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Thermal Comfort in Tropical Classrooms

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ABSTRACT

This paper examines the comfort criteria of ANSI/ASHRAE Standard 55-1992 for their applicability in tropical classrooms. A field study conducted in Hawaii used a variety of methods to collect the data: survey questionnaires, physical measurements, interviews, and behavioral observations. A total of 3,544 students and teachers completed questionnaires in 29 naturally ventilated and air-conditioned classrooms in six schools during two seasons. The majority of classrooms failed to meet the physical specifications of the Standard 55 comfort zone. Thermal neutrality, preference, and acceptability results are compared with other field studies and the Standard 55 criteria. Acceptability votes by occupants of both naturally ventilated and air-conditioned classrooms exceeded the standard's 80% acceptability criteria, regardless of whether physical conditions were in or out of the comfort zone. Responses from these two school populations suggest not only a basis for separate comfort standards but energy conservation opportunities through raising thermostat set points.

INTRODUCTION

Architects and engineers use thermal comfort standards such as *ANSI/ASHRAE Standard 55-1992, Thermal Environmental Conditions for Human Occupancy* (ASHRAE 1992) to design systems that provide a physical environment appropriate for thermal comfort. This paper examines the comfort criteria of Standard 55 for their applicability in tropical classrooms. The standard specifies exact physical criteria (minimum and maximum limits for temperature, air speeds, and humidity) for producing thermal environments that are acceptable to at least 80% of the occupants—developed primarily from climate-controlled, laboratory experiments in temperate climates. The primary questions in this paper ask whether or not laboratory-based air-conditioning standards are applicable in tropical climates or if a different set of criteria exists for people accustomed to hot and humid climates than for those living in temperate climates. If so, these questions are important for schools undergoing renovation and construction, faced with the quandary of long-term energy costs associated with air conditioning.

One major significance of examining the comfort standards in the tropics lies in the potential for conserving energy through modifying building design and careful temperature control. Nicol (1993) suggested that one-quarter of all energy used in developed economies is used for indoor temperature control, a circumstance that could be altered by reducing the indoor-outdoor temperature difference. After finding satisfaction with temperatures and humidities outside the ASHRAE comfort zone by Thai office occupants, Busch (1992) concluded that higher set-point adjustments can potentially yield significant energy savings, particularly in the developing regions of the hot and humid tropics. Aggregate building systems (HVAC and lighting) add up to approximately 38% of the United States' annual energy use (Benton 1994). This statistic becomes important because of the influence that U.S. buildings have as models for the Pacific Rim cities now witnessing unprecedented economic development and construction of modern, air-conditioned buildings. Rarely mentioned in this quest toward modernization are discussions of occupant well-being (comfort) or the architectural loss of vernacular designs—often passive strategies in naturally ventilated buildings that allow the occupant a wide range of personal control and connections to the physical and temporal conditions of the outdoor climate.

While a substantial database of recent field investigations exists for office building (de Dear and Brager 1998), a review of literature (Kwok 1997) revealed a number of studies that

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have taken place prior to 1980. School studies in the 1960s and 1970s examined the effects of heat and cold stress on a range of factors including behavior, comfort, and a variety of task performances, such as memorization, reading comprehension, and multiplication (Pepler 1968; Auliciems 1969, 1972, 1975; Holmberg 1969; Lofstedt 1969; Wyon 1972, 1979; Humphreys 1973, 1976; Faust 1976; Davies 1995). These studies found reduced task performance, comfort, and motivation as a result of heat stress; however, establishing direct influence on mental performance or learning capacity was less conclusive. Most of these studies used elementary school age children in temperate climatic zones of North America, Europe, and Australia and established the importance of thermal conditions to the learning environment while also reflecting the inherent difficulties in finding causal relationships between achievement, comfort, and the physical environment.

Schools in the tropics offer a setting to study the application of Standard 55. Hawaii is the only U.S. state truly located in the tropics and, because of its dependence on imported fuel, commercial energy costs rank among the most expensive in the country (EUN 1995). The majority of schools in Hawaii are more than 30 years old. With a rising school-age population, the trend toward year-round schooling, and an aging building stock, school districts will require a program of renovation, expansion, or construction of new schools. We are at a "fork in the road," where decisions made in the early design stages of school expansion could chart distinctly different energy courses, as well as the architectural design of buildings.

The objectives of this research were to determine the applicability of thermal comfort (Standard 55) to school settings in a tropical climate. To determine the standard's applicability, the following specific questions directed this study.

1. What ranges of thermal environmental conditions are found in typical tropical classrooms and do these physical conditions comply with Standard 55?
2. What is the relationship between measured indoor climate and the subjective comfort responses?
3. Do classroom occupants find their conditions in accordance with the 80% acceptability criterion from Standard 55?
4. How well do the prediction models of comfort match the observed subjective responses?
5. Can the naturally ventilated and air-conditioned data from Hawaii classrooms inform future revisions of the comfort standards?
6. What are the perceptions of other nonthermal conditions such as air quality and dust?

METHODOLOGY

Hawaii's Climate

Hawaii's archipelago lies within the tropical zone, ranging from the southern tip of the island of Hawaii at 18.0°N latitude to the northern coast of the island of Kauai at 22.15°N. The collection of thermal responses occurred during the two seasons: the "hot," or summer season, between May and October, when the weather is warm and dry with persistent tradewinds, and the "cool," or winter season, between October and April, characterized by cool, rainy periods and interrupted tradewinds (Armstrong 1983). Specifically, the field study took place during September-October 1996 and during January 1997. While most people consider Hawaii's climate ideal, Hawaii is often warmer than the traditional comfort zone. Shown in Figure 1, temperatures during the hot and cool seasons fell within ranges of 24°C - 33°C and 20°C - 29°C, respectively. Relative humidity was higher during the cool season than in the hot season, occasionally reaching 90%. From the standpoint of indoor comfort, the combination of thermal conditions contributes in part to making Hawaii a suitable tropical setting to carry out the objectives of this study.

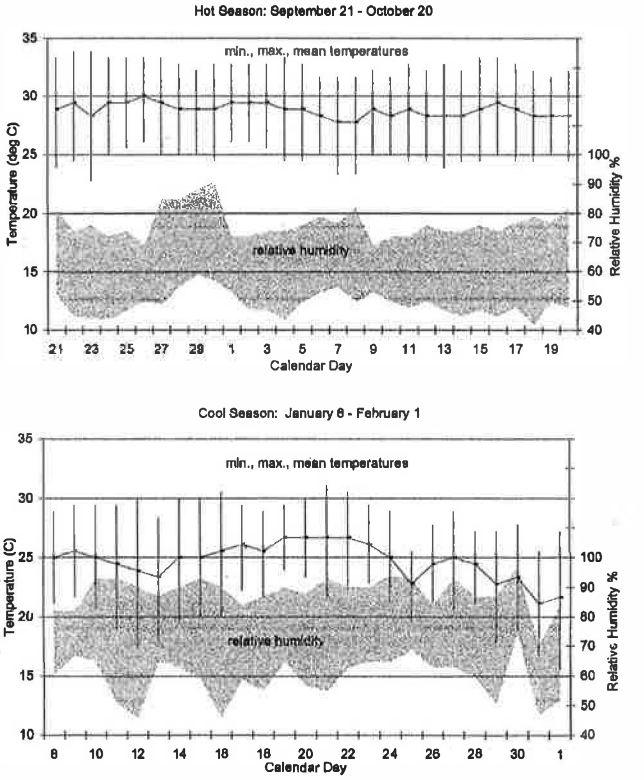

Figure 1 *Cool season daily outdoor minimum and maximum temperatures and humidity.*

School Selection and Descriptions

Several criteria guided the selection of school buildings for this study: a balance of air-conditioned and naturally ventilated classrooms; selection of naturally ventilated buildings of similar age, orientation, and design; a mix of public and private schools; permission and accessibility granted by school administrators; voluntary faculty and student participation; project budget; logistics and time. Because of the technical equipment used and the nature of this study, science

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classrooms seemed the most appropriate rooms in which to conduct the field study.

Comfort Survey

A six-page standardized questionnaire consisted of four sections of inquiry and required approximately 15 minutes to complete. It was administered approximately 25 minutes after the start of the last period to allow students to reach a stable metabolic rate. The first section incorporated classic thermal comfort questions, asking subjects to assess their comfort on a variety of subjective scales—thermal sensation, thermal preference, and thermal acceptability. Respondents answered the thermal sensation question by marking an "X" along the graphic, seven-point continuous scale (cold = −3; cool = −2; slightly cool = −1; neutral = 0; slightly hot = +1; warm = +2; hot = +3). The McIntyre preference scale asked, "Right now I would prefer to be: cooler, no change, warmer." The question of acceptability is not considered a scale, but it is important for comparison to the satisfaction criteria found in Standard 55. Respondents were asked to determine their current thermal conditions as "acceptable" or "unacceptable." Questions on other variables, such as humidity, air movement, air quality, and acoustics, subsequently used the formats of both the preference and acceptability scales. Subsequent sections asked respondents about other environmental conditions (e.g., acoustics, air quality, and thermal conditions) and their influence on school work, clothing items worn during the class visit, and demographic information about age, gender, weight, height, and number of years spent in the tropics.

Physical Measurements

The equipment fit compactly on a laboratory tray or cart, shown in Figure 2, with the sensors measuring air temperature, globe temperature, air movement, humidity, carbon dioxide, and particles. Limitations on equipment and time did not allow measurements to be taken at three heights, as specified in Standard 55, so 1.1 m (43 in.) was selected as the most appropriate height to reflect the thermal experience of the seated occupant. A sensor mounting bracket holding the temperature, globe temperature, and relative humidity transducers, connected to the data-acquisition system, served as a weighted base. A globe thermometer was constructed using a 38-mm table tennis ball and type "T" thermocouple wire. An omni-directional, temperature-compensated anemometer measured air velocity. The data-acquisition system controlled the timing and sequence of sensor-polling, relaying data to a laptop computer for display and storage. Handheld instruments included a carbon-dioxide monitor connected to the data-acquisition system and a particle counter that operated independently on its own data-acquisition system. Since most science classroom seating is typically situated in the center of the classroom (with lab desks along the perimeter walls), the instrumentation was located at a mid-classroom location, enabling measurements for one location rather than the laborious but more rigorous process of taking measurements at individual workstations. This location, however, assumes thermal heterogeneity of the classroom environment, primarily because students are seated in individual chairs in close proximity to each other, rather than in office cubicles. Sensors were allowed to come to equilibrium for five minutes after which data were collected at one-second intervals and averaged every five minutes. It was assumed that radiant asymmetries were negligible and did not have an influence on the occupant because of earlier spot measurements taken.

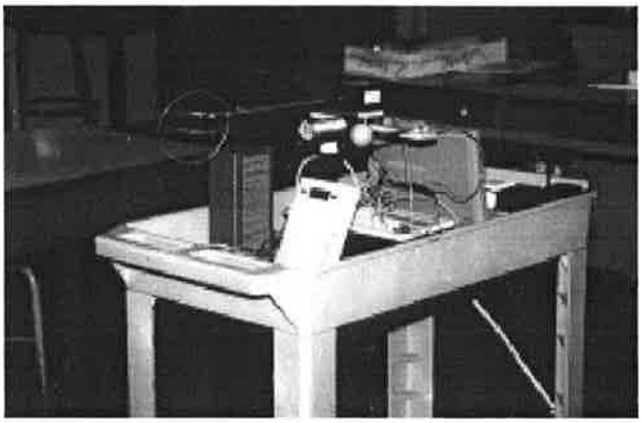

Figure 2 *Equipment to measure indoor climate.*

Calculations

Clothing insulation values were first tabulated from the clothing checklists marked on the questionnaire (ASHRAE 1992) and then increased by 0.10 clo, estimated as the incremental insulating value of the typical classroom chair (Fanger and Langkilde 1975; McCullough et al. 1994). This is slightly less than the 0.15 clo value assumed for typical office chairs with relatively more cushioning (Brager et al. 1994). Metabolic rate was estimated to be 1.2 met (70 W/m^2) in both seasons for both genders, which corresponded to light office activity in the *1993 ASHRAE Handbook—Fundamentals* (ASHRAE 1993). Clothing and metabolic rate were then combined with averaged physical measurements as inputs to a thermal comfort simulation program (Fountain and Huizenga 1996) used to calculate the following climate and comfort indices: new effective temperature (ET*), new standard effective temperature (SET*), predicted mean vote (PMV), predicted percentage dissatisfied (PPD), predicted thermal discomfort (DISC), and predicted percent dissatisfied due to draft (PD).

RESULTS

Sample Characteristics

Table 1 presents statistical summaries of the 3,544 classroom occupants polled at six schools during the hot (1,755) and cool (1,789) seasons. Most respondents took the survey twice, once in the hot season and once in the cool season, though no specific identification or "tracking" of subjects took place from season to season. Across both seasons, approximately two-thirds of the respondents (2,181) were from 19 naturally ventilated classrooms and the other third (1,363) were from 9 air-conditioned classrooms. The sample included a total of 3,492 high school students and 52 teachers.

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TABLE 1
Statistical Summary of Building Occupants

		Naturally Ventilated		Air-Conditioned	
		Hot	Cool	Hot	Cool
Sample Size	3,544	1052	1129	703	660
Gender					
male	1,735	496	535	372	332
female	1,809	556	594	331	328
Age (years)					
mean	16.6	16.7	16.5	16.6	16.4
std. dev.	3.7	4.6	2.7	4.2	2.8
minimum	13.1	13.8	14.0	13.2	13.1
maximum	64.6	64.6	55.8	60.0	61.0
Height (cm)					
mean	166.3	165.9	166.5	166.5	166.5
std. dev.	9.4	9.6	9.6	9.2	9.0
minimum	127.0	129.5	137.2	127.0	144.8
maximum	208.3	208.3	195.6	198.1	195.6
Weight (kg)					
mean	59.1	58.6	59.2	59.8	59.1
std. dev.	13.0	13.0	12.8	13.5	12.6
minimum	31.8	31.8	34.1	34.1	34.1
maximum	149.6	136.4	149.5	129.5	135.5
Years in Tropics					
mean	13.9	13.4	13.8	14.3	14.2
std. dev.	5.0	5.5	4.8	5.0	4.3
minimum	0.1	0.1	0.1	0.1	0.1
maximum	52.4	50.0	40.2	52.4	35.0
CLO					
mean	0.41	0.36	0.40	0.41	0.51
std. dev.	0.16	0.13	0.15	0.15	0.17
minimum	0.19	0.19	0.19	0.20	0.21
maximum	1.04	0.94	1.01	0.99	1.04

Each of the 182 class visits represents a different group of students. For some of the analyses, individual responses and environmental conditions are expressed as group or classroom averages. For example, a single classroom during the course of a day had up to eight different groups or classes (expressed as eight class visits). A class typically contained approximately 20 students; however, some groups were as small as 7 students or as large as 33 students.

Clothing and Metabolic Factors

Table 1 also shows the slight variability between seasons and ventilation type. Generally, people wore more clothing (+0.06 clo) during the cool season than during the hot season, and air-conditioned students wore more clothing (+0.08 clo) than in those in naturally ventilated classrooms. This increase corresponds to a student wearing a long-sleeved rather than a short-sleeved T-shirt or long pants instead of shorts. The 0.04 clo difference between seasons for naturally ventilated subjects can be considered only a slight seasonal adjustment for cooler ambient conditions. However, the more significant difference of 0.10 clo from hot to cool seasons for the air-conditioned subjects suggests that students came to expect that the air-conditioned rooms would feel cool or cold and adapted their clothing patterns accordingly.

Clothing fashions in schools differ greatly from office attire, and dress codes in schools allowed students to wear shorts and T-shirts. Typically, both male and female students wore similarly fashioned clothing such as cotton T-shirts, shorts, and athletic shoes. Footwear is required of all students, specifically covered footwear to be worn in science laboratories where the surveys took place. Local fashion for some boys included wearing two pairs of shorts, "baggy" walking shorts worn over a set of swimming trunks. Although it was expected to see fashion trends dominating clothing preference, students appeared to dress comfortably, casually, and appropriately for the climate. Students carried sweatshirts or jackets, and adjusted clothing levels as much as eight times a day as they moved in and out of air-conditioned classes or the library.

Physical Measurements

Table 2 summarizes both the measured and calculated physical classroom conditions. Averaged temperature and humidity data for each class visit are plotted on a psychrometric chart and are compared to the criteria specified by Standard 55 for summer conditions in Figure 3. (Note that the summer comfort zone was selected for both seasons because of the relatively low clothing levels worn.) More than 75% of the total number of classroom visits (139 of 182) fell outside the standard's comfort zone requirements. In the naturally ventilated classrooms, 92% (94 of 102 visits) had warm and humid conditions well outside of the Standard 55 prescriptions, exceeding the standard's upper humidity limit (20°C wet-bulb). Less than half (44%) of the air-conditioned class visits had conditions within the boundaries of the comfort zone, most falling beyond the cool boundary (<23°C ET*), reflecting overcooled conditions by the air-conditioning systems. Both a temperature and humidity shift is clearly evident between naturally ventilated and air-conditioned classrooms. Although seasonal differences are graphically less distinct, Table 2 indicates more than a 2.5°C temperature difference between the hot and cool seasons in the naturally ventilated classrooms.

Subjective Measurements

Thermal Sensation. Table 3 provides a cross-tabulation of responses on the thermal sensation scale as a function of ET* for both building types, revealing a bimodal distribution

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TABLE 2
Summary of Indoor Climatic Data

	Naturally Ventilated		Air-Conditioned	
	Hot Season	Cool Season	Hot Season	Cool Season
Number of Classrooms	18	19	9	8
Number of Visits	48	54	40	40
Sample Size	1,052	1,129	703	660
Air Temperature (°C)				
mean	28.8	26.1	23.6	22.6
std. dev.	0.9	1.4	1.2	0.7
min.	26.6	21.1	19.8	21.2
max.	30.5	27.7	27.0	23.5
Mean Radiant Temp. (°C)				
mean	28.5	26.1	23.1	22.4
std. dev.	0.9	0.9	1.3	0.7
min.	26.4	24.0	19.4	20.9
max.	30.3	27.5	26.9	23.5
Relative Humidity (%)				
mean	59.8	66.2	57.0	64.0
std. dev.	5.0	7.1	7.2	6.5
min.	51.3	47.5	43.1	51.8
max.	75.5	81.5	74.9	72.6
Air Velocity (m/s)				
mean	0.36	0.33	0.15	0.15
std. dev.	0.10	0.14	0.07	0.05
min.	0.20	0.10	0.07	0.07
max.	0.72	0.66	0.33	0.24
Carbon Dioxide (ppm)				
mean	497	444	1,482	1,688
std. dev.	25	55	513	851
min.	452	338	651	612
max.	562	657	2,436	3,117

	Naturally Ventilated		Air-Conditioned	
	Hot Season	Cool Season	Hot Season	Cool Season
Particulate (#/ft^3)				
mean	21,500	71,700	29,500	58,400
std. dev.	14,600	26,900	14,000	19,300
min.	3,200	26,200	6,800	18,900
max.	93,800	118,900	59,500	92,700
Operative Temperature (°C)				
mean	28.6	26.1	23.3	22.5
std. dev.	0.9	1.1	1.2	0.7
min.	26.5	23.1	19.6	21.0
max.	30.4	27.6	26.9	23.5
ET* (°C)				
mean	28.9	26.3	23.4	22.7
std. dev.	0.9	1.1	1.3	0.7
min.	26.8	23.1	19.7	21.2
max.	30.9	28.2	27.7	23.8
SET* (°C)				
mean	26.2	24.2	21.9	22.0
std. dev.	1.5	1.6	2.0	1.6
min.	22.7	19.6	15.4	18.3
max.	32.2	29.0	30.6	26.4
SET* (°C) (+0.10 chair insulation)				
mean	27.1	25.1	22.8	22.9
std. dev.	1.4	1.6	1.9	1.6
min.	23.7	20.6	16.6	19.3
max.	32.8	29.8	31.3	27.3

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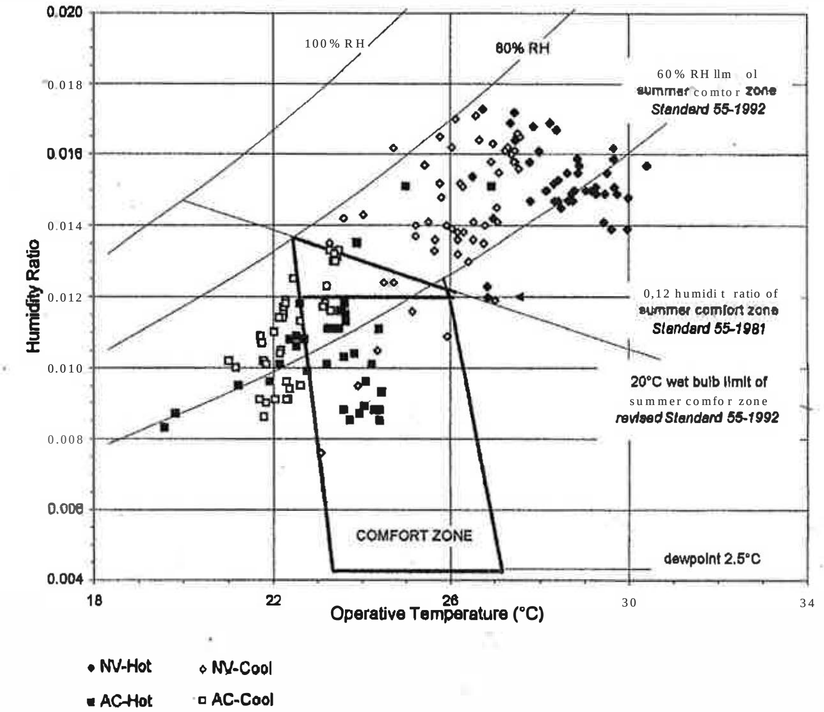

	NV		AC			
Within Comfort Zone	Hot	Cool	Hot	Cool	Row Totals	
Classrooms Within Comfort Zone/Total Visits (Plotted)	0/48	8/54	24/40	11/40	43/182	(24%)
Occupants (Not Plotted)	0/1052	164/1129	441/703	215/660	820/3544	(23%)

Figure 3 *Indoor climatic conditions on Standard 55 revised summer comfort chart (each symbol represents averaged climatic values for a class visit).*

of responses from subjects in naturally ventilated and air-conditioned classrooms. Conditions ranged from 22.5°C to 31.0°C ET* for the naturally ventilated classrooms and 19.5°C to 27.5°C ET* for the air-conditioned classrooms.

The mean thermal sensation vote for the air-conditioned subjects centered around –0.9 (slightly cool), while naturally ventilated subjects' responses averaged 0.2 (neutral). Seasonal differences varied between the two building types. In naturally ventilated buildings, the cool season responses were nearly a full unit lower on the thermal sensation scale than during the hot season, as expected, since ET* was lower (2.6°C) and mean clothing varied little between seasons. A different pattern emerged in the air-conditioned buildings. Although the mean indoor ET* dropped slightly in the cool season (0.7°C), there was an increase in mean clo values (0.10 clo), resulting in a slight increase in mean thermal sensation (0.2 units).

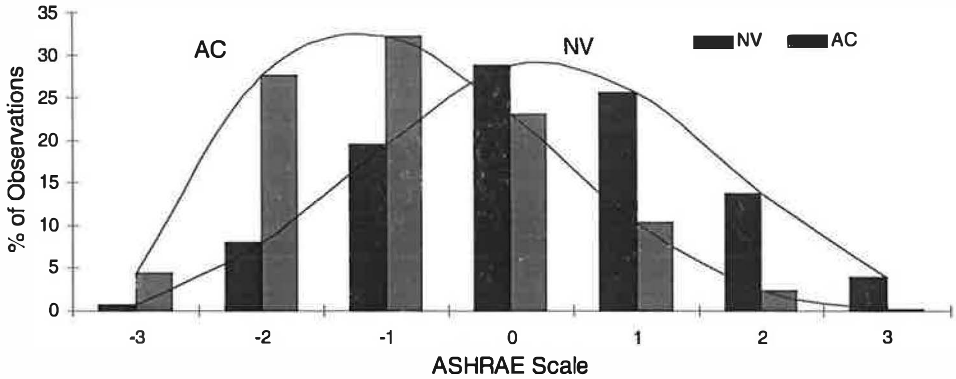

Figure 4 *Relative frequency of ASHRAE votes.*

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TABLE 4
Cross-Tabulation of Thermal Sensation and Thermal Preference Scales by Season and Building Type

	Naturally Ventilated				Air-Conditioned			
HOT	Thermal Preference Scale *Right now I would prefer to be:*				Thermal Preference Scale *Right now I would prefer to be:*			
TS Scale	Cooler	No Change	Warmer	Totals	Cooler	No Change	Warmer	Totals
+3, +2	96%	4%	0%		69%	31%	0%	
	(233)	(9)	(2)	(244)	(9)	(4)	(0)	(13)
+1, 0, −1	62%	37%	1%		32%	62%	6%	
	(483)	(286)	(11)	(780)	(140)	(272)	(29)	(441)
−3, −2	21%	68%	11%		8%	53%	39%	
	(6)	(19)	(3)	(28)	(21)	(131)	(97)	(249)
Totals	69%	30%	1%		24%	58%	18%	
	(722)	(314)	(16)	(1052)	(170)	(407)	(126)	(703)
COOL	Cooler	No Change	Warmer	Totals	Cooler	No Change	Warmer	Totals
+3, +2	86%	14%	0%		77%	23%	0%	
	(118)	(20)	(0)	(138)	(17)	(5)	(0)	(22)
+1, 0, −1	43%	52%	5%		28%	55%	17%	
	(357)	(432)	(42)	(831)	(128)	(246)	(78)	(452)
−3, −2	9%	58%	33%		4%	36%	60%	
	(14)	(93)	(53)	(160)	(7)	(68)	(111)	(186)
Totals	43%	48%	9%		23%	48%	29%	
	(489)	(545)	(95)	(1129)	(152)	(319)	(189)	(660)

We can also test the assumption that people will feel dissatisfied at the more extreme thermal sensations. In naturally ventilated buildings, 68% (hot season) and 58% (cool season) of people feeling cool or cold (−2, −3) thermal sensations preferred "no change" to their thermal environment. These results demonstrate that many people in the tropics want to feel much cooler than neutral, and standards based on a goal of neutrality may be inappropriate.

Thermal Acceptability. Standard 55 defines an acceptable thermal environment as one that satisfies at least 80% of the occupants. Figure 5 compares several methods of determining acceptability (Brager et al. 1994) to determine compliance to the 80% thermal acceptability criterion of Standard 55.

The traditional and most commonly used method is an indirect measure that equates satisfaction (or acceptability) with the three central categories of the seven-point thermal sensation scale, indicated by the shaded portions in Table 3.

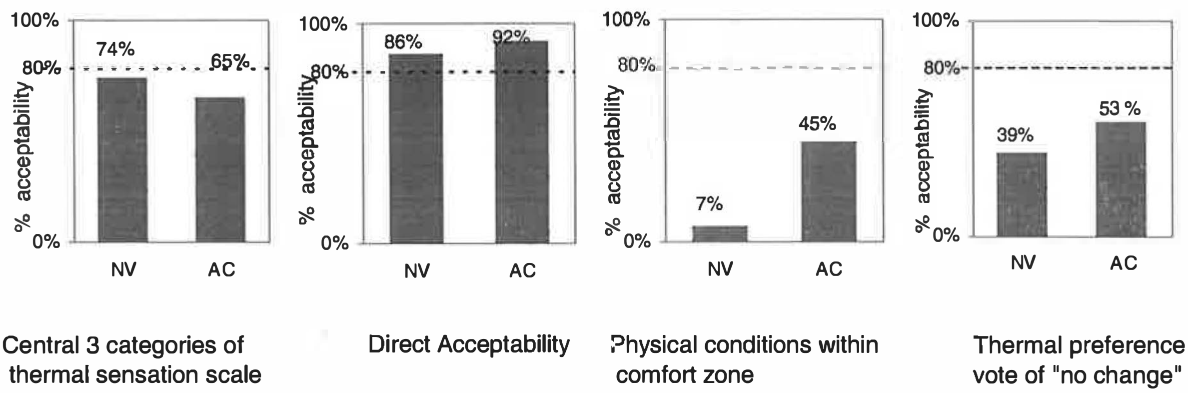

Figure 5 Various methods of acceptability.

TABLE 3
Cross Tabulation of ET* and Thermal Sensation by Building Type

ET*	Naturally Ventilated								Air -Conditioned							
	Thermal Sensation Scale								Thermal Sensation Scale							
	−3	−2	−1	0	1	2	3	Total	−3	−2	−1	0	1	2	3	Total
19.5	0	0	0	0	0	0	0	0	0	5	6	4	0	0	0	15
20	0	0	0	0	0	0	0	0	0	7	6	1	1	0	0	15
20.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	1	7	4	1	1	0	14
21.5	0	0	0	0	0	0	0	0	4	19	17	8	2	0	0	50
22	0	0	0	0	0	0	0	0	9	59	54	42	11	3	0	178
22.5	0	0	0	0	0	0	0	0	16	80	102	73	37	7	0	315
23	4	6	4	2	0	0	0	16	2	29	30	16	4	0	0	81
23.5	0	3	6	8	4	3	0	24	17	99	126	94	40	8	2	386
24	2	10	15	6	1	1	0	35	4	47	59	37	24	8	0	179
24.5	5	17	10	18	6	2	0	58	7	30	27	23	7	3	0	97
25	1	10	14	11	6	2	0	44	0	0	0	0	0	0	0	0
25.5	1	15	28	13	10	7	1	75	0	0	2	5	7	1	0	15
26	0	22	43	54	61	16	1	197	0	0	0	0	0	0	0	0
26.5	1	33	67	59	35	16	1	212	0	0	0	0	0	0	0	0
27	1	25	85	103	63	23	5	305	0	0	2	5	3	0	0	10
27.5	0	6	32	48	54	36	4	180	0	0	0	2	4	2	0	8
28	0	7	29	64	55	36	14	205	0	0	0	0	0	0	0	0
28.5	0	4	37	85	70	41	12	249	0	0	0	0	0	0	0	0
29	0	5	19	64	83	30	10	211	0	0	0	0	0	0	0	0
29.5	0	4	25	54	55	25	12	175	0	0	0	0	0	0	0	0
30	0	5	9	32	48	49	22	165	0	0	0	0	0	0	0	0
30.5	0	1	2	5	4	10	3	25	0	0	0	0	0	0	0	0
31.0	0	0	0	2	3	0	0	5	0	0	0	0	0	0	0	0
Column Totals	15 (1%)	173 (8%)	425 (19%)	628 (29%)	558 (26%)	297 (14%)	85 (4%)	2181	59 (4%)	376 (28%)	438 (32%)	314 (23%)	141 (10%)	33 (2%)	2 (0%)	1363

The distribution of thermal sensation votes for both seasons and building type (Figure 4) shows the curve of air-conditioned responses centered over the category of slightly cool (−1). This is consistent with the data shown in Figure 3, where a large number of the air-conditioned classroom visits had conditions on the cool side of the comfort zone. The shift in central tendency of the air-conditioned votes raises the question: does the clustering of votes around thermal sensation −1 suggest that a significant number of people are uncomfortably cool, or do they prefer a sensation of "slightly cool" instead of "neutral"?

Thermal Preference. Comparison of simultaneous votes on both the thermal sensation and preference scales shown in Table 4 suggests that neutral thermal sensations are not always the ideal, or preferred, thermal state for people. This was most apparent in the naturally ventilated buildings during the hot season where 62% experiencing near neutral thermal sensations still wanted to feel cooler. During the cool season in these same buildings, the pattern was lower but still significant. Only half (52%) of people experiencing the central sensations found those to be ideal, while 43% still wanted to feel cooler. The majority of air-conditioned occupants experiencing neutral thermal sensations preferred "no change" between seasons, which is what one would expect since temperatures varied by less than 1 °C.

Seventy-four percent of naturally ventilated occupants and 65% of air-conditioned occupants are assumed to be satisfied with their thermal conditions. The higher acceptability percentage for naturally ventilated occupants may in part be because the naturally ventilated responses were centrally distributed around the neutral thermal sensation category, encompassing more of the population.

The second method asks the direct question and uses a present-time condition: "Are the conditions in this classroom acceptable to you right now?" Both naturally ventilated and air-conditioned occupants in Figure 5 found conditions acceptable, exceeding the 80% acceptability criterion specified by Standard 55. The direct method is useful in that it provides an additional measure by which to differentiate between the various zones surrounding the comfort zone.

The third method assumes that those within the comfort zone prescriptions of Standard 55 will find conditions acceptable. Figure 5 shows that a low proportion of the total sample had conditions within the comfort zone—7% of the naturally ventilated and 45% of the air-conditioned occupants, less than a quarter of the entire sample (820 of 3544 subjects), had environments complying with Standard 55 specifications.

In the fourth method, votes of "no change" on the preference scale represents an assumption of acceptability and are far below the standard's 80% satisfaction criterion. It should be noted that the question forces the response into a particular category and demonstrates the difference between a more stringent measure of ideal (preferred) conditions vs. wider acceptable range. For example, the majority of naturally ventilated occupants preferred to feel cooler but still found surrounding warm conditions acceptable.

Air Movement. Standard 55 sets an upper limit of around 0.2 m/s (assuming typical turbulence around 40%) for air velocities within the basic comfort zone to reduce the risk of discomfort from drafts. Higher air speeds are acceptable in an extended zone up to 0.8 m/s "if the person has individual control of the local air speed" and "to increase temperatures to 3°C above the comfort zone" (ASHRAE 1992). In the majority of classrooms, students have virtually no individual control of the windows or ceiling fans. Strictly speaking, the Standard 55 comfort zone prescriptions do not apply in these schools because there is no individual control. In this study, roughly half of the thermally comfortable, naturally ventilated occupants wanted more air movement even as they experienced air velocities beyond the 0.2 m/s draft limit of Standard 55. These results suggest that the standard's draft criterion should be reexamined in the context of naturally ventilated buildings, since the draft limit is based on draft risk in air-conditioned spaces and may not be appropriate in naturally ventilated environments. Further discussion of the air movement acceptability and preference responses are detailed by Kwok (1997).

Optimum Temperatures. Probit regression analysis determined thermal neutralities using thermal sensation data from 0.5°C temperature bins (Table 3), which were then divided into two groups: "warmer than neutral" and "cooler than neutral" (neutral category divided equally). The curves in Figure 6 show the point where the maximum number of people voted "neutral," which occurred at 26.8°C in naturally ventilated classrooms (with 95% confidence limits at 26.2°C and 27.2°C) and at 27.4°C in air-conditioned classrooms (wide interval estimate of 25.5°C and 38.3°C indicates no confidence). The oddity of such a high air-conditioned response is an artifact of the clustering of the majority of responses over a narrow range of temperatures.

Preferred Temperature. From the cross-tabulations of thermal preference responses and operative temperature, probit analysis was used to estimate preferred temperature from the groups of "want warmer" and "want cooler" responses. The intersection point of the two probit curves represents the preferred temperature in Figure 7, occurring at approximately 24.3°C (ET*) for naturally ventilated classrooms and 23.2°C (ET*) for air-conditioned classrooms.

Table 5 provides a basis for comparing these temperatures and gives rise to the question, "What scale best represents thermal comfort for tropical populations?" It appears that natu-

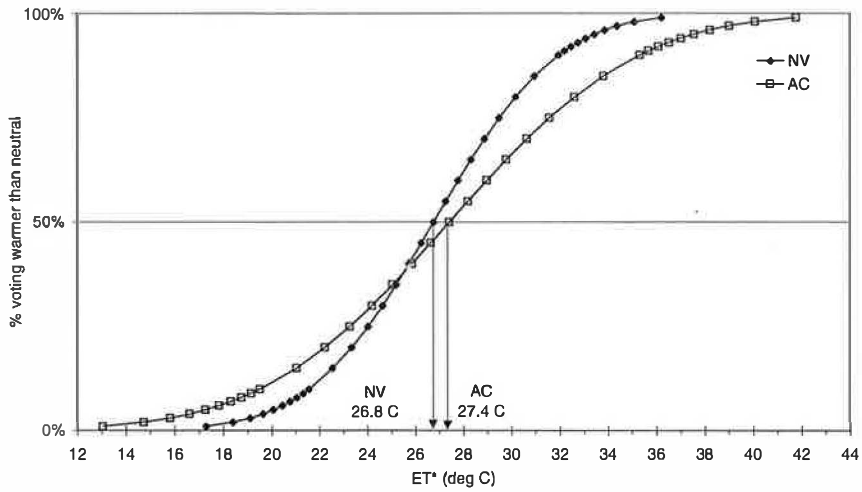

Figure 6 *Probit regression models using thermal sensation votes to calculate thermal neutrality.*

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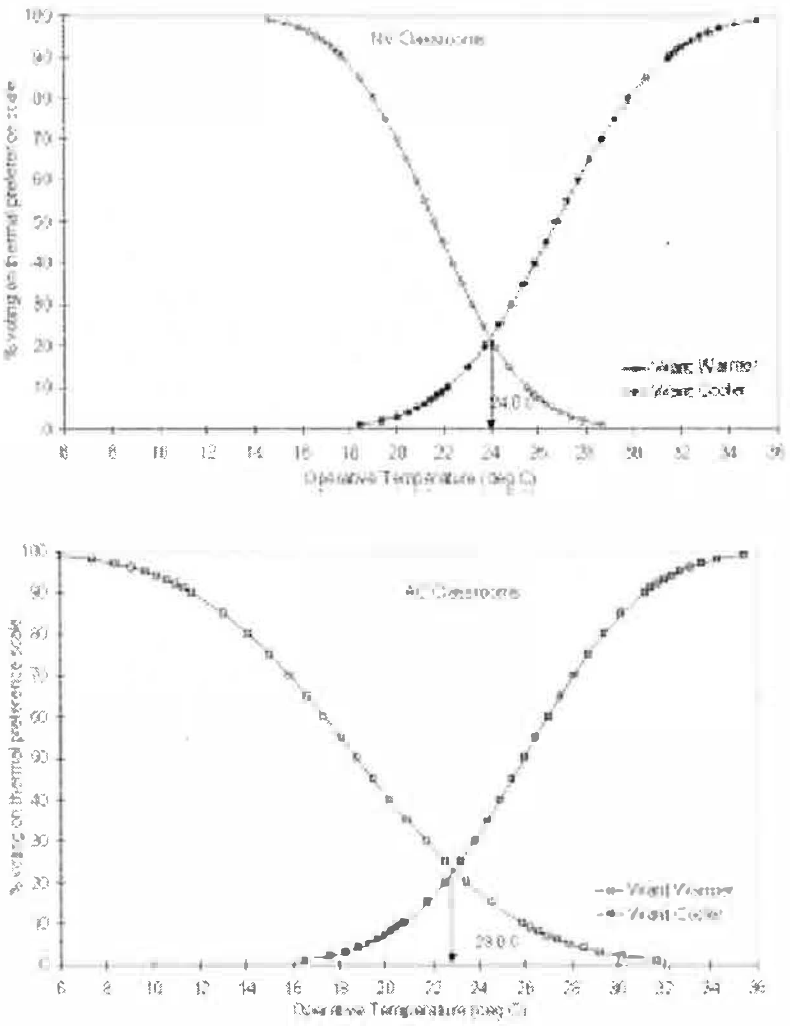

Figure 7 *Preferred effective temperature in naturally ventilated and air-conditioned classrooms.*

TABLE 5
Summary of Various Optimum Temperatures Based on Thermal Sensation and Preference

	ET* (°C)		SET* (°C)		Top (°C)	
	NV	AC	NV	AC	NV	AC
Neutral Temperature	26.8	27.4*	24.1	27.8	26.5	28.1
Preferred Temperature†	24.3	23.2	21.0	23.0	24.0	23.0

* Wide confidence limits
† Probit regression of McIntyre preference scale, "want warmer" and "want cooler" votes

rally ventilated occupants prefer temperatures of approximately 2.5°C ET* cooler than that which produced thermal neutrality. Air-conditioned occupants prefer a temperature approximately 4°C ET* cooler than the neutrality temperature. Seasonal differences were less distinct for both naturally ventilated and air-conditioned environments. These results in part support McIntyre's hypothesis (1978) that there is a climate-based semantic bias in people's responses. Subjects surveyed in a cold climate might respond that their preferred neutral state is "slightly warm," and people in warm climates such as Hawaii's might vote that their preferred neutral state is "slightly cool."

Predicted Comfort

Heat Balance Mode. Table 6 presents a statistical summary of calculated comfort indices, PMV, PPD, PD, and DISC, organized by ventilation type and season and also comfort indices that take into account the insulative effect of chairs that students used in the classroom. PMV calculations indicated conditions slightly cooler than neutral in both naturally ventilated and air-conditioned classrooms during the cool season. The incremental +0.10 clo from the chair increased PMV by 0.3 units for both naturally ventilated and air-conditioned classrooms. Without the additional chair insulation, PMV closely predicted observed thermal sensations. These results differ from office studies where the addition of the incremental clo value for an office chair improved PMV predictions.

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TABLE 6
Statistical Summary of Predicted Responses to Classroom Comfort

	Naturally Ventilated		Air-Conditioned	
	Hot Season	Cool Season	Hot Season	Cool Season
Number of Classroom Visits	48	54	40	40
Sample Size	1052	1129	703	660
PMV				
mean	0.7	−0.1	−0.8	−0.8
std. dev.	0.4	0.5	0.7	0.5
min.	−0.5	−2.1	−3.4	−1.9
max.	1.9	1.0	1.2	0.3
PMV (+0.10 chair insulation)				
mean	0.9	0.2	−0.5	−0.5
std. dev.	0.4	0.5	0.6	0.4
min.	−0.2	−1.7	−2.8	−1.6
max.	2.0	1.2	1.3	0.4
PPD (%)				
mean	19.9	10.7	24.6	24.6
std. dev.	12.8	8.9	21.8	21.8
min.	5.0	5.0	5.0	5.0
max.	73.0	82.0	100.0	100.0
PPD (%) (+0.10 chair insulation)				
mean	25.6	9.8	17.2	13.7
std. dev.	13.8	6.1	17.6	9.3
min.	5.0	5.0	5.0	5.0
max.	76.0	60.0	98.0	54.0
DISC (from 2-node)				
mean	0.4	0.1	−0.2	−0.2
std. dev.	0.4	0.2	0.2	0.1
min.	−0.1	−0.4	−0.8	−0.4
max.	2.3	1.2	1.6	0.3
DISC (from 2-node) (+0.10 chair insulation)				
mean	0.6	0.2	−0.1	−0.1
std. dev.	0.4	0.3	0.2	0.1
min.	−0.1	−0.3	−0.6	−0.4
max.	2.6	1.4	1.9	0.6
PD (%)				
mean	15.9	22.0	18.6	18.6
std. dev.	4.7	10.1	10.0	4.6
min.	8.0	8.0	10.0	12.0
max.	27.0	48.0	57.0	29.0

Adaptive Models. In the proceedings to a conference, "Thermal Comfort: Past, Present and Future," de Dear (1994) writes,

> The fundamental distinction between the heat balance and adaptive models is their underlying basis or cause for a shift in comfort temperatures. The former permits only adjustments to heat balance variables such as clothing or air velocity, whereas the adaptive model is premised on changing the expectations of building occupants.

The underlying hypothesis of the adaptive model is that one's satisfaction with the thermal environment is guided by adaptive adjustments (behavioral, physiological, and psychological) to not only the prevailing environmental conditions (outdoor climate) but to what we expect our indoor conditions to be. Several adaptive models of comfort are selected from the proceedings for comparison to this study's data set to examine the reliability of predictive models as a means of assessing comfort for tropical populations.

Humphreys (1976) developed two equations: one, based on data from naturally ventilated buildings, found thermal neutrality (t_ψ) strongly associated with outdoor (t_o) climate; with the other, air-conditioned buildings were correlated to the outdoor mean monthly temperature.

$$\text{Humphreys (nv)} \quad t_{\psi,o} = 0.534\ t_o + 11.9 \tag{1}$$

$$\text{Humphreys (ac)} \quad t_{\psi,o} = 23.9 + 0.295\ (t_o - 22)\ e^{-\left(\frac{(t_o - 22)}{(24 \times \sqrt{2})}\right)^2} \tag{2}$$

After revising Humphreys' data set, removing outliers and adding new studies from various climatic zones, Auliciems (1983) developed an equation by combining naturally ventilated and air-conditioned data sets and running a linear regression. Current discussions (de Dear 1994; de Dear and Brager 1998) on the adaptive model use this equation:

$$\text{Auliciems:} \quad t_{\psi,o,i} = 0.48\ t_i + 0.14\ t_o + 9.22 \tag{3}$$

Thermal neutralities calculated by probit analysis using mean monthly outdoor temperatures obtained from three-hour, local climatological data (NOAA 1995, 1996) keyed to each class visit for both adaptive models are shown in Table 7. For naturally ventilated classrooms, both Humphrey's ($t_{\psi o}$) Equation 1 and Auliciems' ($t_{\psi o,i}$) Equation 3 predicted the observed neutrality to within 0.4°C. Predictions for air-conditioned neutralities were less congruent, differing from the observed neutralities by 2°C - 4°C.

A New Temperature Range for Naturally Ventilated Classrooms

Standard 55 forms the comfort zone using an 80% acceptability criterion for environments that are defined by thermal conditions ranging from 23°C - 26°C ET* for summer conditions. Compared to votes of direct acceptability (or direct dissatisfaction), predicted percentage dissatisfied (PPD) is a closer match than the dissatisfied thermal sensation votes. Figure 8 illustrates the similarity in the percentage

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TABLE 7
Comparison of Neutral Temperatures (°C)

			Probit Regression	Humphrey [Eq 1] nv	Humphrey [Eq 2] ac	Auliciems [Eq 3]
	T_i	T_o	Tψ (ET*)	Tψ (o)	Tψ (o)	Tψ (i,o)
NV	27.5	28.6	26.8	27.2 (0.4)	24.8 -(2.0)	26.4 –(0.4)
Hot Seas: NV	28.8	30.1	26.7	28.0 (1.3)	24.8 –(1.9)	27.3 (0.6)
Cool Seas: NV	26.1	26.6	26.7	26.1 –(0.6)	24.7 –(2.0)	25.5 –(1.2)
AC	23.1	27.3	27.4*	26.5 –(0.9)	24.7 –(2.7)	24.1 –(3.3)
Hot Seas: AC	23.6	30.0	26.5	27.9 (1.4)	24.8 –(1.7)	24.7 –(1.8)
Cool Seas: AC	22.6	24.6	26.1	25.0 –(1.1)	24.5 –(1.6)	23.5 –(2.6)

Note: Numbers in parentheses are the Tψ difference between given equations and probit regression.
* Confidence limits unreliable

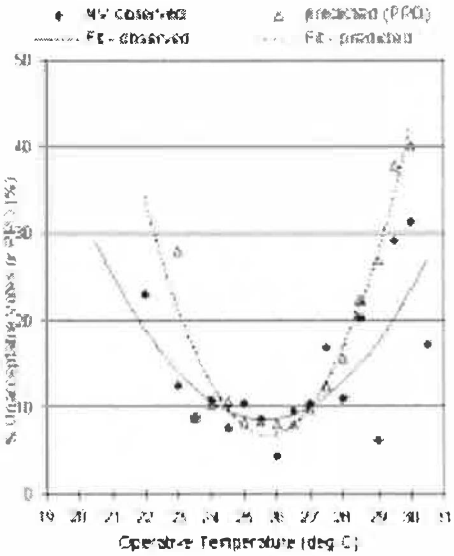

Figure 8 *Comparison of observed and predicted thermal acceptability to operative temperature in naturally ventilated classrooms.*

dissatisfied between the observed curve and the polynomial fit to the PPD data and is also useful for determining ranges of acceptable operative temperatures.

The new range of operative temperatures taken at the 20% PPD line (80% acceptable) shows the naturally ventilated subjects were tolerant of a wider range of operative temperatures (22.0°C - 29.5°C) than was predicted (23.0°C - 28.5°C). The method extends the warm boundary of the Standard 55 summer comfort zone by 3.5°C. Although the lower limit is approximately 1°C cooler than the comfort zone, given the typical warm conditions in naturally ventilated classrooms, people's preferences for cooler temperatures, and any clothing adjustments taken by classroom occupants, a lower boundary might not be of great concern.

DISCUSSION

Do classroom occupants' responses match the 80% acceptability criteria from Standard 55?

Indirect, Direct, and Preference. These methods of measuring acceptability showed differing results. The direct method yielded high acceptability levels from both naturally ventilated (86%) and air-conditioned subjects (92%), exceeding the standard's 80% criterion shown in Figure 5. In fact, when dividing the sample across the coordinates of the comfort zone to those within the comfort zone (representing a small portion of the sample) and those outside the comfort zone, both found conditions acceptable above the standard's criteria.

In contrast to the traditional indirect measure of acceptability (three central categories of the thermal sensation scale), votes of both naturally ventilated occupants (74%) and air-conditioned occupants (65%) did not meet the 80% acceptability criterion of Standard 55. This method does not take into account the fact that people experiencing non-neutral thermal sensations might consider conditions acceptable, which the Hawaii sample expressed through the question of direct acceptability.

Direct thermal acceptability data of the Hawaii air-conditioned occupants corroborated the results of the data in Townsville (de Dear et al. 1993), which also met the standard's 80% acceptability goal.

The assumptions associated with the indirect method become more apparent when examining thermal preferences. A significant number of people (62% during the hot season and 43% during the cool season) in naturally ventilated classrooms preferred to feel cooler while experiencing neutral thermal sensations. This matches the results of Busch's Bangkok study where 64% of naturally ventilated office workers preferred cooler conditions while experiencing neutral sensations (Busch 1990b, 1992). These findings strongly suggest that "neutral" thermal sensations do not correlate to people's ideal or preferred thermal state.

Neutralities. Neutrality calculated through probit from thermal sensations by naturally ventilated occupants was 26.8°C ET*, similar to the neutralities of tropical studies in Singapore (de Dear et al. 1991), Bangkok (Busch 1990b), and Jakarta (Karyono 1996). Yet, the Hawaii naturally ventilated occupants preferred temperatures 2.5°C cooler than the observed neutrality. Neutrality for air-conditioned classrooms was 27.4°C ET*, but occupants preferred cooler temperatures. This finding was consistent with the preferences in most air-conditioned studies for cooler conditions; however, because of the wide confidence limits, the magnitude of the air-conditioned neutrality and other field studies was unreliable.

The contrasting results between the indirect and direct methods has shown that the validity of the assumptions that associate neutral sensations with acceptability are questionable for two reasons: (1) a significant number of people experiencing non-neutral thermal sensations voted the conditions as acceptable, and (2) thermal neutralities calculated by thermal sensation did not match those calculated using preference. Results also suggest that neutrality is not necessarily ideal and that measures of direct acceptability and thermal preference are perhaps better tools for determining ideal conditions (single, optimum temperatures) instead of neutral temperatures. One approach might ask subjects to mark on the thermal sensation scale their preferred thermal condition (rather than the three choices, "want warmer," "no change," or "want cooler"). In turn, the results might be easier to compare to the thermal sensation scale itself.

How well do the prediction models of comfort match the observed subjective responses?

Fanger's PMV prediction model (without the chair insulation value) matched the average thermal sensation votes of the naturally ventilated and air-conditioned subjects to within 0.1 PMV unit. The chair insulation (+0.10 clo) to the PMV calculations weakened the agreement by predicting warmer thermal sensations than those observed for both naturally ventilated and air-conditioned occupants by approximately 0.4 units. Since this overprediction occurred in similar magnitudes for both regimes, it suggests there might have been a systematic uncertainty introduced, such as clothing insulation, met, or simply the assumptions of the PMV model itself.

Several factors may have contributed to the difference between PMV and thermal sensation.

- Clothing—students wearing shorts are more susceptible to asymmetric radiation and air movement (drafts on legs), and, consequently, their thermal response would change. It is possible, but unlikely, that clothing estimates were too high since the mean clo values for the sample of 0.38 and 0.46, respectively, for naturally ventilated and air-conditioned occupants were well below intrinsic clothing values in other tropical field studies: 0.69 and 0.59 in air-conditioned offices in Townsville (de Dear et al. 1993); 0.50 clo in naturally ventilated offices; 0.56 in air-conditioned offices in Bangkok (Busch 1990a).
- Transient effects might have enhanced feelings of coolness. After being outside and most likely sweaty, students might feel even cooler in their air-conditioned surroundings. PMV would then estimate warmer thermal sensation values.
- As one of the inputs into the PMV model, the assumed met rate of 1.2 could have also contributed to the overestimation. Although, this may be a conservative estimate in schools, given the general state of activity engaged in by high school students.
- Since the uncertainties were virtually the same in both building types, it is possible that the additional chair clo was not appropriate for a school setting where classroom occupants are not seated for long periods of time (less contact between the chair and their seat back), as are office workers. In previous office studies, the addition of the insulation value provided by office chairs reduced or eliminated the discrepancies between PMV and thermal sensations (Brager et al. 1994).

Assumptions inherent to the PMV model are that the PMV/PPD relationship represents only overall thermal response. Because the model was developed in the laboratory, local asymmetries that might have caused local discomfort were controlled, minimized, or eliminated. However, in Standard 55's 80% acceptability criterion, the 20% dissatisfied includes 10% due to general, overall discomfort and 10% due to local discomfort. Thus, when people are asked to vote on the thermal sensation scale in the field, the thermal sensation they are experiencing is a combination of all conditions they are exposed to (general and local effects), and their votes are not likely to distinguish between the two. Therefore, it is the author's interpretation that observed thermal sensation votes combine both general and local discomfort, whereas PMV predictions, using ambient measurements as inputs, will only predict general thermal response. If we were able to remove local asymmetries from the thermal sensation data, PMV might have come closer to thermal sensation.

Can the naturally ventilated and air-conditioned data from hawaii classrooms inform future revisions of the comfort standards?

Schools in the tropics have several key "opportunities" that might contribute information in order to change the comfort standard. Schools might take advantage of the transient effects of comfort (sensations experienced when moving from one thermal environment into another). Throughout this study, references are made to the assumptions of acceptability and neutrality when using the central three categories of the thermal sensation scale. Students move in and out of classes during the course of a typical school day, sometimes eight to ten times a day. Their movement from the hot outdoor environment into cool classrooms may enhance cool feelings. Consequently, students probably responded with cool thermal sensations, as seen in the Hawaii air-conditioned data where thermal sensations occurred toward the cold side of the thermal sensation scale. Combined with a significant number of occupants preferring warmer temperatures, the opportunity lies in the fact that air-conditioned classrooms need not aim to cool to the degree that was practiced in Hawaii classrooms.

A second opportunity relates to clothing. Compared to offices, schools have relaxed fashion norms where students are often free to wear what they please. Measured clo values were in some cases more than 1.0 clo lower than other tropical field studies. Even in schools that had dress codes (e.g., collared shirts, covered shoes), observations showed students dressing sensibly for the tropical climate. Students brought extra clothing with them for use in their air-conditioned classes. "Slightly cool" thermal sensations and preferences for warmer conditions by air-conditioned students indicate in part that clothing level adjustments were not enough to offset heat loss. Even though students wore a jacket or sweatshirt over their T-shirts, their legs were exposed because they wore shorts, contributing to local discomfort. Cool sensations would be enhanced, particularly if they arrived from outdoors where they were likely perspiring. The adaptive opportunity means that students will adjust their clothing levels accordingly, and rooms need not be overcooled.

The third opportunity is specific to the design of naturally ventilated environments. The "jurisdiction" or universal applicability of Standard 55 to all building types is a questionable premise because of (1) the distinct character of the physical conditions in naturally ventilated and air-conditioned classroom environments and (2) the differences in occupant response and attitudes to those conditions. The basic architectural nature of the two building types is different in terms of controls, orientation, siting, and building envelope. A building designed with passive features uses the building envelope and form of the building to modify climate, such as external shades, operable windows, narrow building plan, and orientation for maximum cross-ventilation. Mechanically controlled buildings modify the climate through mechanical means, and the form of the building is essentially irrelevant. Naturally ventilated buildings have dynamic conditions, while air-conditioned buildings maintain static environments. In Hawaii classrooms, occupants found higher temperature and humidity combinations satisfactory by direct acceptability and preference measures. Whether those combinations could be used as expectation-benchmarks about thermal comfort in air-conditioned buildings remains to be studied. The contrasting results between building regimes suggests the need for separate comfort standards for naturally ventilated and air-conditioned classrooms.

CONCLUSIONS

The most significant conclusion of this study is that people in naturally ventilated schools are comfortable in conditions that are outside of the comfort zone specifications of Standard 55. The fact that occupants were satisfied with conditions beyond the limits of the Standard 55 is not a trivial point because of the amount of energy and resources spent to achieve comfort zone conditions in our buildings. By extension, this offers schools an extraordinary opportunity to save long-term energy costs should they be well-designed, naturally ventilated environments. The following key conclusions are drawn from this study.

1. More than 75% of the indoor climatic conditions in Hawaii classrooms did not meet the requirements of the Standard 55 summer comfort zone. The distribution of ET*, T_{op}, and SET* frequencies represents the distinct nature of the interior environment in naturally ventilated and air-conditioned classrooms.
2. By direct measures of acceptability, naturally ventilated and air-conditioned occupants found conditions acceptable, thus meeting and exceeding the 80% acceptability criterion of Standard 55. Results from indirect measures using the central three categories of the thermal sensation scale did not meet the acceptability criterion. A significant number of people experiencing sensations of ±2, 3 still found these conditions to be acceptable. Direct measures of acceptability for naturally ventilated classrooms form a broad range of operative temperatures similar to other tropical field studies, 22.0°C to 29.5°C.
3. Thermal neutrality occurred at 26.8°C ET* in naturally ventilated buildings and 27.4°C ET* in air-conditioned buildings, using the thermal sensation responses regressed with probit analysis. However, preferred temperatures were 2.5°C cooler than the observed naturally ventilated neutrality and 4°C cooler than observed air-conditioned neutrality. The findings are supported by other tropical studies and suggest that neutral thermal sensations do not correlate to people's ideal or preferred thermal state.
4. Auliciems' adaptive model predicted observed neutralities closely, estimating to within 0.3°C of observations for all naturally ventilated classrooms and 1.5°C for air-conditioned classrooms.
5. Clothing adjustments, one of the few adaptive mechanisms available to school occupants, occurred in both seasons but, more importantly, during the course of the day. Observations noted students putting on warmer clothing (e.g., sweatshirts) in air-conditioned classes and then taking them off when outside.
6. Clothing insulation (estimated from Standard 55) for Hawaii's naturally ventilated occupants were 0.38 clo and 0.46 clo, respectively. These clo levels were approximately 1.0 clo lower than office occupants of other field studies because of relaxed dress norms in schools. Thermal sensations might have been lowered if students, wearing shorts, felt local discomfort on their legs. Chairs were estimated to add 0.10 to the clothing insulation of classroom occupants. The addition of the chair insulation may have contributed to the overestimation of PMV across both building types. Since students do not sit for as long a period as office workers, the additional chair insulation may have been unnecessary.

7. Discomfort from draft or excessive air movement was not a problem in classrooms. In fact, the problem in naturally ventilated classrooms was not enough air movement. The majority of naturally ventilated classrooms were beyond the prescriptions of the basic Standard 55 comfort zone. Many of those classrooms were, however, located within limits of the extended comfort zone if the air movement is under individual control. However, most of the occupants of those classrooms expressed a desire for more air movement (while experiencing air velocities beyond the 0.2 m/s draft limit) and do not have any means of individual control of windows or fans for more air movement. The standard's draft limit, based on draft risk for air-conditioned environments, may be inappropriate for naturally ventilated tropical classrooms.

8. Naturally ventilated classroom occupants found a wide range (22.0°C - 29.5°C T_{op}) of conditions thermally acceptable. Tolerance for a wide range of thermal conditions found by naturally ventilated occupants and the distinct and dynamic conditions characterizing naturally ventilated environments suggest the need for a standard specifically for naturally ventilated buildings.

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