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Cold comfort: thermal satisfaction in academia

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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 university students in six different classrooms at the University of Massachusetts-Amherst during three seasons (fall, winter and spring). Our questions focused on the students' perception of comfort in varied environmental (temperature and humidity, and air speed) conditions. We collected records of the students' 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

The quality of the indoor environment (IEQ) impacts occupant productivity (Kim and de Dear, 2012). Occupant performance is correlated to healthy indoor air, as well as acoustic, thermal and visual comfort (Fisk and Rosenfeld, 1997, Shendell et al., 2004, Mumovic et al., 2009). 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.

Good quality indoor environments depend on proper building design, operation, and maintenance. This directly influences building energy use. Poorly performing buildings are not only uncomfortable and energy intensive, they are also more expensive to operate. These impacts have an additional academic penalty when the building serves an educational purpose. Though numerous studies show that poor indoor air quality (IAQ) affects student performance (Bakó-Biró et al., 2012, Haverinen-Shaughnessy et al., 2011, Clements-Croome et al., 2008), air quality and ventilation rates are not the whole story (Corgnati et al., 2007, De Giuli, 2012). The hypothesis of this research is that student performance suffers when students feel discomfort and increasing thermal satisfaction in university classrooms should translate into improved academic achievement among students.

2 Background

Research on human thermal comfort began in 1970 (Fanger, 1970) and has been the basis for a number of comfort models and standards (ASHRAE, 2010) 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 that people find comfortable under similar conditions of clothing, activity, humidity, and air movement are remarkably equivocal (Fanger, 1972, de Dear and Leow, 1990, Busch, 1992). Quantifying the heat exchange between a body and the environment involves developing heat balance models, where independent environmental parameters (air temperature, mean radiant temperature, relative humidity, and relative air velocity) are measured in addition to independent personal variables such as metabolic activity and clothing.

Understanding occupants' needs is important for all actors involved in the building and operation process--from designers, engineers, and developers to facility managers. Research has demonstrated that the quality of the indoor environment has considerable impact on human health, stress, productivity and wellbeing (Fisk, 2000, Niemelä et al., 2002, Humphreys and Nicol, 2007, Loftness et al., 2007). This has largely been driven by the awareness that IEQ issues impact office-based workforces and sick building syndrome. Much of the existing scholarship is focused on quantifying the relationship between occupant comfort and thermal conditions (such as temperature and humidity), acoustic quality, air quality, and visual access, based on the adaptive comfort model. The adaptive comfort model, in contrast to heat balance models, suggests that comfort is a variable condition that is influenced by behavioral, physiological, and psychological processes (Fountain et al., 1996, Nicol and Humphreys, 2002). Adaptive models provide evidence that people naturally adapt or make adjustments to themselves and their surroundings to reduce discomfort.

There are a range of direct and indirect mechanisms that influence 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 (Frontczak and Wargocki, 2011). (Lee et al., 2012) analyzes (thermal, indoor air, visual and acoustic) IEQ in air conditioned university classrooms in Hong Kong against self-reported learning performance where respondents used a percentage value that best described their own performance in four learning-related activities, calculating, reading, understanding and typing. (Bell et al., 2005) examines the relationship between clothing comfort and cognitive performance, where student test scores are compared against comfort ratings in a single class. While these studies suggest that there is 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). There are no published examples of studies that take all three variables into account and this paper presents preliminary analysis of measurements from 409 students in six different classrooms during three different seasons.

3 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 focuses on classroom teaching activities that are typically scheduled between 9:00 a.m. and 6:00 p.m. 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.

3.1 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 that were analyzed. All data collection and surveys were conducted on weekdays during the class period (Monday–Friday, 10:30–3:30 p.m.) during the spring and fall terms.

Table 1. Characteristics of the classrooms

Classroom	#students /room capacity	Month of study	Windows	HVAC system	Operating during data collection
S-B1	55/58	November	Yes, open	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 4500 at six different points in the volume over the class period and averaged. Outdoor measurements for temperature and humidity were also taken using a Kestrel 4500 weather meter. All instruments were calibrated according to the manufacturer's instructions prior to all measurements. The data are presented in Table 2.

Table 2. Environmental parameters in and around classrooms

Classroom	Outdoor temp (ºF)	Indoor temp (ºF)	Outdoor RH (%)	Indoor RH (%)	Indoor air speed (FPM)
S-B1	56	68	96%	75%	236
S-B2	10	72	89%	38%	100
S-B3	67	76	59%	43%	120
L-B1	30	80	41%	50%	100

L-B2	39	74	57%	28%	100
L-B3	20	70	86%	22%	100

3.2 Student Population

Cross-sectional data were collected from students (*N*=409) enrolled in six different undergraduate courses at the University of Massachusetts. The courses were all second or third year courses and we collected data about student gender and age. The mean age was 20.7 (*SD* = 4.2 years); 45% (*n*=184) were female. All of the procedures used in this study were conducted in accordance with principles and procedures for the protection of human subjects.

We measured the environmental parameters on the day the students took an exam as well 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 their gender, age, and to characterize their comfort level using the ASHRAE descriptive scale (Table 3). We did not collect data about ethnicity, clothing, or activity prior to class though these data may have had some influence on comfort perceptions. We decided instead to ask questions that would require very little time and effort, in order to minimize the data collection time (to not interfere with the exam). Every effort was made to keep interventions by the researchers to a minimum.

Table 3. Comfort Indicators using the ASHRAE scale

Answer	ASHRAE descriptor	Numerical equivalent
A	Hot	2
B	Warm	1
C	Neutral	0
D	Cool	-1
E	Cold	-2

3.3 Academic Performance Measurements

We obtained the student exam scores, which were calculated from 0 to 100, as well as their responses to our three study questions. Statistical methods were used to analyze the data to define the association between environmental parameters, comfort indicators, and test scores. The aim was to find the combination of thermal variables (temperature, humidity, and air speed) which the students consider ‘neutral’ or ‘comfortable’ and associate this with their test scores.

4. Results

4.1 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 test scores. Indeed, there is a statistically significant negative correlation between thermal discomfort and test scores $r(408) = -0.564$, $p < 0.001$. The negative correlation means that, in general, students who felt thermal discomfort performed worse on tests than those with no thermal discomfort. Following Cohen (1988) a correlation (r) of +/-0.5 should be considered to be large for a difficult to control area of research. In addition, the effect size ($\eta 2 = .338$) indicates that approximately 34% of the variance is accounted for by thermal discomfort. Given that one would expect most of the variance in test scores to 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 remarkably large.

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

Thermal Discomfort	Mean Test Score	N	Std. Deviation
no thermal discomfort	89.95	129	6.625
thermal discomfort moderate	85.09	198	7.486
thermal discomfort high	75.26	82	7.620
Total	84.65	409	8.891

As evident in the box plot in figure 1, however, there is a high degree of variability in test scores, such that thermal discomfort is not highly predictive of test score outcomes.

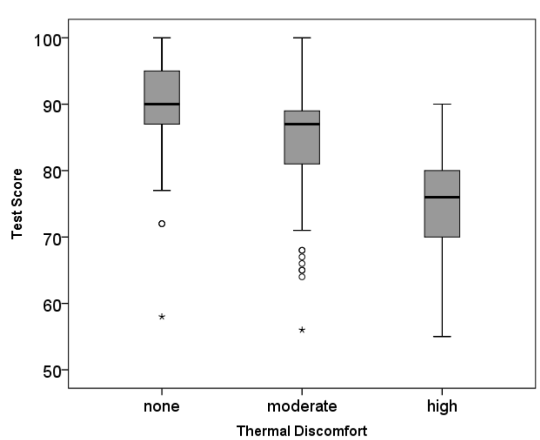

Figure 1. Plot of Thermal Discomfort against Test Scores

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 test scores. Thus, in general, roughly a third of the variability in test scores is explained, not by the typically expected social and academic variables, but by the student's perceived thermal discomfort.

4.2 Factors influencing comfort perception

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 is weakly correlated to indoor measured temperature, $r(408)=0.122$, $p=0.014$. Most likely, some other combination of factors would 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 as the ratio of the lowest and highest surface temperatures in the room. For radiant ceilings, the mean surface temperature was assumed to be 10°F above the mean room air temperature. Floors were assumed to be 2°F below room air temperature. Interior walls were assumed to match mean air temperature. To calculate exterior window and wall temperatures, we used known R-values for the specific building elements in question and indoor and outdoor air temperatures to calculate surface air temperatures using the following equation.

$$T_s = \frac{(T_{in} - T_{out})}{(T_{in})} \times \frac{R_{af}}{R_{asbl}}$$

Where
T_s = temperature of the inside surface
T_{in} = inside air temperature
T_{out} = outside air temperature
R_{af} = R value of the inside air film
R_{asbl} = R value of the wall or window assembly

As shown in table 5, none of these variables are strongly correlated to comfort. Despite small correlation coefficients (r), and thus small effect sizes, the correlations are significant and worth exploring. We hypothesized that 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 5. Mean, Standard Deviations, and Correlation Coefficients among variables

Variable	Mean	SD	1	2	3
1. Comfort	.17	1.122			
2. Gender	.46	.499	-.251**		

3. Radiant Asymmetry	.581	.282	-.142**	-.002	
4. Room Fill	.953	.062	-.175**	.019	.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 6).

Table 6. Hierarchical Regression Predicting Thermal Comfort Rating

		Total Sample (N=409)		
Variables		β	Tolerances	VIF
Step 1.				
Gender	$F(1, 407) = 27.334$	-.251**	1	1
	$R^2 = 0.063$			
Step 2.				
Control				
Gender		-.248**	1	1
Predictor				
Room Filled	$F(2, 406) = 20.560$	-.170**	1	1
	$R^2 = 0.092$			
	$\Delta R^2 = 0.029$			
Step 3.				
Control				
Gender		-.248**	1	1
Room Filled		-.143**	.932	1.073
Predictor				
Radiant Asymmetry	$F(3, 405) = 15.393$	-.106*	.932	1.073
	$R^2 = 0.102$			
	$\Delta R^2 = 0.010$			
Note β = Standardized beta coefficients, VIF = Variance Inflation Factors * p < 0.05, **p < 0.001				

This combination of variables significantly predicted comfort rating, with all three variables significantly contributing to the prediction. However, it should be noted that of the three, gender contributes the most, with females being slightly more likely than males to report feeling cold. Even so, the R^2 value was only 0.1, suggesting that the model only explains 10% of the variance. This is a fairly small effect. Iterative model construction demonstrated that this combination of variables resulted in the highest R^2 value, besides being supportable theoretically.

5 Discussion

The research design of this study attempts to associate thermal satisfaction and student scores and it suggests that 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. It also complicates building HVAC systems design and sizing strategies because it suggests that we 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—suggest that a large variety of factors may lead to varying of different perceptions of comfort. Though not demonstrated by this study, it seems likely that the same 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.

An alternate conclusion of this study is that student reports of thermal discomfort reflect their own feelings of anxiety or frustration at doing poorly on an exam or anticipating a difficult exam. If emotional states are important factors in determining whether a person feels thermal discomfort, then there are implications for understanding how people interact with tools for controlling their thermal environment, like thermostats and window operation.

The results of this exploratory 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 that could be manipulated in future studies include ventilation rates and light color temperatures, as these factors may also contribute to perceptions of thermal comfort.

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