable condition influenced by behavioral, physiological, and psychological processes [19, 20]. Adaptive models provide evidence on how people naturally adapt or make adjustments to themselves and their surroundings to reduce discomfort.

There are a range of direct and indirect mechanisms influencing comfort, such as outdoor conditions, gender, age, clothing, activity schedules or levels, as well as control over air movement, ventilation, and local temperatures. However, little is known about whether and how much perceptions of comfort affect academic performance [21]. As mentioned above, most studies on the link between thermal comfort and performance focus on productivity, stress, and well-being in commercial office settings [1]. Lee, et al. [22] analyzed IEQ in air conditioned university classrooms in Hong Kong against self-reported learning performance, where respondents used a percentage value to best describe their own performance in four learning-related activities: calculating, reading, understanding and typing. Bell, et al. [23] examined the relationship between clothing comfort and cognitive performance; student test scores were compared against comfort ratings in a single class. While these studies suggested a relationship between perceived comfort and academic achievement, there is little information available about how environmental parameters influence *both* sensations of thermal discomfort *and* student performance. The purpose of this research is to quantify the relationship between thermal comfort parameters (temperature, humidity, and air speed), the psychological comfort, and academic performance (test scores). This paper presents preliminary analyses of measurements from 409 students in six different classrooms during three different seasons.

2. METHOD

This study was conducted at University of Massachusetts-Amherst during a nine-month period between January-May (spring term) and September-December (fall term) 2013. It focused on classroom teaching activities typically scheduled between 9:00 a.m. and 6:00 p.m. from Monday to Friday. We solicited faculty who would be willing to participate and collected data on class meeting time, location, and nominal room capacity. Preliminary class capacity assessments were made to ensure our study population would contain a sufficient number of respondents.

As per requirements for human subject research, we applied for and were approved by the University's Institutional Review Board (IRB) for this study (IRB Protocol Number 2013-1614). Following approval, we developed the questionnaire and obtained informed consent from the subject population. All of the procedures used in this study were conducted in accordance with principles and procedures for the protection of human subjects.

2.1 Study Area

This analysis focuses on four different buildings (B-type) in three 60-seat seminar rooms (S-type) and three 80-seat lecture halls (L-type). Table 1 provides additional characteristics of the six different rooms analyzed. Data collection and surveys were conducted on weekdays during specific class periods Monday–Friday, 10:30 a.m. – 3:30 p.m. during the spring and fall terms.

TABLE 1. Characteristics of the classrooms.

Classroom	#students/ room capacity	Month of study	Windows	HVAC system	HVAC operating during data collection
S-B1	55/58	November	Yes, open partially	Radiant ceiling	Yes
S-B2	60/64	December	Yes, closed	Forced Hot Air	Yes
S-B3	63/60	April	Yes, closed	Convector	Yes
L-B1	77/80	March	Yes, closed	Radiant ceiling	Yes
L-B2	82/81	October	Yes, closed	Forced Hot Air	Yes
L-B3	72/80	February	No	Convector	No

Air speed, temperature and humidity parameters were collected in each classroom using a Kestrel Meter 4400 at six different points, at student head height, over the class period (approximately 75 minutes) and averaged. Outdoor measurements for temperature and humidity were also taken using a Kestrel 4400 weather meter. Instruments were calibrated according to the manufacturer's instructions prior to every measurement. These instruments were within 99% accuracy based on calibration tests. MRT, or Mean Radiant Temperature, is

TABLE 2. Average values for environmental parameters in and around classrooms.

Classroom	Outdoor temp (°F, °C)	Indoor temp (°F, °C)	Outdoor RH (%)	Indoor RH (%)	Indoor air speed (FPM, L/s)	MRT (°F, °C)
S-B1	56 (13)	68 (20)	96%	75%	236 (119)	76 (24)
S-B2	10 (-12)	72 (22)	89%	38%	100 (51)	80 (27)
S-B3	67 (19)	76 (24)	59%	43%	120 (61)	83 (28)
L-B1	30 (-1)	80 (27)	41%	50%	100 (51)	86 (30)
L-B2	39 (4)	74 (23)	57%	28%	100 (51)	78 (26)
L-B3	20 (-7)	70 (21)	86%	22%	100 (51)	80 (27)

a parameter used to describe the overall radiant temperature of the room and can sometimes reflect more accurately an occupant's thermal sensation. MRT was calculated in each classroom using the globe temperature reading from the Kestrel meter based on ISO 7726 [24]. Data are presented in Table 2.

2.2 Student Population

Cross-sectional data were collected from students (*N*=409) enrolled in six different undergraduate courses at the University of Massachusetts. These were second or third year science or engineering courses. Data about student gender and age were collected. The mean age was 20.7 (*SD* = 4.2 years); 45% (*n*=184) were female.

We measured the environmental parameters on the day the students took an exam and collected data on thermal comfort perceptions from the students. The final three questions on the exam were questions pertinent to this study. Students were asked for gender, age, and to characterize their comfort level using the ASHRAE descriptive scale based on ISO 7730 [25] (Table 3). While the ASHRAE thermal sensation scale is a seven-point scale, we used a collapsed five-point Likert scale to assure statistical robustness. Using an ordinal scale with a large number of choices increases the likelihood that for any given replicate, there might be a small sample size selecting any given choice [26]. We did not collect data about clothing or activity prior to class though these data may have had some influence on comfort perceptions. We assumed typical winter indoor clothing with a large portion of the students wearing heavy overcoats over thermal layers (Clo = 1.1) because data collection took place largely during the colder months with outdoor temperature ranging from -12 to 19°C. This was confirmed by observation, where a majority of students removed their overcoats but kept on thermal layers. The metabolic rate was calculated as a time-weighted average of sitting for a test for 45 min and walking to class for 15 min (Met = 1.2).

We asked questions that would require little time and effort, to minimize the data collection time, i.e., not interfere with the exam.

TABLE 3. Indicators using a modified thermal comfort scale.

ASHRAE descriptor	Thermal Comfort Scale	Numerical equivalent
Hot	Hot	2
Warm	Warm	1
Slightly warm		
Comfortable	Neutral	0
Slightly cool	Cool	-1
Cool		
Cold	Cold	-2

2.3 Academic Performance Measurements

We obtained the student exam scores, calculated from 0 to 100, and responses to the three study questions. Statistical methods, including Pearson's correlation, multiple hierarchical linear regression, and ANOVA were used to analyze data to define the association between environmental parameters, comfort indicators, and test scores. SPSS was used for statistical analysis [27]. The aim was to find the combination of thermal variables (temperature, humidity, and air speed) which the students considered 'neutral' or 'comfortable' and associate this with their test scores.

3. RESULTS

3.1 Comfort perception and academic performance

Due to the inherently subjective nature of comfort, the first question of interest is whether there is a relationship between self-reported comfort and performance as measured by test scores. We converted the comfort scale (-2, cold; 0, neutral; +2, hot) using absolute values to a discomfort scale (0, comfortable; 2, high thermal discomfort) to evaluate this question. The discomfort scale is useful because there is no consensus in the literature regarding the relative impact of feeling too hot or too cold. Also, as discussed below, we found only a very weak relationship between actual dry bulb temperature and individual self-reported perception of feeling cold or hot. Prior to analysis, checks of the assumptions of normality, linearity, and homoscedasticity were met. As evident in table 4, increased thermal discomfort is associated with lower mean test scores. Indeed, there was a statistically significant negative correlation between thermal discomfort and test scores ($p < 0.001$). The negative correlation meant, in general, students who felt thermal discomfort performed worse on tests than those with no thermal discomfort. Following Cohen [28] a correlation (r) of +/-0.5 should be considered large. In addition, the effect size ($\eta 2= .338$) indicated approximately 34% of the variance is accounted for by thermal discomfort. Given most of the variance in test scores may likely be attributable to factors not measured in this study, such as the difficulty of the material, whether students studied well and the natural aptitude of the students, this effect size is large.

TABLE 4. Test score means, standard deviations, and sample size for three levels of thermal discomfort.

Thermal Discomfort	N	Mean Test Score	Std. Deviation
no thermal discomfort	129	89.9	6.63
moderate thermal discomfort	198	85.1	7.49
high thermal discomfort	82	75.3	7.62
Total	409	84.7	8.89

A one-way analysis of variance (ANOVA) was calculated on the test scores comparing groups by their levels of thermal discomfort. The analysis was significant, $F(2,406) = 103.5$, $p < 0.0001$. Participants with no thermal discomfort had higher test scores than those with more thermal discomfort, and those with moderate thermal discomfort had higher test scores than those with high thermal discomfort (see Table 4 for means and standard deviations). Cohen's [28] effect size f was calculated for the ANOVA, $f = 0.57$. This is considered a large effect. Comparisons indicated that all differences between groups were significant. The effect size r was calculated for all t-tests. The "high thermal discomfort" condition was significantly different from the "moderate thermal discomfort" condition, $t(278) = 9.95$, $p < 0.0001$,$r = 0.51$. The "high thermal discomfort" condition was significantly different from that for "no thermal discomfort," $t(209) = 14.75$, $p < 0.0001$,$r = 0.71$. The "moderate thermal discomfort" condition was significantly different from the "no thermal discomfort condition," $t(325) = 5.92$, $p < 0.0001$,$r = 0.31$. While almost half of the difference between "high discomfort" and "no discomfort" groups may be related to their thermal discomfort, only 9% of the difference between moderate and no discomfort groups may be related to thermal discomfort. As evident in the box plot in figure 1, however, there is a high degree of variability in test scores; thermal discomfort alone may not be used to predict test score outcomes.

None of the other variables, including age, gender, class size, number of students, and environmental variables (such as temperature and humidity) were correlated to, or showed any significant mean difference in mean test scores.

3.2 Factors influencing comfort perception

The combination of six well known factors to define thermal comfort should be more predictive of reported comfort rating [11]. We used Fanger's comfort calculation [29] to compare the predicted mean vote (PMV) to the actual mean comfort rating reported by study participants for each room. Of the six factors, air and globe temperature, air speed, and relative humidity, were recorded directly. Metabolic rate and clothing level were applied as average values. For convenience, we entered these values into the *CBE Thermal Comfort Tool* [30]. The PMV values and the mean comfort rating values used appear in table 5.

FIGURE 1: Plot of Thermal Discomfort against Test Scores.

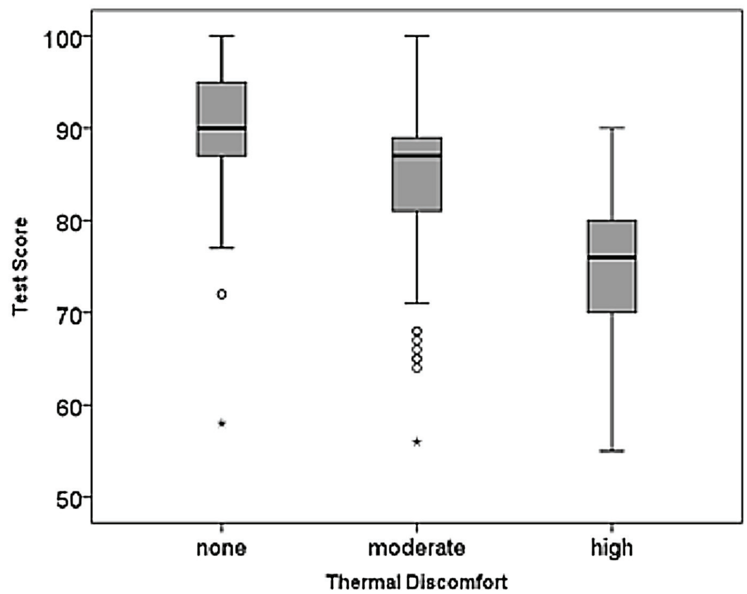
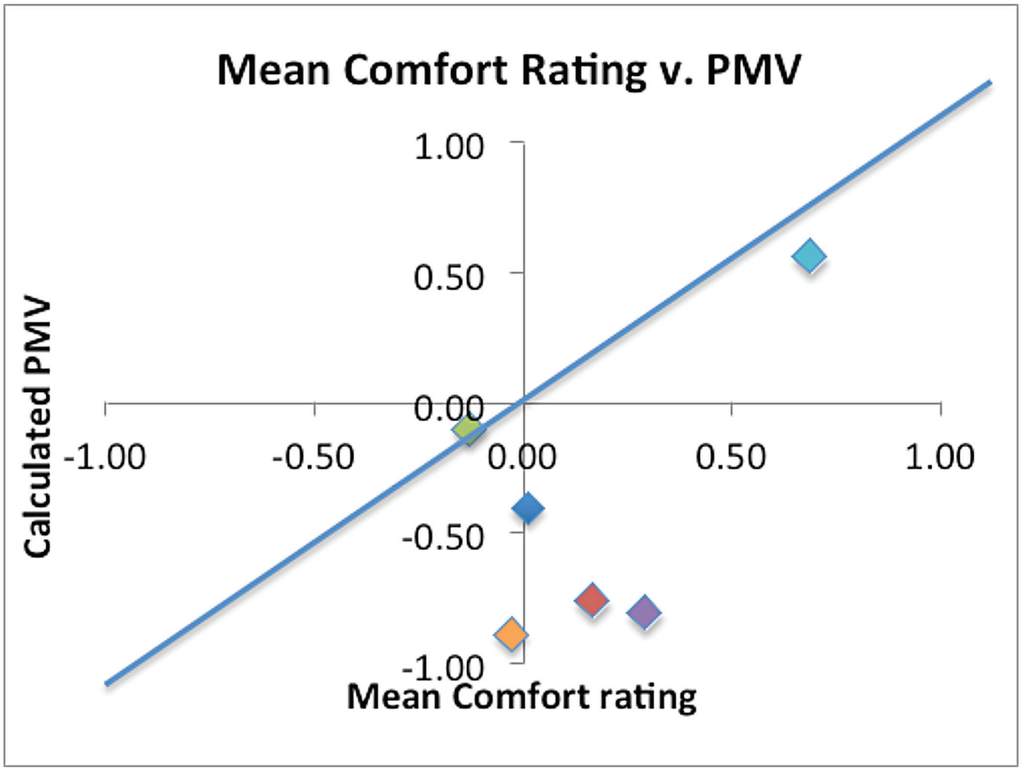


TABLE 5. PMV values and mean comfort rating values.

Room	Mean Comfort	PMV
S-B1	0.01	-0.40
S-B2	0.17	-0.76
S-B3	-0.13	-0.10
L-B1	0.29	-0.81
L-B2	0.69	0.56
L-B3	-0.03	-0.89

These values are only weakly correlated, without statistical significance (r= 0.556, p = 0.252). To the degree these values are correlates, there might be an indication of some similarity in direction, but the values are almost unrelated because PMV calculated values are negative (i.e., "cool") while the reported values are mostly positive (i.e., "warm"). As shown in figure 2, only two of the classrooms mean comfort rating and PMV lie near the 1:1 correspondence line.

FIGURE 2: Correspondence between mean comfort rating and calculated PMV.



In the above analysis, we used the absolute value of the participant's comfort rating in part because of the weak relationship between measured dry bulb temperature and reported thermal perception. Comfort on a scale from "too cold" = -2 to "too hot" = +2 was weakly correlated (r=0.122) to indoor measured temperature (p=0.014). Some other combination of factors may help to better explain thermal comfort ratings. Factors we considered included how crowded a room might feel, radiant asymmetry, gender, and age. The crowding variable was calculated as a ratio of room population to room capacity. Radiant asymmetry was calculated based on the relative difference between the measured average air temperature and MRT. As shown in table 6, none of these variables were strongly correlated to comfort; however, small correlations were significant. We hypothesized a linear hierarchical regression model could be constructed, such that these variables together explain variability in thermal comfort better than any single variable separately.

TABLE 6. Mean, Standard Deviations, and Correlation Coefficients among variables

Variable	Mean	SD	1	2	3
1. **Comfort**	0.17	1.122			
2. **Gender**	0.46	0.499	-0.251**		
3. **Radiant Asymmetry**	0.581	0.282	-0.142**	-0.002	
4. **Room Fill**	0.953	0.062	-0.175**	0.019	0.261**

None of the variables were correlated above 0.3, suggesting an absence of multi-collinearity. Prior to analysis checks of the theoretical assumptions underlying multiple regression were undertaken, including normality, linearity, and homoscedasticity. The assumptions were met, and a hierarchical regression analysis controlling for gender was undertaken. Each variable was entered as a separate step to assess the impact of each variable on the strength of the model (Table 7).

TABLE 7. Hierarchical Regression Predicting Thermal Comfort Rating.

		Total Sample (N=409)
Variables		β
Step 1.		
Gender	$F(1, 407) = 27.334$	-.251**
	$R^2 = 0.063$	
Step 2.		
Control		
Gender		-.248**
Predictor		
Room Filled	$F(2, 406) = 20.560$	-.170**
	$R^2 = 0.092$	
	$\Delta R^2 = 0.029$	
Step 3.		
Control		
Gender		-.248**
Room Filled		-.143**
Predictor		
Radiant Asymmetry	$F(3, 405) = 15.393$	-.106*
	$R^2 = 0.102$	
	$\Delta R^2 = 0.010$	

Note β = Standardized beta coefficients
* p < 0.05, **p < 0.001

This combination of variables significantly predicted comfort rating; three variables significantly contributed to the prediction and gender contributed the most, as females were slightly more likely than males to report feeling cold. Even so, the R^2 value was only 0.1, suggesting this model only explained 10% of the variance.

4. DISCUSSION

This study attempted to associate thermal satisfaction and student scores. Data suggested by enhancing thermal comfort, we can improve academic performance. If high thermal discomfort is a factor in decreased academic performance (as measured by test scores), then the practical implication is to increase the emphasis in providing increased thermal comfort in academic, office and other buildings where occupant performance is highly valued. However, because thermal perception is apparently difficult to predict using environmental variables, this study offers little guidance for assuring thermal comfort. This creates a greater challenge for facilities management staff who are responsible for maintaining building temperature and humidity set points, and complicates building HVAC systems design and sizing strategies because we may know less about how to quantify comfort in high occupancy buildings. The lack of association between environmental variables and thermal comfort perception – and the small effect size of associated variables—suggested a large variety of factors may lead to varying of different perceptions of comfort. Though not demonstrated by this study, it seems likely each individual may experience a wide range of thermal comfort responses to the same environmental stimuli at different times and in different emotional or social contexts.

One artifact of a collapsed Likert scale with five instead of seven gradations, is that "-1" and "+1" cannot be interpreted as "acceptable" as they are in the seven-point ASHRAE scale. Because +2 and -2 are the most extreme choices available, these necessarily indicate the highest level of thermal discomfort. Since respondents had only their own perceptions as reference points, there is no way to standardize their responses (i.e., to be sure that one person's "-2" is not equivalent to another person's "-1"). However, within the acknowledged limitations correlational studies such as this one, in the aggregate the response vector allows for a reasonable assessment of effect size even if the dimensions of the ordinal values are of unknown (or unknowable) [31]. It is worth noting the limitations of a comparison between our five-point scale and the seven-point scale of the PMV including the necessarily generalized assumptions we used to calculate the PMV for each replicate. The purpose here is not to question the validity or robustness of the PMV method, but rather to contextualize the counterintuitive findings of this exploratory study.

The results of this study are exploratory and associational, and thus it is impossible to determine causation. A future research design would involve controlled experimental conditions. These would include providing identical educational content to research subjects, controlling the air temperature, humidity, air speed and surface temperatures (this study used existing conditions not controlled by the researchers). This would allow not only control and test groups (for between group effects), but also control of temperature extremes (the temperatures in this study were warmer than may be typical, and had no examples of atypically cool temperatures). Other environmental variables potentially assessed in future studies include ventilation rates, wall colors and light color temperatures, as these factors may also contribute to perceptions of thermal comfort [32].

REFERENCES

1. Kim, J. and R. de Dear, Nonlinear relationships between individual IEQ factors and overall workspace satisfaction. *Building and Environment, 2012*. 49(0): p. 33-40.
2. Fisk, W.J. and A.H. Rosenfeld, Estimates of Improved Productivity and Health from Better Indoor Environments. *Indoor Air, 1997*. 7(3): p. 158-172.
3. Shendell, D.G., et al., Associations between classroom CO2 concentrations and student attendance in Washington and Idaho. *Indoor Air, 2004*. 14(5): p. 333-341.
4. Mumovic, D., et al., Winter indoor air quality, thermal comfort and acoustic performance of newly built secondary schools in England. *Building and Environment, 2009*. 44(7): p. 1466-1477.
5. Bakó-Biró, Z., et al., Ventilation rates in schools and pupils' performance. *Building and Environment, 2012*. 48(0): p. 215-223.
6. Haverinen-Shaughnessy, U., D.J. Moschandreas, and R.J. Shaughnessy, Association between substandard classroom ventilation rates and students' academic achievement. *Indoor Air, 2011*. 21(2): p. 121-131.
7. Clements-Croome, D.J., et al., Ventilation rates in schools. *Building and Environment, 2008*. 43(3): p. 362-367.

8. Corgnati, S.P., M. Filippi, and S. Viazzo, Perception of the thermal environment in high school and university classrooms: Subjective preferences and thermal comfort. *Building and Environment, 2007*. 42(2): p. 951-959.
9. de Giuli, V., Indoor environmental quality and pupil perception in Italian primary schools. *Building and Environment, 2012*. 56: p. 335-345.
10. Fanger, P.O., *Thermal Comfort Analysis and Applications in Environmental Engineering* 1970, New York: McGraw-Hill.
11. ASHRAE, Standard 55 Thermal Environmental Conditions for Human Occupancy, ASHRAE, Editor 2010, American Society of Heating Ventilating and Air Conditioning Engineers: Atlanta.
12. Fanger, P.O., Thermal Comfort1972, New York: McGraw-Hill.
13. de Dear, R.J. and K.G. Leow, Indoor climate and thermal comfort in high-rise public housing in an equatorial climate: A field-study in Singapore. Atmospheric Environment. Part B. *Urban Atmosphere, 1990*. 24(2): p. 313-320.
14. Busch, J.F., A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in Thailand. *Energy and Buildings, 1992*. 18(3–4): p. 235-249.
15. Fisk, W.J., Health and Productivity Gains from Better Indoor Environments and their Relationship with Building Energy Efficiency Annual Review of Energy and the Environment, 2000. 25(1): p. 537-566.
16. Niemelä, R., et al., The effect of air temperature on labour productivity in call centres—a case study. *Energy and Buildings, 2002*. 34(8): p. 759-764.
17. Humphreys, M.A. and J.F. Nicol, Self-Assessed Productivity and the Office Environment: Monthly Surveys in Five European Countries. *ASHRAE Transactions, 2007*. 113(1): p. 606-616.
18. Loftness, V., et al., Elements That Contribute to Healthy Building Design. *Environmental Health Perspectives, 2007*. 115(6): p. 965–970.
19. Fountain, M., G. Brager, and R. de Dear, Expectations of indoor climate control. *Energy and Buildings, 1996*. 24(3): p. 179-182.
20. Nicol, J.F. and M.A. Humphreys, Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings, 2002*. 34(6): p. 563-572.
21. Frontczak, M. and P. Wargocki, Literature survey on how different factors influence human comfort in indoor environments. *Building and Environment, 2011*. 46(4): p. 922-937.
22. Lee, M.C., et al., Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms. *Building and Environment, 2012*. 49(0): p. 238-244.
23. Bell, R., A.V. Cardello, and H.G. Schutz, Relationship Between Perceived Clothing Comfort and Exam Performance. *Family and Consumer Sciences Research Journal, 2005*. 33(4): p. 308-320.
24. Ergonomics of the thermal environment - Instrument for measuring physical quantities, in ISO 77261998: Geneva, Switzerland.
25. Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, in ISO 77302005: Geneva, Switzerland.
26. Norman, G., Likert scales, levels of measurement and the "laws" of statistics. *Advances in Health Sciences Education, 2010*. 15(5): p. 625-632.
27. IBM SPSS Statistics for Windows, 2013, IBM Corp.: Armonk, NY.
28. Cohen, J., *Statistical Power Analysis for the Behavioral Sciences*. 2nd. edition ed1988: Lawrence Erlbaum Associates.
29. Fanger, P.O., *Thermal Comfort 1982*, Malabar, Florida: Robert E. Krieger Publishing Company.
30. Hoyt, T., et al. CBE Thermal Comfort Tool. 2013; Available from: http://cbe.berkeley.edu/comforttool/.
31. Gaito, J., Measurement scales and statistics: Resurgence of an old misconception. Psychological Bulletin, 1980. 87: p. 564-567.
32. de Giuli, V., et al., Measurements of indoor environmental conditions in Italian classrooms and their impact on children's comfort. *Indoor and Built Environment 2014* (24): p. 689-712.