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A FIELD STUDY OF THERMAL ENVIRONMENTS AND COMFORT IN OFFICE BUILDINGS

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ABSTRACT

This paper presents the initial findings of ASHRAE research project RP-462, a field study of environmental conditions and occupant comfort in ten office buildings in the San Francisco Bay region. We made a total of 2342 visits to 304 participants during two seasons, collecting a full set of physical measurements and subjective responses at each visit. In this paper we describe the building environments and their conformity to the requirements of the thermal standards, the distribution of thermal sensation responses, neutral and preferred temperatures, conditions of thermal acceptability, and gender and seasonal effects on comfort responses. A few of the results are as follows: 78.2% (winter) and 52.8% (summer) of the workstation measurements fell within the ASHRAE Standard 55-81 comfort zones; the higher summer comfort zone was judged as too warm based on several rating scales; neutral temperatures were 22.0°C (winter) and 22.6°C (summer), and preferred temperatures were 0.3-0.6°C cooler.

INTRODUCTION

The great majority of thermal comfort research has been done in the laboratory rather than in actual workspaces. The laboratory offers consistent conditions for measurement not possible in the "field." However, laboratory subjects are not in their familiar surroundings or engaged in their usual work activities during the period of testing. They may, therefore, perceive and accept the thermal environment atypically, influencing the study's results. A field study avoids this potential problem by investigating people's thermal response to their normal working conditions. Humphreys (1976) gives a worldwide summary of a large number of field studies performed over many years. Fishman and Pimbert (1978), Gagge and Nevins (1976), Dedear and Auliciems (1985), and Howell and Stramler (1981) report on several of the largest recent studies of this type.

For those comfort studies that have been performed in the workspace, the details of the physical environment measurements typically have been much less than those of laboratory tests. As a result, there have been few attempts to fully characterize the relationships between comfort and the thermal environment in field studies. In order to obtain correlations between comfort votes and physical variables that are as complete as current laboratory practice, the field study described here made very detailed measurements based on the requirements of ASHRAE Standard 55-81 (1981).

Objectives and Scope

This study was performed in the San Francisco Bay area and was conceived to shed light on several issues related to comfort in offices. The objectives of this project were established by its original work statement and included the following activities:

Dr. Gail Schiller is Assistant Professor; Dr. Edward Arens is Professor; Fred Bauman is Development Engineer, Building Science Laboratory; Charles Benton is Associate Professor; Marc Fountain is a graduate research assistant; Tammy Doherty is a graduate research assistant (Bioengineering Graduate Group); all positions except for Ms. Doherty are in the Dept. of Architecture, University of California, Berkeley.

1. *Development of a detailed data base on the thermal environment and subjective responses of occupants in existing office buildings.* This study measured buildings in two San Francisco Bay area climates: a cool coastal climate and a drier, more variable inland climate. Measurements were repeated in winter and summer. In addition to physical measurements of the thermal environment, concurrent thermal comfort assessment surveys polling the building occupants provided subjective data.

2. *Documentation of comfort conditions in the monitored office environments.* The field measurements were used to determine whether current comfort standards (ASHRAE Standard 55-81 and ISO Standard 7730, 1984) were being met in the buildings.

3. *Analysis of the compiled data to identify relationships between physical, psychological, and demographic parameters.* We calculated commonly used temperature indices and derived comfort parameters from the measured data, and used statistical analysis to identify significant correlations and trends between thermal conditions and comfort responses.

4. *Development of instrumentation, measurement procedures, and occupant survey techniques to assess thermal comfort.* The project developed methods of collecting detailed thermal measurements of the workstation conditions, eliciting subjective responses to the current thermal environment, and obtaining appropriate psychological background measures to explain occupants' response patterns.

This paper reports on all of items 1 and 2 above and parts of items 3 and 4. Subsequent papers will discuss reliability and validity of the survey instruments, the conceptual meaning of thermal comfort (based on analysis of the background survey), and recommendations for a standardized thermal comfort assessment procedure. A discussion of the relationship between thermal sensation or discomfort, and the thermoreceptors and physiological state, is beyond the scope of this research.

METHOD

Buildings and Participants

Criteria for Selection. The ten buildings used in the study were chosen to obtain a representative heterogeneous sample of existing office buildings in the San Francisco Bay Area. The building sites were divided roughly into two climatic zones: inland valley and coastal. We selected buildings on the basis of occupants' willingness to participate, climatic zone, building characteristics (size, age, interior layout), occupant characteristics, and expected interior thermal conditions. No attempt was made to ensure that they were statistically representative of the buildings stock as a whole, but instead that they reflect a wide range of common building types. The subjects of the study volunteered in response to a written invitation circulated by a contact person in the office. We selected the subjects from the pool of respondents based on the following the criteria (in rough order of priority): willingness to participate, majority of workday hours spent at desk, coverage of thermally variant zones of the buildings, equal proportions of male and female, and age distribution from 20 to 50 years.

Description of Buildings. Table 1 summarizes characteristics of the ten buildings monitored in the project. The first building was treated as the pilot building and is labeled P, while the other nine buildings are referred to as A through I. The buildings include several examples each of new and old construction, private and open-plan layouts, single and multi-tenant offices, and sealed and openable envelopes. Examples of the range of building types studied include a non-air-conditioned 54,000 ft^2. architectural office converted from a factory originally built in 1913 and a 2,000,000 ft^2. complex completed in 1985 with 7 ft overhangs and automatic photocell controlled blinds. Five of the buildings were in various districts of San Francisco, while the other five were located in the generally inland climates of San Ramon, Walnut Creek, Palo Alto, and Berkeley. Half of the buildings had openable windows, including a 23-story high-rise with private balconies around the perimeter.

Description of Subjects. We made a total of 2342 visits to 304 participants in the ten buildings during two seasons. The subjects participating in the study were composed of 187 females (62%) and 117 males (38%). Of the 261 participants who provided demographic data, 76% were within 20-40 years of age, and 81% were Caucasian. Of the 304 subjects, 264 participated in the winter study and 221 participated in the summer (181 of these participated jointly in each).

Clothing insulation was determined using the Thermal Assessment Survey, described in a later section of this paper. Effective clothing insulation is described in terms of the "clo" unit, defined as 1 clo = 0.155 $m^2{}^\circ C/W$. Clothing patterns were not significantly different between the seasons, and mean clothing insulation was 0.58 clo (winter) and 0.52 clo (summer). In comparison, ASHRAE Standard 55-81 assumes values of 0.9 clo (winter) and 0.5 clo (summer).

Women wore slightly lighter clothing than men in both seasons; mean clo values for men were 0.62 (winter) and 0.57 (summer), and for women were 0.56 (winter) and 0.49 (summer). Women also had greater variation in their clothing values; standard deviations for men were 0.12 (winter) and 0.08 (summer), and for women were 0.14 (winter), 0.13 (summer). The correlations between clothing insulation and ET* in the winter were $r = -0.32$ for men, and $r = -0.24$ for women. During the summer, r values were nearly zero. This suggests that women's clothing patterns were somewhat less responsive than men's to changes in thermal conditions during the winter, while neither men nor women responded to changes in thermal conditions during the summer. A frequency histogram of clothing insulation worn by men and women in both winter and summer is shown in Figure 1.

Outdoor Climatic Conditions. Throughout the period of the experiment, we obtained temperature and humidity data from a network of weather stations. After dividing the San Francisco Bay area into zones represented by these stations, the zone associated with each of the office buildings was identified. The stations supplied daily minimum and maximum temperatures. Figure 2 summarizes the temperature data during the summer and winter measurement periods. The bars represent the extreme range of temperature experienced at each office building's weather station during the week that measurements were made at that building. The (W)inter and (S)ummer symbols are positioned at the mean temperature for the weekly period.

Thermal Environment Measurements

We developed two measurement systems, one mobile and one stationary, to measure the buildings' thermal environments. The mobile system was used to characterize the environment at the individual workstations at the same time as subjective responses were taken. Each workstation was visited an average of five times during the week-long period of measurement in each building. The stationary system recorded trends through the week. We performed all thermal measurements in accordance with the accuracies and procedures described in the ASHRAE 55-81 and ISO 7726 (1985) Standards.

Mobile Measurements. Figure 3 shows the cart that carried the mobile measuring system. We attached the seat of a molded fiberglass chair to the front of the cart to represent the shielding effect of the occupant's seat. The various sensor elements were mounted above and below the chair at the 0.1, 0.6, and 1.1 meter levels (representing ankles, mid-body, and head/neck). The sensors were surrounded (at the 0.1 and 1.1 meter heights) with black metal tubing for protection against encounters with office workers and furniture. The tubing and sensors were separated by sufficient space to minimize any effect of the tubing on the readings. The shelves on the cart behind the chair contained the remainder of the mobile data acquisition system, including signal conditioners, data-recording devices, cables, and battery power. The instrumented cart was placed directly in the subject's workstation, replacing the chair on which s/he had been sitting.

Table 2 summarizes the sensors used for the mobile measurements, with location, accuracy, and response time for each. Measurement accuracies required by ASHRAE Standard 55-81 and ISO Standard 7726 are given for comparison. The table indicates that all accuracies (manufacturer's specifications or as obtained through in-house calibration) were in general accordance with those of the standards.

We measured globe temperature with a custom-built sensor constructed by placing a thermocouple inside a 38 mm-diameter grey table tennis ball. Based on tests conducted of globe sensors of various design, the table tennis ball sensor was found to have the most rapid response time without losing accuracy. Although the 90% response time of the globe sensor (see Table 2) was longer than the prescribed five-minute measurement period, in practice the thermal differences between workstations were sufficiently small that thermal lag errors were below the resolution of the instruments. The table tennis ball globe was also chosen because Humphreys (1975) showed that for low air velocity (< 0.15 m/s) a 40 mm diameter globe has radiative and convective losses in the same ratio as the human body. Since measured air speeds in the office buildings were typically low (mean less than 0.1 m/s), this was judged to be the appropriate sensor. It should be noted that the standard specifies 6 inch (152 mm) diameter globe temperatures, and that the globe temperatures described in this report can be converted to 6 inch (152 mm) diameter values using Equation 24 and Table 1 found in chapter 18 of ASHRAE Systems (1984).

Stationary Thermal Measurements. We also monitored temporal variation in each building's interior thermal environment throughout the week-long measurement period. The stationary instrumentation was placed in a location representative of the areas being monitored (typically, an unoccupied workstation). The sensors are included in Table 2, listing the sensor height, measurement accuracy, and response time. We left the stationary system in place during the entire week of measurement to provide a continuous record of trends in interior conditions that could not be detected by the roving measurement cart, which was moving through numerous thermal zones in the building. We used the data primarily to help diagnose effects observed in the mobile measurements.

Questionnaires

We collected subjective measurements both to reveal the occupants' responses to the measured thermal environments, and to examine conceptual and methodological issues related to the meaning of comfort. Survey instruments used in this project fell under two categories: (1) a *Thermal Assessment Survey*, to measure the office user's subjective impression of work conditions at a specific time and place and (2) a *Background Survey*, designed to assess the office users' conceptual meaning of comfort, in addition to assessing the general experience of office work areas and characteristics of office users.

Thermal Assessment Survey. We administered this repetitive survey on a laptop microcomputer and presented it to the subject several times during the course of a week. An opaque plastic cover was built for the keyboard, exposing only the limited number of keys necessary for answering the questions. The survey consisted of a series of questions and scales addressing thermal sensation and comfort, clothing and activity, and affective state. These questions are briefly described below.

Thermal Sensation and McIntyre scales. These measures were employed as the primary measures of thermal sensation and comfort. The ASHRAE Thermal Sensation Scale has been widely used in comfort research to assess thermal sensation. We used a continuous form of this scale in which the subject could move a computer cursor between -3 and +3, the selected position being encoded in 0.1 increments . The McIntyre scale focuses more directly on thermal satisfaction by probing the participants' judgments of whether conditions are acceptable. The subject responds to three choices: "I want to be: warmer, no change, cooler" (McIntyre and Gonzalez 1976). These data were then encoded as -1, 0, and +1, respectively, for subsequent analysis.

Office work area comfort ratings, and estimated temperature. Three questions used a six-point scale to rate the participants' immediate impressions of comfort with regard to air flow, lighting, and general comfort. In contrast to the previously described scales, these focus on the state of the office work area rather than on the subject. The general comfort scale provides a tool for assessing comfort, as opposed to thermal sensation. In addition, the subjects recorded estimates of room temperature.

Affective state. This 26-adjective form was designed to examine whether experienced affective states played a role in assessments of thermal comfort and asked participants to rate on a 6-point scale the appropriateness of each adjective for describing their current mood.

Clothing and activity checklists. The clothing checklist presented an itemized list of clothing pieces and asked for a rating on a four-point scale indicating the relative weight of each item. We developed separate female and male versions of the clothing screens. The activity checklist inquired about physical activity, eating, drinking (hot, cold, or caffeinated beverages), and smoking during the 15 minutes previous to taking the survey. From these responses, we computed both metabolic rate (met) and effective clothing insulation (clo) using the ASHRAE HOF (1985).

Background Survey. The Background Survey included questions designed to elicit a general description of the office work areas; the office user's degree of satisfaction with components of the work area; reports of personal and comparative comfort; and personal characteristics (demographic information, affective dispositions, job satisfaction, health status, and environmental sensitivity). There were two purposes for the Background Survey. The first was to provide respondents with multiple channels for expressing dissatisfaction or discontent with other features of the work setting. The second was to examine the conceptual meaning of comfort and allow for greater analysis of the relationship between comfort and various psychological parameters. The Background Survey will be described in more detail in a subsequent paper, which will present the results of further analyses.

Data Collection Procedures

Field researchers spent a total of one week in each monitored building. On the first morning of the measurement week, the 25 to 30 survey participants attended a brief orientation meeting where we described their role in the procedures and administered the Background Survey. We then visited them at their workstations five to seven times during the course of the week. We measured the ten buildings twice, during the 1987 winter season (January - April) and again during the summer (June - August). The protocol for each workstation visit and approximate length of time for each task was as follows:

1. Researcher approaches subject--if convenient, presents survey computer (1 minute).
2. Subject completes Thermal Assessment Survey (3-10 minute).
3. Subject leaves desk and measurement cart is put in place (1 minute).
4. Thermal measurements are made (5 minute).
5. During survey and measurement periods, researcher records additional observations and sketches, takes photographs, and arranges for next workstation visit.

The Thermal Assessment Survey was administered to the subject through a program developed for this project and run on a battery-powered laptop microcomputer. After the computer was placed on the desk, the subject completed the survey by responding to a series of questions appearing on the computer screen. Answers (typically yes/no, numerical, or positioning of the cursor along a scale) were typed on the keyboard, with results going directly onto storage on diskette. During the survey period the researcher left the workstation area to avoid disturbing the subject.

Immediately after the survey was completed, we asked the subject to leave to allow the thermal environment to be measured. After removing the subject's desk chair, we wheeled the mobile measurement cart into the spot previously occupied by the subject. We collected data for a total of five minutes, during which time all sensors were scanned at a minimum rate of once per second. The chilled-mirror dewpoint sensor, however, produced a new reading only every two minutes. The first two minutes of the data collection period were used to allow all sensors to equilibrate with their surroundings. For each sensor, we recorded ten-second average data for the entire five-minute period, along with a single average value based on the final three-minute interval. The environmental indices (T_{op}, MRT, ET*, SET) and comfort indices (PMV, DISC, TSENS) were calculated only for the three-minute average values.

The field researcher observed and recorded additional information including: (1) sketches of the office layout and cart position (first visit only); (2) photographs of the work area (first visit only); (3) location, type, and status (on/off) of equipment affecting local thermal conditions (e.g., fans, electric heaters, HVAC diffusers, computer equipment, etc.); (4) openable window and movable shade positions; (5) unusual clothing on the subject; (6) unusual subject behavior patterns; and (7) observable thermal conditions (e.g., drafty, incident beam sunlight, etc.).

RESULTS

Existing Thermal Environments

Description of Comfort Standards. A major objective of this study was to test for compliance of existing thermal environments in office buildings with current comfort standards (ASHRAE Standard 55-81 and ISO Standard 7730). The acceptable ranges of environmental parameters under winter conditions as defined by each of these standards are described briefly below.

ASHRAE Standard 55-1981. In the winter, operative temperature and humidity limits are defined by a comfort zone on the psychrometric chart having the following coordinates: T_o = 19.5-23.0°C at 16.7°C T_{dp} and T_o = 20.2-24.6°C at 1.7°C T_{dp}. The two slanted sides are defined by the new effective temperature, ET* (ASHRAE 1985). The winter limits are ET* = 20.0°C and 23.6°C. In the summer, the coordinates are: T_o = 22.6-26.0°C at 16.7°C T_{dp} and T_o = 23.3-27.2°C at 1.7°C T_{dp}. The slanted sides are defined by ET* = 22.8°C and 26.1°C. The maximum limit for mean air velocity in the winter is 0.15 m/s. In the summer the limit is nominally 0.25 m/s, increasing an additional 0.275 m/s for each °C above 26°C dry-bulb temperature, up to a maximum of 0.8 m/s for temperatures above 28°C. Nonuniformity limits are defined by the following conditions: the vertical air temperature difference between the 0.1 and 1.7 m heights shall not exceed 3°C; radiant temperature asymmetry in the vertical direction shall be less than 5°C and in the horizontal direction less than 10°C; and the floor surface temperature shall be between 18°C and 29°C.

ISO Standard 7730. The ISO standard is very similar to the ASHRAE standard with a few minor exceptions. It does not specify humidity limits, resulting in a comfort zone defined strictly in terms of operative temperature limits: in the winter, T_o shall be between 20-24°C and during the summer, between 23-36°C. These limits correspond roughly with the ASHRAE operative temperature range at the 50% relative humidity level. The maximum allowable air velocity is similarly set at 0.15 m/s in the winter and 0.25 m/s in the summer (but with no increase for higher air temperatures). The maximum acceptable vertical temperature difference is the same, but it is taken between the 0.1 and 1.1 m heights.

Physical Measurements and Comparison to Comfort Standards. Figure 4 presents a frequency distribution of ET* values, binned by 0.5°C, for both winter and summer. The distributions are remarkably similar in both seasons, with the summer curve shifted only 0.5-1.0°C higher. Figure 5 shows a frequency distribution for air velocity (mean of 3 heights), binned by 0.02 m/s, for both winter and summer. Higher air movement rates are prominent in the hotter summer conditions, in some cases from portable fans and open windows and in some cases from the HVAC air supply.

Tables 3a and 3b provide statistical summaries of the measured physical data in the ten buildings, and Table 4 compares these results with the ASHRAE winter and summer comfort standards. Due to the similarity of the ASHRAE and ISO comfort standards and the fact that humidity was a measured quantity in the collected data base, comparisons are presented only for ASHRAE Standard 55-81. We made comparisons to the comfort standards for dewpoint temperature, ET*, and air velocity independently and then with all three considered simultaneously.

Winter. Dewpoint temperature never fell above the maximum limit of 16.7°C during the winter measurements. In four of the five buildings located in the coastal zone (C, D, E, and G), humidity was within the limits of dewpoint temperature 100% of the time. In the inland buildings (P, A, B, H, and I), conditions were only slightly drier, with a maximum of 7.9% of the measurements falling below the lower humidity limit. Overall, humidity conditions were within the comfort limits 97.1% of the time. For all ten buildings, ET* ranged between 17.4°C and 28.3°C, with a mean of 22.5°C. Overall, 83.9% of the ET* measurements were within the comfort zone limits, with only 2.8% below and 13.2% above. Of all the ET* values falling above the winter maximum limit, only two observations were above 26.1°C (the maximum limit for the summer comfort zone). Given the low clothing insulation worn in these buildings during the winter, one might have expected more interior temperatures near and exceeding the 26.1°C limit. Air velocities were very low in the buildings, with a mean of 0.06 m/s. Only 4.7% of the air velocity measurements were above the comfort limit of 0.15 m/s. When ET*, humidity, and air velocity were considered simultaneously, 78.2% of the conditions were within the winter comfort requirements. Excessive temperature stratification and horizontal radiant temperature asymmetry were virtually nonexistent.

Summer. In contrast to the winter measurements, dewpoint temperature never fell below the minimum limit of 1.7°C during the summer measurements. In two of the coastal buildings, humidity was frequently high, with dewpoint falling above 16.7°C 88.8% of the time in building F and 38.5% in building G. We are examining the cause of these unusually high numbers, including the possibility of an intermittent instrument error. Overall, humidity conditions were within the dewpoint comfort limits 83.5% of the time. For all ten buildings, ET* ranged between 20.2°C and 29.0°C, with a mean of 23.5°C. Only 68.3% of the ET* measurements were within the summer comfort zone limits, with 4.1% above. Although the buildings are being operated below the lower limit of the summer comfort zone 27.7% of the time, only two of the summer measurements were below the winter comfort zone's lower limit of 20.0°C. Air velocities were again very low in the buildings, but slightly higher than in winter, with a mean of 0.10 m/s. Only 2.4% of the air velocity measurements were above the maximum limit. When ET*, humidity, and air velocity were considered simultaneously, only 52.8% of the conditions were within the summer comfort requirements. As for winter, summer conditions complied with the nonuniformity requirements of the Standard.

As noted in the earlier description of clothing, the tendency in these buildings for operation above the Standard's upper winter limit and below the Standard's lower summer limit is probably linked (either as cause or effect) to the uniformity of seasonal clothing levels.

Indices and Predictors of Thermal Sensation and Comfort

Several forms of observer-based reports regarding comfort are compared and discussed below. Unless otherwise noted, all correlation coefficients (r) were significant beyond the .001 level.

Comparison of Scales. The relationship between the ASHRAE Thermal Sensation and McIntyre scales was strong, with r-values of 0.45 (winter) and 0.66 (summer). These scales are compared in greater detail in a later section discussing thermal acceptability of the building environments.

Negative correlations between Thermal Sensation and General Comfort in both the winter and summer suggest that cooler conditions in these buildings were more comfortable than warmer conditions. There was a significant negative relationship between the Thermal Sensation and the Air Flow Comfort scales, suggesting that warmth sensations were associated with stuffy (or still) ratings and cool sensations were association with drafty ratings. The correlation coefficients were -0.48 (winter) and -0.49 (summer). These patterns warrant further analysis. The positive relationship of Air Flow to General Comfort, combined with its negative relation to the Thermal Sensation scale, indicates that for both winter and summer, environmental conditions leaning toward cool and drafty were perceived as comfortable, while warm and stuffy were uncomfortable.

Simple Correlations. Personal (clothing, activity) and demographic (age, gender, mass/surface area ratio) variables were only weakly related to thermal sensation. Of the physical measures, the strongest correlations were with the temperature indices. Correlation coefficients ranged between 0.30 - 0.36 for T_a, T_r, T_{op}, and ET*.

In the winter, participants' estimates of temperature were more closely related to their votes on the Thermal Sensation scale ($r = 0.51$) than to the existing air temperature or ET* ($r = 0.29$ for both T_a and ET*). In the summer, however, the correlations were weaker and did not differ by much. Summer correlations with estimated temperature were $r = 0.25$ for Thermal Sensation and $r = 0.23$ for both T_a and ET*. This does not support Howell's findings that perceived temperature was strongly correlated to thermal sensation (Howell and Stramler 1981).

Multiple Regression Analysis. We carried out multiple regression analyses on the winter data set to determine the relative contribution of selected physical, personal (clothing insulation, metabolic rate), and demographic (age, gender) variables to votes on the Thermal Sensation scale. Physical measures were divided into three non-colinear sets describing relevant physical aspects of the ambient environment, and one multiple regression was performed on each set. While the R^2 values were significant ($P \leq .005$) because of the very large sample size, the actual values were low. The cumulative R^2 was .11-.12 for each of the three sets, indicating that no more that 12% of the variance in Thermal Sensation vote were accounted for by the selected physical, personal, and demographic parameters. These values are lower than those reported in the field studies by Howell and Kennedy (1979), Howell and Stramler (1981), and Rohles et al. (1975).

Distribution of Thermal Sensation and Comfort Responses

Frequency Distributions. Figure 6 shows the distribution of the total population of Thermal Sensation votes, with winter and summer values juxtaposed. Figure 7 is the equivalent graph for McIntyre votes. In both, one can see that the negative votes (cool sensation and "I want to be warmer") are more prevalent in the winter than in the summer and that the positive votes are more prevalent in summer. For both seasons, warm votes outnumber cool ones.

Analysis of Mean Responses. In the winter study, the mean Thermal Sensations in nine of the ten buildings were all on the warm side of neutral. Building B was the exception. Means in each of the ten buildings ranged from nearly neutral (-.05) in Building B toward slightly warm (+.46) in Building E. These were also the two buildings ranked as the coldest and warmest of the group based on physical measurements. Standard deviations ranged between 0.99 and 1.21, consistent with McIntyre's observation that 1.0 is probably the minimum standard deviation one can achieve in realistic surveys (McIntyre 1980). Based on encoding the McIntyre scale with -1/0/+1 values, means in the winter ranged from -0.11 to 0.35 in the ten buildings, and standard deviations ranged between 0.62 and 0.75.

In the summer, the mean Thermal Sensation was again on the warm side of neutral in nine of the ten buildings. Building I was the exception (with -0.07). Building F had the highest at "slightly warm" (0.80). It was also the warmest building measured in terms of ET* and had a T_{dp} significantly in excess of the limit in ASHRAE Standard 55-81. Summer means and standard deviations for the McIntyre scale were also similar to the winter values. Means ranged from 0.08 to 0.52 and standard deviations from 0.50 to 0.77. As with the Thermal Sensation scale, the highest mean was for building F, and building I had the lowest.

Regression of Mean Responses. The mean vote as a function of thermal conditions was obtained by grouping all people experiencing the same ET* and calculating the mean of all Thermal Sensation votes in that group. Differences between gender were slight, and inconsistent. Since the influence of gender was not overly significant, a regression analysis was based on the whole population. The regression was weighted by the number of observations for each value of ET*. Within the narrow temperature range for which a sufficient number of sample points were obtained (20-25°C), thermal sensation can be described by the following regression equations:

Winter $$TS = 0.328\,ET^* - 7.20 \tag{1a}$$

Summer $$TS = 0.308\,ET^* - 7.04 \tag{1b}$$

The slopes of these lines are in close agreement with values of 0.30 - 0.33 obtained by Berglund (1979), Auliciems (1977), Rohles (as referenced by Berglund 1979), and many other researchers' results as summarized by McIntyre and Gonzalez (1976). The offset of approximately 0.5°C between summer and winter curves will be seen to be consistent with the different approaches taken below in Figures 8 and 9.

Neutral and Preferred Temperatures. The frequency distributions of Thermal Sensation and McIntyre votes as a function of ET* are summarized in Tables 5a and 5b. Thermal Sensation votes were cast on a continuous scale, then categorized around integer values; ET* values in this table were categorized around 0.5°C values.

"Neutral temperature," T_n, is defined as the temperature at which the greatest percentage of people are experiencing neutral thermal sensation by voting within the central category of the Thermal Sensation scale (McIntyre 1978). The data are given in Tables 5a and 5b and are illustrated in Figures 9a and 9b. Neutral temperature can be determined from the regression analysis of mean vote vs. ET*. Based on the regression equations, Equations 1a and 1b presented above, the winter neutral temperature corresponding to TS = 0 is 22.0°C (22.1°C for men and 21.7°C for women). In the summer, the value is 22.6°C (22.4°C for men and 22.7°C for women). Although neutral temperatures for both men and women were slightly higher in the summer as compared to the winter, gender differences were not consistent across the seasons (women's neutral temperature was lower than men's in the winter, yet higher in the summer).

Our values for neutral temperature are in close agreement with those found by Auliciems (1977), 20.5-23.1°C, and Fishman and Pimbert (1978), 22°C , but slightly lower than values obtained by Gagge (1976), 24°C, Fanger (1970), 25.6°C, and Rohles (as referenced by Berglund 1979), 25.3°C. Using data from over 30 field studies, Humphreys (1976) demonstrated that acclimatization can affect the temperature required for thermal neutrality and developed a regression equation predicting the neutral temperature from the mean indoor air temperature. Auliciems (1984) reanalyzed these data to restrict them to office work, giving the equation:

$$T_n = 5.41 + 0.73\,T_m \tag{2}$$

The mean air temperature, T_m, of our winter data set was 22.8°C (based on readings taken during working hours). Auliciems' equation then predicts a neutral temperature of 22.1°C, in close agreement with the value determined from our distribution of Thermal Sensation votes. For the summer, T_m was 23.3°C, giving a predicted T_n of 22.4°C, which is only 0.2°C lower than our regression value.

"Preferred temperature" is defined as the temperature at which a subject requests no change in temperature or at which the greatest percentage of a group of people request no change (McIntyre 1978). Using the McIntyre scale, a regression analysis of the winter data indicated that the preferred temperature was slightly lower than the neutral temperature of 22.0°C (preferred temperature was 21.6°C for men and 21.7°C for women). In the summer, the preferred temperature was again slightly lower than the neutral temperature of 22.6°C (22.0°C for men, 22.3°C for women). For both seasons, preferred temperatures were 0.3-0.6°C cooler than neutral temperatures, and values for women were just slightly higher than for men.

Cumulative Frequency Distributions. Cumulative frequencies of Thermal Sensation votes as a function of ET* are plotted in Figures 8a and 8b. The distribution of the data allowed smooth curves to be plotted only in the range of 20-25°C (winter) and 21-26°C (summer). These fitted curves were weighted by the number of observations at each ET*, and each curve represents the percentage of people voting in any of the categories labeled below the curve. The vertical difference between two curves is, therefore, the percentage of people voting within the single category labeled between them. The category width is measured along the horizontal line at 50%, representing the median response. Data from the winter indicate the central category had a width of approximately 3.3°C. (The range of our data was not sufficient to determine widths of the other categories). Transition temperatures between the -1/0 and 0/+1 categories were approximately 20.5°C and 23.8°C, respectively. For the summer, the central category width was approximately 3.8°C and the transition temperatures, 21.0°C and 24.8°C. These transitions were not symmetrical about the neutral temperature, suggesting that, for both seasons, people felt cool faster than they felt warm when conditions deviated from neutral.

McIntyre (1978) summarized results from numerous field and laboratory studies and found that the width of the central category of seven-point scales used in field studies was 4.7°C and that of laboratory studies was 3.8°C. Fishman and Pimbert (1978), in their field study, calculated a central category width of 4.9°C. The 3.3°C (winter) and 3.8°C (summer) widths found here are clearly less.

Thermal Acceptability

Sensation vs. Acceptability. ASHRAE Standard 55-81 specifies conditions in which "80% or more of the occupants will find the environment thermally acceptable." As used in this definition, acceptability implies satisfaction with the thermal environment. Although there is certainly a range of attributes that might influence a worker's overall impression of the office environment, this analysis focuses on the thermal conditions. Various approaches have been used by researchers to relate thermal acceptability to environmental conditions and corresponding thermal sensation (Berglund 1979). The adjectives used in the Thermal Sensation scale do not directly relate to thermal satisfaction. A conventional approach has been to regard the central three categories of the Thermal Sensation scale as indicating a comfortable state and assume that only people voting outside these central categories are dissatisfied with their thermal state. This approach was first proposed by Fanger (1970) in developing PPD (Predicted Percent Dissatisfied) and has been used in a wide variety of studies. The McIntyre scale is an alternative method of assessing thermal acceptability, by directly asking the participants whether they would prefer to be warmer or cooler, rather than assuming satisfaction based on specified votes of thermal sensation.

Tables 6a and 6b are frequency matrices of people voting in each category of the Thermal Sensation and McIntyre scales. For winter, the results suggest that of all the people voting within the three central categories of thermal sensation, 38% were dissatisfied and wanted to be either warmer or cooler; of the group voting a neutral thermal sensation, 16% still wanted a change in their thermal state. For summer, 41% of people voting in the three central categories were dissatisfied, and of the group voting neutral thermal sensation, 19% wanted a change in their state. These results suggest that a neutral state is not necessarily the most desirable for all people, and some individuals might prefer a state where they feel warm or cool. This idea has been discussed by McIntyre (1980), among others, and finds support in the experimental results of Rohles (1980) and Gagge and Nevins (1976).

Acceptable Thermal Conditions. Figures 9a and 9b present relative frequency curves of both Thermal Sensation and McIntyre votes as a function of ET*, for winter and summer, plotted across the ranges of temperatures for which we have a sufficient number of sample points (20-25°C for winter, and 21-26°C for summer). The McIntyre curve represents the percentage of people at a given ET* voting in the central category, i.e., wanting "no change." The two curves from the Thermal Sensation represent the percentage of people (1) voting in the neutral category, and (2) voting within the three central categories.

Using Fanger's assumption that the three central categories of the Thermal Sensation scale represent comfortable conditions, Figure 9a suggests that approximately 80-85% (based on the fitted curve) of the winter subjects were comfortable across a temperature range of 20.5-24.0°C. Except for the low end of the winter comfort zone (where approximately 62% were comfortable at 20°C), these results support the notion that the edges of the comfort zone represent 80% acceptability. However, responses were generally uniform across this range, rather than peaking at optimum conditions. Using the central category of McIntyre as the criterion for acceptability, the data suggest the optimum acceptability is only 59% at the neutral temperature. Compared to using the Thermal Sensation scale, acceptability here has a stronger peak at the optimum temperature, dropping to 47% comfortable at the two boundaries of the winter comfort zone.

Figure 9b shows the same patterns for the summer data set. As in the winter graph, roughly 80% of the population was comfortable (top curve) at every temperature from 21°C (the lower temperature at which there was a significant number of observations) to slightly over 24°C. This fits the requirement of the winter comfort zone of ASHRAE Standard 55-81. By the time the upper boundary of the summer comfort zone (26.1°C) is reached, the comfortable percentage drops to 59%. Conversely, there is no drop-off of comfort percent below the lower limit of the summer comfort zone (22.8°C). This suggests that the winter comfort zone applies for both seasons for the subjects studied here--in spite of the fact that the subjects' clothing was closer to the Standard's assumed <u>summer</u> values during both summer and winter.

Figure 10 presents the relative frequencies of the three McIntyre votes for the combined winter and summer data set. The boundaries of the ASHRAE winter comfort zone (20.0 - 23.6°C) coincide with the intersection of the 50% line with the curve for the central category ("I want no change"). This implies that up to half the participants wanted a change in their thermal state even when conditions met Standard 55-81. At the top boundary of the summer comfort zone (26.1°C), the percent of subjects voting "no change" dropped significantly, down to approximately 25%. All these measures in the figure show a symmetry around 22°C, and it appears that the consequences of lowering the 20.0°C lower bound of the winter comfort zone are similar to those of raising the upper bound beyond 23.6°C.

RECOMMENDATIONS FOR FUTURE WORK

The initial findings from this research project suggest a number of areas in which further research is needed. In general, these fall into the categories of field studies in other climatic zones, opportunities for providing individual control, reliability of scales used for assessing thermal acceptability, and multiple-feature assessments of office worker comfort.

The limits in the ASHRAE Standard 55-81 comfort zones were developed based on extensive laboratory studies, and it is not clear how well these standards apply to realistic office environments. For example, office workers in our study displayed a wider response to given thermal conditions than was found in laboratory studies, and they also preferred cooler conditions than the optimum suggested by Standard 55-81. It would be useful to repeat this type of experiment in other (both hotter and colder) climatic zones. Expanding the data base to other climates would also allow an investigation of the potential influence of acclimatization on the optimum and comfortable range of thermal conditions.

Our data indicated that optimum satisfaction with the thermal environment in the office buildings was lower than that found in laboratory conditions and implied in Standard 55-81. This suggests that centralized, autonomous environmental systems have substantial inherent limitations to their effectiveness. As a result, it may be profitable to investigate new methods of providing individuals some means of control over their immediate environment. Studies might examine sealed vs. openable building envelopes or novel user-controlled systems such as task ventilation or spot heating and cooling.

Research results also suggest a need to examine the different scales and assumptions used to assess thermal acceptability. Analysis of our data produced very different results when acceptability was evaluated using both the ASHRAE Thermal Sensation and McIntyre scales. Comparing results from different researchers is also difficult without a standard procedure for assessing thermal acceptability. A careful examination of both panel reliability and cross-occasion reliability of the various comfort assessment scales currently in use would be extremely valuable.

Finally, our results indicate a need for multiple-feature assessments of office workers' perceptions of comfort. The low correlations obtained in our multiple regression analysis suggest the relative importance of psychological parameters in realistic settings. In addition, the results obtained in our conceptual analysis of comfort using the Background Survey indicate a need to study the interaction of thermal comfort with specific thermal (e.g., ventilation) and nonthermal (e.g., lighting) environmental attributes.

CONCLUSIONS

A field study of environmental conditions and occupant comfort has been carried out in ten San Francisco Bay area office buildings. We conducted a week of assessment in each building during the 1987 winter season, and again during the following summer. We collected physical measurements and occupant responses during 1308 visits to 264 workstations in the winter and 1034 visits to 221 workstations in the summer. A total of 304 different workstations were visited during the project (with 181 people participating jointly in both the winter and summer studies). The occupants were volunteers, surveyed during their normal work activities. The physical measurements were taken from a mobile cart, focusing on the local workstation environment at the time the occupant was surveyed. We administered two types of surveys: a portable computer-based questionnaire of immediate thermal assessments, and a paper survey for obtaining data on the occupants' personal characteristics and their attitudes toward their working conditions.

We compared the collected data base of thermal conditions with the ASHRAE 55-81 comfort standard for winter and summer conditions. In the winter study, 78.2% of all measurements fell within the winter comfort zone defined by the combined ET*, dewpoint temperature, and air velocity limits in 55-81. Only 4.7% of all measured air velocities exceeded the specified comfort limit. Excessive temperature stratification and horizontal radiant temperature asymmetry occurred only on very rare occasions. The mean clothing insulation worn by the subjects was 0.58 clo. In the summer study, 52.8% of all measurements fell within the combined limits of the summer comfort zone, and only 2.4% of air velocities exceeded the standard's maximum. The mean clothing was 0.52 clo.

The regression of thermal sensation responses against effective temperature compared closely to results from previous studies. Slopes of the regression lines were 0.328 (winter) and 0.308 (summer), expressed as scale units per °C. Multiple regression analyses found that only 12% of the variance in thermal sensation responses was accounted for by the selected physical, personal, and demographic parameters. This is lower, though essentially in line with, the findings of other studies of this type.

We examined thermal sensation and acceptability by comparing responses from the ASHRAE Thermal Sensation and McIntyre scales. Of the people voting neutral thermal sensation, 16% (winter) and 19% (summer) preferred to feel warmer or cooler. Considering the three central thermal sensation categories, this percentage increased to 38% (winter) and 35% (summer). Neutral temperature was approximately 22.0°C in winter, increasing to 22.6°C in summer. Preferred temperature was approximately 0.4°C cooler than neutral in both seasons. The neutral temperature value compares well with the equation for neutral temperature based on mean indoor conditions, as given by Auliciems (1984). Maximum acceptability at this optimum condition was estimated using two methods. Assuming that the central three categories of the Thermal Sensation scale represented comfortable conditions, responses in both seasons were fairly uniform between 20.5-24.0°C, with 80-85% acceptability. However, using the central category of the McIntyre scale, only 60% of the people were comfortable at the neutral (or preferred) temperature in either season, dropping to approximately 47% at the 23.6°C upper boundary of the ASHRAE Standard 55-81 winter comfort zone and to 20% at the 26.1°C upper boundary of the summer comfort zone. The study shows that approximately 80% of the subjects are comfortable (using the central three categories of the Thermal Sensation Scale) within the winter comfort zone in both seasons, and that the 23.6-26°C extension of the summer comfort zone is judged as too warm based on several rating scales.

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TABLE 1

Description of Buildings

Code	Climate (Coastal/Inland)	# visits Winter	# visits Summer	# participants Male	# participants Female	# participants Total	const. date	# floors	total sq.feet	local control†	Comments
P	Berkeley (C/I)	121	123	3	22	25	'52-67	4	236,600	1,3	crowded, open plan no mechanical air-conditioning
A	San Ramon (I)	123	119	9	20	29	'85	4	2,000,000	---	overhangs, computerized blinds thermal ice storage, ponds for evaporative cooling
B	Palo Alto (I)	101	92	11	21	32	'65	5	187,000	2,3	mostly private offices, ASHRAE energy-award for retrofit, multizone HVAC with EMS
C	S.F. (C)	134	108	6	22	28	'78	20	191,000	1,3	private balconies on perimeter, open plan, heat pump mech. system
D	S.F. (C)	132	115	14	16	30	'13	4	54,000	2,3	open plan, converted factory, no mech. a.c., roof-mounted HV unit
E	S.F. (C)	136	123	21	9	30	'49-51	3	90,000	1,3	small perimeter area, open plan and private offices
F	S.F. (C)	122	107	19	16	35	'83	23	265,000	1,4	open plan and private offices, thermal ice storage, VAV with perimeter reheat
G	S.F. (C)	148	117	19	16	35	'85	25	634,000	4	large open plan, mostly rows of tables with no partitions
H	Walnut Creek (I)	145	23	11	20	31	'85	10	316,400	4	triangular with rectangular core open plan and private offices
I	Walnut Creek (I)	146	107	4	25	29	'85	10	368,000	4	mostly interior zones, open plan with partitions and private offices.
TOTALS		1308	1034	117	187	304					

† local control implies usage of: (1) desk fan (2) floor heater (3) operable windows (4) manually operated shades

TABLE 2

Instrumentation Description and Accuracy

QUANTITY	SENSOR DESCRIPTION	SENSOR LOCATION*	MEASUREMENT ACCURACY: ASHRAE 55-81	ISO-7726	MANUFACTURER	CALIBRATION	RESPONSE TIME
Air Temperature	shielded platinum RTD	M: 0.6 m	± 0.2°C	Required: ± 0.5°C Desired: ± 0.2°C	± 0.2°C over range 5 to 40°C	± 0.1°C over range 18.7 to 25.1°C	50 sec (90%) in still air
	shielded thermistor	S: 0.6, 1.1, 1.7 m	± 0.2°C	Required: ± 0.5°C Desired: ± 0.2°C	± 0.1°C over range 0 to 70°C	± 0.2°C over range 20.7 to 28.5°C	5 sec (90%)
	shielded type T thermocouple	M: 0.1, 0.6, 1.1 m	± 0.2°C	Required: ± 0.5°C Desired: ± 0.2°C	± 1.0°C over range 0 to 100°C	± 0.1°C over range 18.7 to 25.1°C	< 3 sec (90%)
Globe Temperature	type T thermocouple inside 38 mm diameter table tennis ball (painted grey)	M: 0.1, 0.6, 1.1 m; S: 1.1 m	Desired: ± 0.2°C (for MRT)	Required: ± 2.0°C Desired: ± 0.2°C (for MRT)	± 1.0°C over range 0 to 100°C (for thermocouple)	± 0.1°C over range 18.7 to 25.1°C (for thermocouple); ± 1°C (for operative temp.)	2.5 min (63.2%); 5.8 min (90%)
Air Velocity	elliptical omnidirectional constant temperature anemometer	M: 0.6 m	± 0.05 m/s over range 0.05 to 0.5 m/s	Required: ± 5% ± 0.05 m/s Desired: ± 2% ± 0.07 m/s over range 0.05 to 1.0 m/s	± 5% ± 0.05 m/s over range 0.05 to 1.0 m/s	factory calibration checked by intercomparison	0.2 sec (90%)
	spherical omnidirectional temp. compensated anemometer	M: 0.1, 1.1 m; S: 1.1 m	± 0.05 m/s over range 0.05 to 0.5 m/s	Required: ± 5% ± 0.05 m/s Desired: ± 2% ± 0.07 m/s over range 0.05 to 1.0 m/s	± 3% ± 0.02 m/s for flow at 90° to probe; for other angles: < ± 10%	factory calibration checked by intercomparison	2 sec (67%); 4.1 sec (90%)
Humidity	chilled-mirror dew point sensor	M: 0.6 m	± 0.6°C (for dew point temp.)	± 0.15 kPa (for water vapor partial press)	± 0.5°C (for dew point temp. over range: T_{air}-T_{dp} < 10°C)	factory calibration checked with sling psychrometer	2 minute measurement period
Radiant Temperature Asymmetry	opposing plane radiant temperature sensors	M: 1.1 m	± 1.0°C	Required: ± 1.0°C Desired: ± 0.5°C	± 0.5°C for $\lvert T_{pr} - T_{air}\rvert \le 15$°C	± 0.4°C over range 18.7 to 25.1°C (for plane radiant temp.)	60 sec (90%)
Surface Temperature	spring loaded platinum RTD	M: 0.6 m	N/A	N/A	± 0.5°C over range 5 to 40°C	± 0.2°C over range 18.7 to 25.1°C	7 sec (90%)
Illumination	silicon photo-voltaic photometer	M: 1.1 m; S: 1.1 m	N/A	N/A	± 5%	factory calibration checked by intercomparison	instantaneous

* M: mobile cart sensor; S: stationary sensor

TABLE 3a

Distribution of Physical Data - Winter

Building	Pilot	A	B	C	D	E	F	G	H	I	All
Sample Size	121	123	101	134	132	136	122	148	145	146	1308
Clothing (clo)											
mean	0.57	0.55	0.70	0.59	0.61	0.61	0.54	0.57	0.56	0.55	0.58
standard deviation	0.13	0.12	0.14	0.13	0.14	0.12	0.11	0.13	0.15	0.13	0.14
minimum	0.30	0.30	0.39	0.33	0.24	0.38	0.24	0.26	0.26	0.31	0.24
maximum	0.90	0.90	1.13	1.07	1.00	1.14	0.83	0.93	0.99	1.14	1.14
Air Temperature (°C)											
mean	23.1	23.1	21.3	22.7	22.2	23.4	22.9	23.0	22.4	23.2	22.8
standard deviation	1.0	0.9	1.7	0.6	1.2	1.1	0.8	0.9	1.4	0.6	1.2
minimum	20.4	21.2	17.4	20.8	19.2	20.6	20.9	20.7	20.0	21.5	17.5
maximum	25.4	25.7	24.9	24.1	24.8	25.6	25.0	25.0	29.8	24.5	29.8
Vapor Pressure (torr)											
mean	7.4	6.4	6.2	8.9	8.9	10.6	6.2	8.8	6.6	7.6	7.8
standard deviation	1.3	0.7	1.0	0.6	0.8	0.6	1.3	1.4	1.0	1.0	1.7
minimum	5.4	4.8	4.6	8.0	6.9	8.9	4.6	6.4	5.1	4.6	4.6
maximum	9.0	7.8	11.2	10.3	10.9	11.8	9.2	11.4	8.8	9.3	11.8
Dew Point Temp. (°C)											
mean	6.6	4.6	4.0	9.5	9.5	12.1	4.1	9.2	4.9	7.1	7.3
standard deviation	2.7	1.6	2.2	0.9	1.3	0.9	2.7	2.3	2.2	1.9	3.3
minimum	2.3	0.6	0.1	7.9	5.8	9.5	0.1	4.7	1.4	0.0	0.0
maximum	9.6	7.5	13.0	11.6	12.5	13.7	10.0	13.3	9.4	12.1	13.7
Air Velocity (m/s)	(mean of 3 heights)										
mean	0.10	0.06	0.06	0.04	0.04	0.06	0.05	0.08	0.05	0.05	0.06
standard deviation	0.07	0.04	0.06	0.06	0.04	0.05	0.02	0.05	0.03	0.03	0.05
minimum	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00
maximum	0.39	0.26	0.37	0.56	0.20	0.27	0.11	0.30	0.19	0.17	0.56
Operative Temp. (°C)											
mean	23.3	23.3	21.4	22.9	22.3	23.6	23.1	22.2	22.6	23.3	22.9
standard deviation	1.0	1.0	1.7	0.6	1.1	1.0	0.8	0.9	1.3	0.5	1.2
minimum	20.7	20.8	17.8	21.1	19.5	21.0	21.1	21.0	20.4	21.8	17.8
maximum	25.7	26.4	25.5	24.2	24.3	25.6	25.3	25.1	28.5	24.6	28.5
ET* (°C)											
mean	22.8	22.7	21.0	22.6	22.0	23.4	22.6	22.8	22.1	22.9	22.5
standard deviation	0.9	0.8	1.6	0.7	1.1	1.0	0.7	0.9	1.3	0.6	1.1
minimum	20.4	20.9	17.4	20.8	19.3	20.6	20.8	20.6	19.8	21.0	17.4
maximum	24.9	24.8	24.3	24.0	24.4	25.5	24.3	24.9	28.3	24.2	28.3

TABLE 3b

Distribution of Physical Data - Summer

Building	Pilot	A	B	C	D	E	F	G	H	I	All
Sample Size	123	119	92	108	115	123	107	117	23	107	1034
Clothing (clo)											
mean	0.47	0.50	0.47	0.54	0.53	0.54	0.55	0.55	0.50	0.53	0.52
standard deviation	0.12	0.13	0.10	0.16	0.11	0.10	0.13	0.12	0.14	0.11	0.12
minimum	0.16	0.23	0.25	0.20	0.26	0.27	0.24	0.28	0.22	0.34	0.16
maximum	0.71	0.92	0.64	1.44	0.97	0.98	0.87	0.99	0.74	0.81	1.44
Air Temperature (°C)											
mean	24.6	22.6	23.4	22.6	22.4	24.3	24.4	22.7	22.4	22.8	23.3
standard deviation	1.6	0.5	0.5	1.0	0.8	1.0	1.2	0.6	0.8	0.6	1.3
minimum	21.8	21.1	22.4	20.1	20.5	21.7	21.0	21.0	21.3	21.4	20.7
maximum	29.5	23.6	25.0	24.5	24.6	26.3	27.6	24.2	24.1	25.4	29.5
Vapor Pressure (torr)											
mean	11.2	12.0	13.2	11.6	13.2	13.6	15.0	13.8	13.3	12.9	12.9
standard deviation	0.7	0.5	0.8	0.5	0.8	0.8	0.6	0.9	0.4	0.6	1.3
minimum	8.6	11.2	11.3	10.7	11.8	10.6	13.2	12.2	12.5	12.0	8.6
maximum	12.7	13.0	16.6	12.9	15.8	15.2	16.7	16.9	14.6	17.7	17.7
Dew Point Temp. (°C)											
mean	13.0	14.0	15.5	13.5	15.5	16.0	17.5	16.2	15.6	15.1	15.1
standard deviation	0.9	0.6	0.9	0.6	0.9	0.9	0.6	1.0	0.5	0.7	1.6
minimum	9.0	12.9	13.1	12.3	13.7	12.1	15.5	14.3	14.7	14.0	9.0
maximum	14.9	15.2	19.1	15.1	18.3	17.7	19.2	19.4	17.0	20.2	20.2
Air Velocity (m/s)	(mean of 3 heights)										
mean	0.20	0.11	0.11	0.10	0.11	0.12	0.11	0.16	0.11	0.11	0.10
standard deviation	0.19	0.02	0.03	0.01	0.03	0.03	0.02	0.09	0.02	0.02	0.09
minimum	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.05	0.02	0.01	0.00
maximum	1.24	0.20	0.24	0.18	0.25	0.30	0.22	0.67	0.19	0.23	1.24
Operative Temp. (°C)											
mean	24.7	22.8	23.6	22.8	22.6	24.5	24.5	23.0	22.6	22.8	23.5
standard deviation	1.6	0.5	0.5	1.0	0.8	1.0	1.1	0.6	0.7	0.6	1.2
minimum	22.1	21.6	22.6	20.3	20.8	22.1	21.3	21.3	21.5	21.4	20.3
maximum	29.5	23.7	25.2	24.6	24.6	26.4	27.6	24.5	24.1	25.4	29.5
ET* (°C)											
mean	24.5	22.7	23.7	22.7	22.7	24.6	24.8	23.1	22.7	23.0	23.5
standard deviation	1.4	0.5	0.5	1.0	0.8	1.0	1.2	0.6	0.7	0.7	1.3
minimum	22.0	21.3	22.7	20.2	20.9	21.8	21.3	21.4	21.7	21.6	20.2
maximum	29.0	23.7	25.0	24.6	24.9	26.5	28.0	24.5	24.4	25.8	29.0

TABLE 4

Comparison to Standard 55-81 Comfort Zones

Building	Pilot	A	B	C	D	E	F	G	H	I	All
WINTER Sample Size	121	123	101	134	132	136	122	148	145	146	1308
Dew Point Temp. (°C)											
% < 1.7°C	0.0	2.4	7.9	0.0	0.0	0.0	16.4	0.0	4.1	0.7	2.9
1.7°C ≤ % ≤ 16.7°C	**100.0**	**97.6**	**92.1**	**100.0**	**100.0**	**100.0**	**83.6**	**100.0**	**95.9**	**99.3**	**97.1**
% > 16.7°C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ET* (°C)											
% < 20.0°C	0.0	0.0	29.7	0.0	3.8	0.0	0.0	0.0	1.4	0.0	2.8
20.0°C ≤ % ≤ 23.6°C	**84.3**	**86.2**	**65.3**	**96.3**	**94.7**	**58.8**	**91.8**	**82.4**	**90.3**	**85.6**	**83.9**
% > 23.6°C	15.7	13.8	5.0	3.7	1.5	41.2	8.2	17.6	8.3	14.4	13.2
Air Velocity (m/sec) (average of 3 heights)											
% ≤ 0.15 m/sec	**81.8**	**95.9**	**97.0**	**97.8**	**97.0**	**94.1**	**100.0**	**91.9**	**97.9**	**99.3**	**95.3**
% > 0.15 m/s	18.2	4.1	3.1	2.2	3.1	5.9	0.0	8.1	2.1	.7	4.7
Dew Point Temp. and ET* Combined, with Air Velocity below maximum											
% cool only	0.0	0.0	25.7	0.0	3.8	0.0	0.0	0.0	1.4	0.0	2.5
% warm only	9.9	13.0	3.0	3.7	.8	39.0	7.4	16.2	6.2	14.4	11.7
% dry only	0.0	0.0	4.0	0.0	0.0	0.0	15.6	0.0	4.1	0.0	2.5
% cool/dry	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.3
% warm/dry	0.0	2.4	0.0	0.0	0.0	0.0	.8	0.0	0.0	.7	.1
% comfort	71.9	80.5	60.4	94.0	92.4	55.1	76.2	75.7	83.2	84.2	78.2
SUMMER Sample Size	123	119	92	108	115	123	107	117	23	107	1034
Dew Point Temp. (°C)											
% < 1.7°C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.7°C ≤ % ≤ 16.7°C	**100.0**	**100.0**	**95.7**	**100.0**	**93.0**	**86.2**	**11.2**	**61.5**	**95.7**	**99.1**	**83.5**
% > 16.7°C	0.0	0.0	4.3	0.0	7.0	13.8	88.8	38.5	4.3	0.9	16.5
ET* (°C)											
% < 22.8°C	7.3	51.3	4.3	52.8	50.4	8.9	2.8	29.9	60.9	31.8	27.7
22.8°C ≤ % ≤ 26.1°C	**72.4**	**48.7**	**95.7**	**47.2**	**49.6**	**88.6**	**84.1**	**70.1**	**39.1**	**68.2**	**68.3**
% > 26.1°C	20.3	0.0	0.0	0.0	0.0	2.4	13.1	0.0	0.0	0.0	4.1
Air Velocity (m/sec) (average of 3 heights)											
% ≤ V_{max}*	**88.6**	**100.0**	**100.0**	**100.0**	**100.0**	**99.2**	**100.0**	**91.5**	**100.0**	**100.0**	**97.6**
% > V_{max}*	11.4	0.0	0.0	0.0	0.0	0.8	0.0	8.5	0.0	0.0	2.4
Dew Point Temp. and ET* Combined: Air Velocity below maximum											
% cool only	7.3	51.3	4.3	52.8	49.6	8.9	2.8	18.8	60.9	31.8	26.3
% warm only	18.7	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	2.4
% humid only	0.0	0.0	4.3	0.0	6.1	13.0	75.7	25.6	4.3	0.9	13.5
% cool/humid	0.0	0.0	0.0	0.0	0.9	0.0	0.0	8.5	0.0	0.0	1.1
% warm/humid	0.0	0.0	0.0	0.0	0.0	0.8	13.1	0.0	0.0	0.0	1.4
% comfort	62.6	48.7	91.3	47.2	43.5	74.8	8.4	38.5	34.8	67.3	52.8

* Summer maximum limit for air velocity is extended for air temperatures between 26-28°C.
For T_a < 26°C, V_{max} = 0.25 m/sec. V_{max} then increases 0.275 m/sec for each degree °C of T_a above 26°C, up to a maximum of 0.8 m/sec at T_a = 28°C.

TABLE 5a

Frequency Distribution of Thermal Sensation and McIntyre Votes - Winter

ET*	Sample Size	Mean Th.Sens.	% Thermal Sensation Votes[1,2] -3	-2	-1	0	1	2	3	% McIntyre Votes[1,3] "I would like to be:" warmer	no change	cooler
17.5	1	0.00	-	-	-	100	-	-	-	-	100	-
18.0	3	-.57	-	-	100	-	-	-	-	100	-	-
18.5	4	-.58	-	25	25	50	-	-	-	75	25	-
19.0	6	-.33	-	-	33	67	-	-	-	33	50	17
19.5	11	-.90	9	36	18	9	-	-	-	54	46	-
20.0	21	-.24	5	19	24	29	5	9	9	38	48	14
20.5	49	-.14	-	6	41	31	16	2	4	47	41	12
21.0	54	-.53	5	9	39	35	7	2	2	43	52	2
21.5	114	-.30	3	12	25	42	14	3	1	33	58	9
22.0	185	-.02	2	4	19	54	14	7	-	20	63	16
22.5	280	.15	1	8	15	41	29	5	1	18	54	27
23.0	281	.32	1	4	16	42	24	11	2	12	56	31
23.5	160	.55	1	2	12	38	33	12	2	6	48	46
24.0	88	.66	2	1	8	36	34	17	2	6	43	51
24.5	32	.66	-	3	9	31	41	16	-	3	38	59
25.0	13	1.71	-	-	8	-	23	61	8	-	8	92
25.5	4	2.00	-	-	-	-	25	50	25	-	25	75
26.0	0	-	-	-	-	-	-	-	-	-	-	-
26.5	0	-	-	-	-	-	-	-	-	-	-	-
27.0	0	-	-	-	-	-	-	-	-	-	-	-
27.5	0	-	-	-	-	-	-	-	-	-	-	-
28.0	1	.30	-	-	-	100	-	-	-	-	100	-
28.5	1	1.00	-	-	-	-	100	-	-	-	100	-
29.0	0	-	-	-	-	-	-	-	-	-	-	-

[1] Percentages are by row, i.e., based on a group exposed to the same ET*
[2] Integer values represent binning of votes made on a continuous scale. Category 0 corresponds to votes within ±0.5, etc.
[3] For some values of ET*, McIntyre totals do not add to 100% because of missing data.

TABLE 5b

Frequency Distribution of Thermal Sensation and McIntyre Votes - Summer

ET*	Sample Size	Mean Th.Sens.	% Thermal Sensation Votes[1,2] -3	-2	-1	0	1	2	3	% McIntyre Votes[1] "I would like to be:" warmer	no change	cooler
17.5	0	-	-	-	-	-	-	-	-	-	-	-
18.0	0	-	-	-	-	-	-	-	-	-	-	-
18.5	0	-	-	-	-	-	-	-	-	-	-	-
19.0	0	-	-	-	-	-	-	-	-	-	-	-
19.5	0	-	-	-	-	-	-	-	-	-	-	-
20.0	1	-1.00	-	-	100	-	-	-	-	-	100	-
20.5	5	1.40	-	-	-	40	20	-	40	40	60	-
21.0	9	.22	-	-	11	56	33	-	-	-	78	22
21.5	29	-.28	3	-	41	38	14	-	3	24	66	10
22.0	78	-.23	-	9	32	39	15	4	1	24	54	22
22.5	148	-.24	3	6	28	45	15	3	1	17	64	19
23.0	222	.13	2	1	16	50	24	6	-	14	55	32
23.5	192	.22	-	5	12	48	30	6	1	10	59	31
24.0	107	.41	-	3	13	42	27	12	3	8	52	50
24.5	67	.10	-	3	21	46	22	8	-	9	51	40
25.0	59	.53	-	2	15	29	37	17	-	5	34	61
25.5	60	.87	-	-	2	37	38	20	3	2	32	67
26.0	21	1.19	-	5	-	14	38	38	5	-	14	86
26.5	18	1.28	-	-	-	28	22	44	6	-	17	83
27.0	11	2.09	-	-	-	9	-	64	27	-	-	100
27.5	5	1.40	-	-	-	20	20	60	-	-	40	60
28.0	1	3.00	-	-	-	-	-	-	100	-	-	100
28.5	0	-	-	-	-	-	-	-	-	-	-	-
29.0	1	2.00	-	-	-	-	-	100	-	-	-	100

[1] Percentages are by row, i.e., based on a group exposed to the same ET*
[2] Integer values represent binning of votes made on a continuous scale. Category 0 corresponds to votes within ±0.5, etc.

TABLE 6a

Thermal Sensation vs. McIntyre Votes - Winter

number of people given in bold face
% of people given in lightface[1]

	McIntyre Scale "I would like to be:" Warmer	No Change	Cooler	Row Total[2]
Thermal Sensation Scale				
3 Hot	**3** 13.6	**3** 13.6	**16** 72.7	**22** 1.7
2 Warm	**4** 3.5	**17** 14.9	**93** 81.6	**114** 8.8
1 Slightly Warm	**10** 3.3	**95** 31.4	**198** 65.3	**303** 23.4
0 Neutral	**34** 6.4	**444** 83.8	**52** 9.8	**530** 40.9
-1 Slightly cool	**100** 42.0	**126** 54.0	**7** 3.0	**233** 18.0
-2 Cool	**70** 93.3	**5** 6.7	**0** 0	**75** 5.8
-3 Cold	**19** 95.0	**1** 5.0	**0** 0	**20** 1.5
Column Total[2]	**240** 18.5	**691** 53.3	**366** 28.2	**1297** 100.0

1 Percentages are by row, i.e., based on a group voting in the same Thermal Sensation category

2 Note that % values in Row and Column Totals are based on set of 1297 visits. This is because McIntyre scale data was missing in 9 of the original 1308 visits.

TABLE 6b

Thermal Sensation vs. McIntyre Votes - Summer

number of people given in bold face
% of people given in lightface[1]

	McIntyre Scale "I would like to be:" Warmer	No Change	Cooler	Row Total
Thermal Sensation Scale				
3 Hot	**3** 17.6	**4** 23.5	**10** 58.8	**17** 1.6
2 Warm	**2** 2.0	**10** 10.0	**88** 88.0	**100** 9.7
1 Slightly Warm	**4** 1.6	**48** 18.8	**203** 79.6	**255** 24.7
0 Neutral	**17** 3.8	**360** 81.4	**65** 14.7	**442** 42.7
-1 Slightly cool	**66** 37.5	**103** 58.5	**7** 4.0	**176** 17.0
-2 Cool	**21** 60.0	**14** 40.0	**0** 0	**35** 3.4
-3 Cold	**8** 88.9	**0** 0	**1** 11.1	**9** .9
Column Total[2]	**121** 11.7	**539** 52.1	**374** 36.2	**1034** 100.0

1 Percentages are by row, i.e., based on a group voting in the same Thermal Sensation category

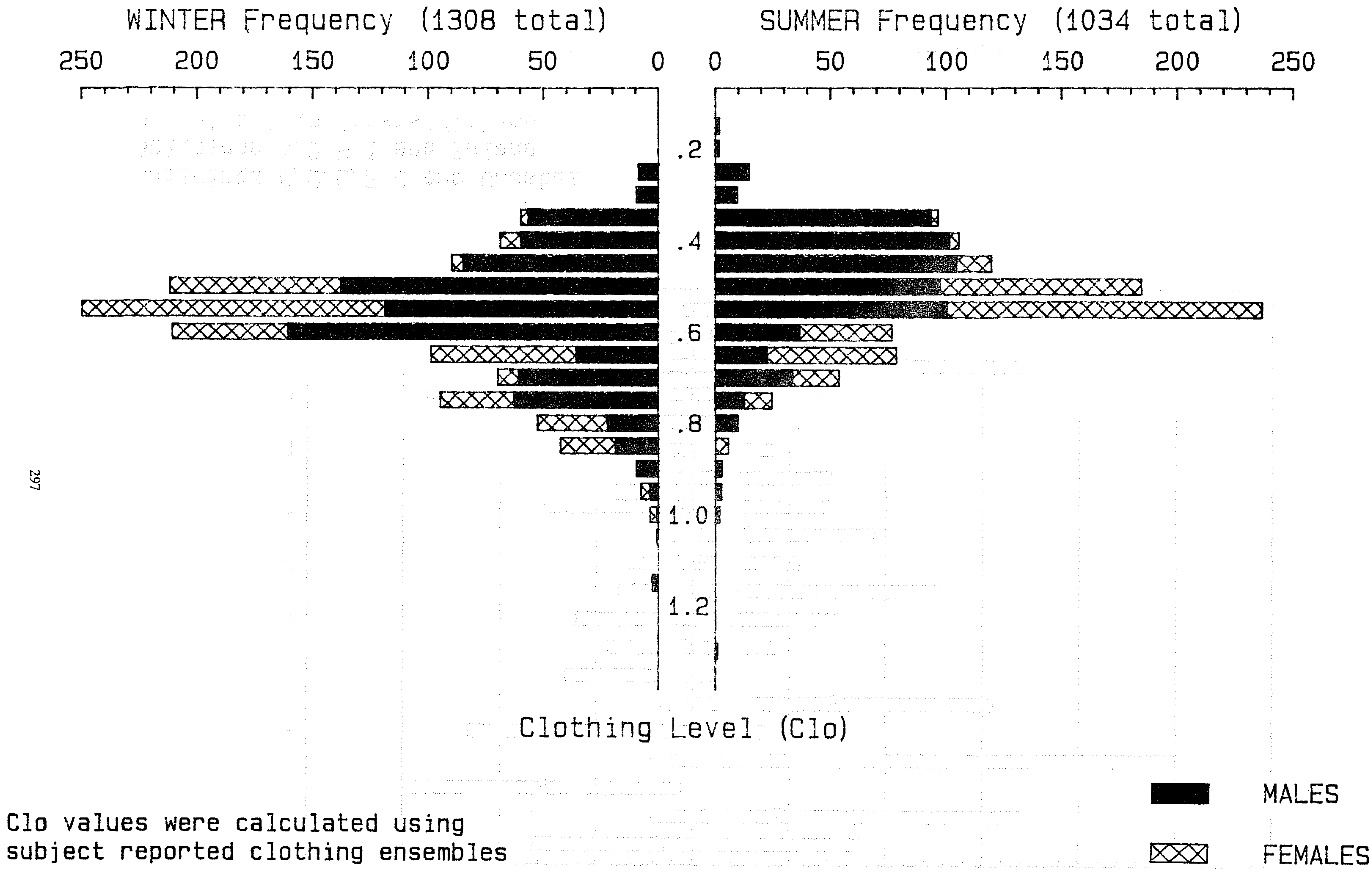


Figure 1 Distribution of clothing insulation

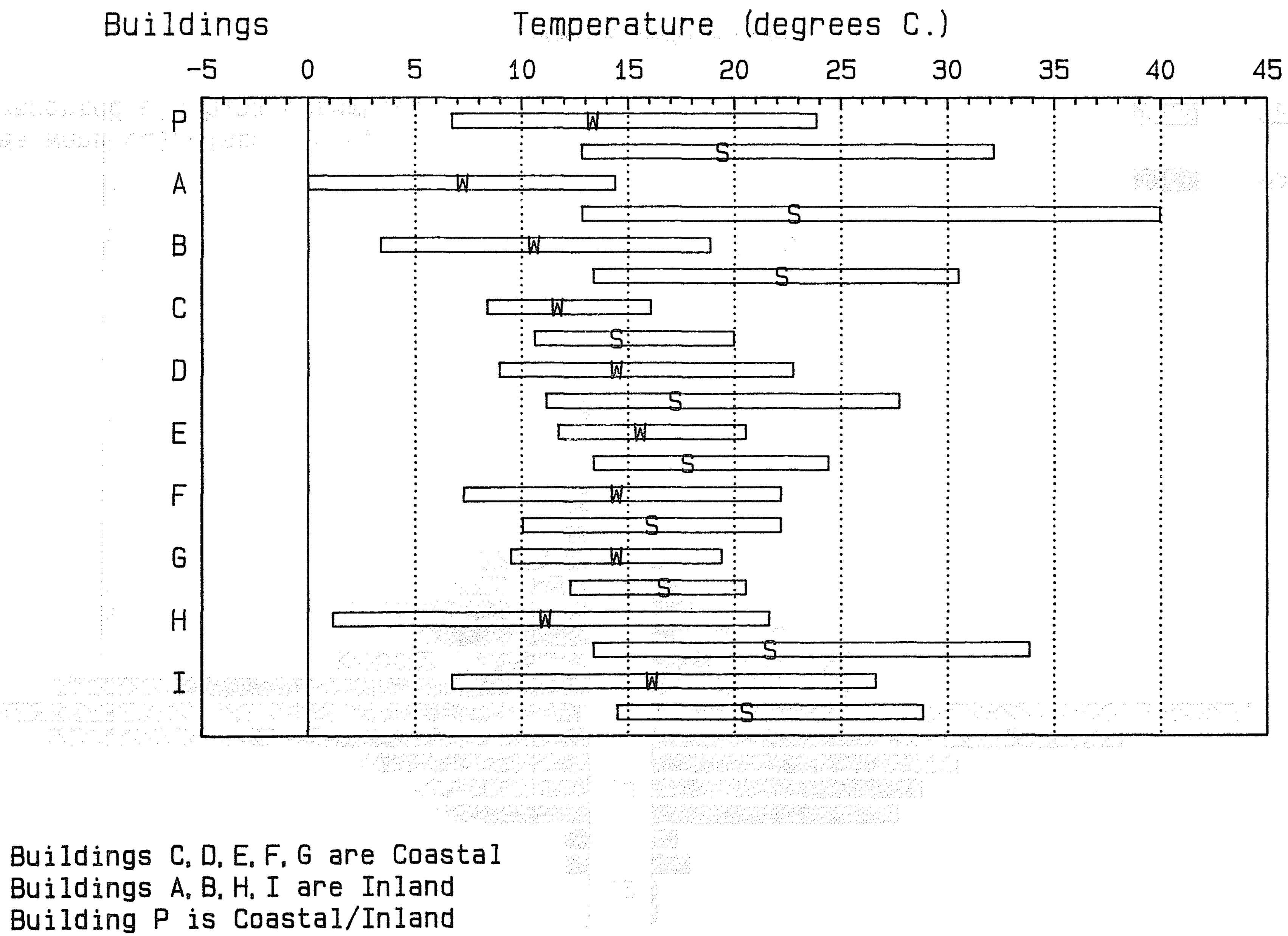


Figure 2 Outdoor air temperatures during monitoring weeks

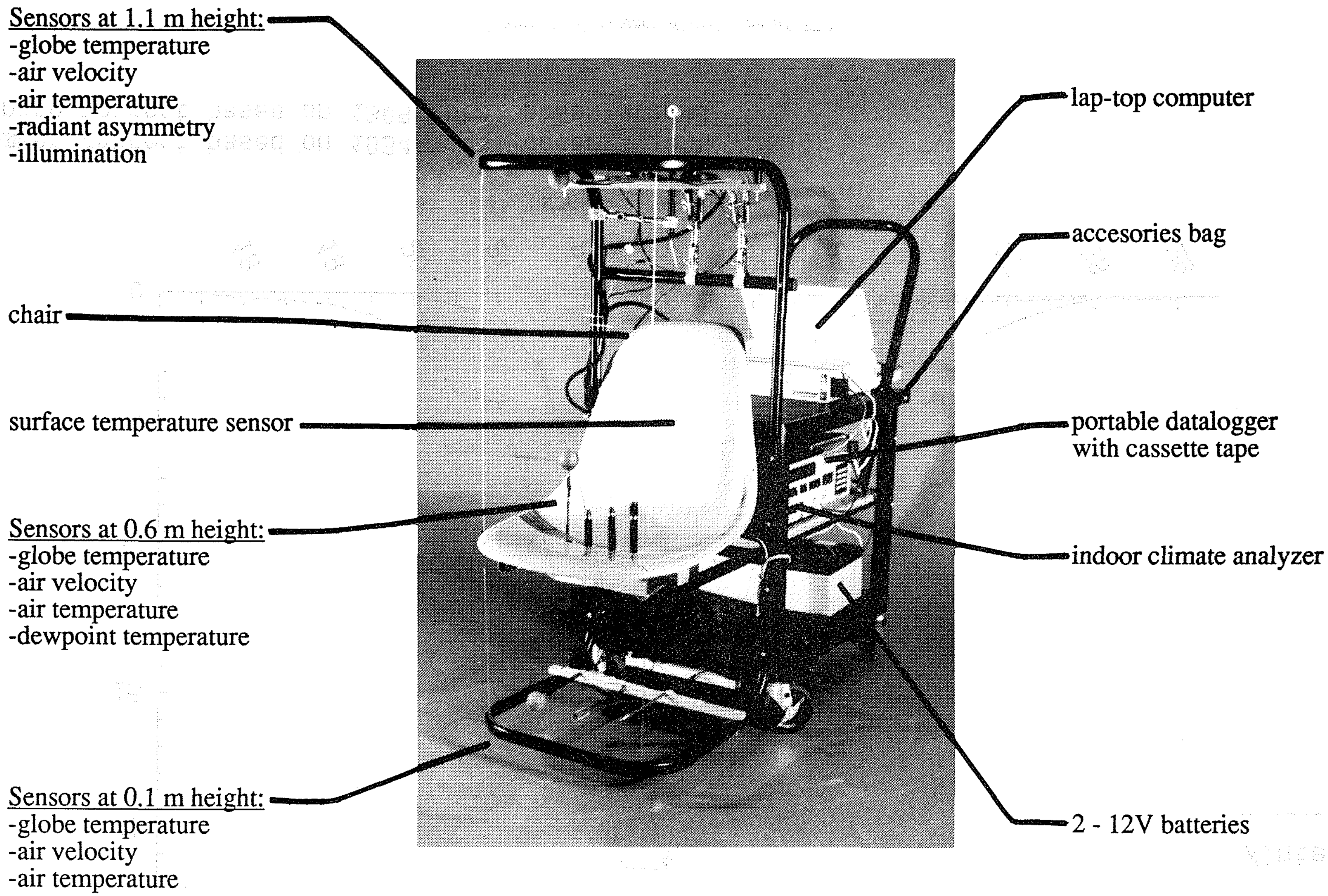


Figure 3 Mobile measurement cart

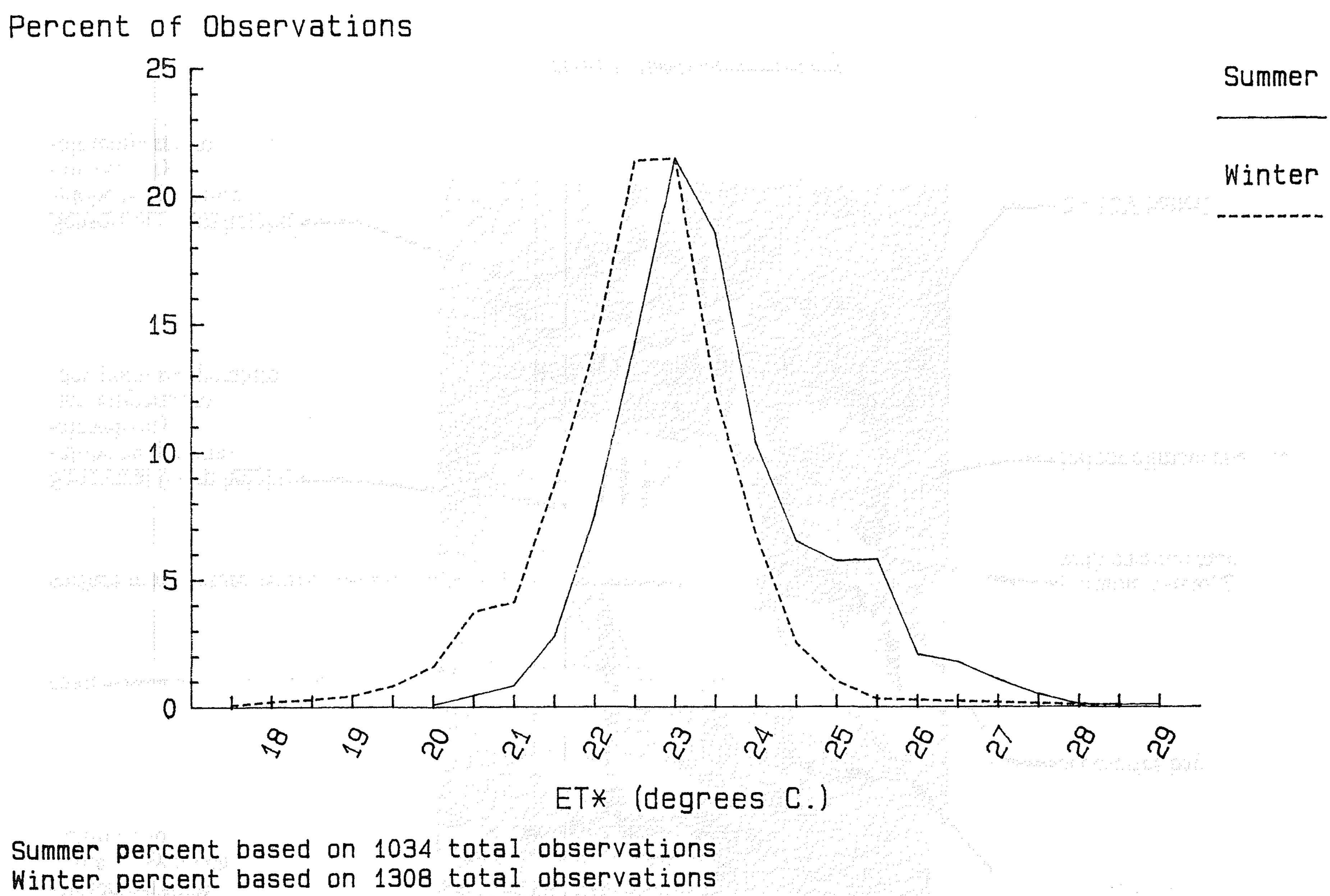
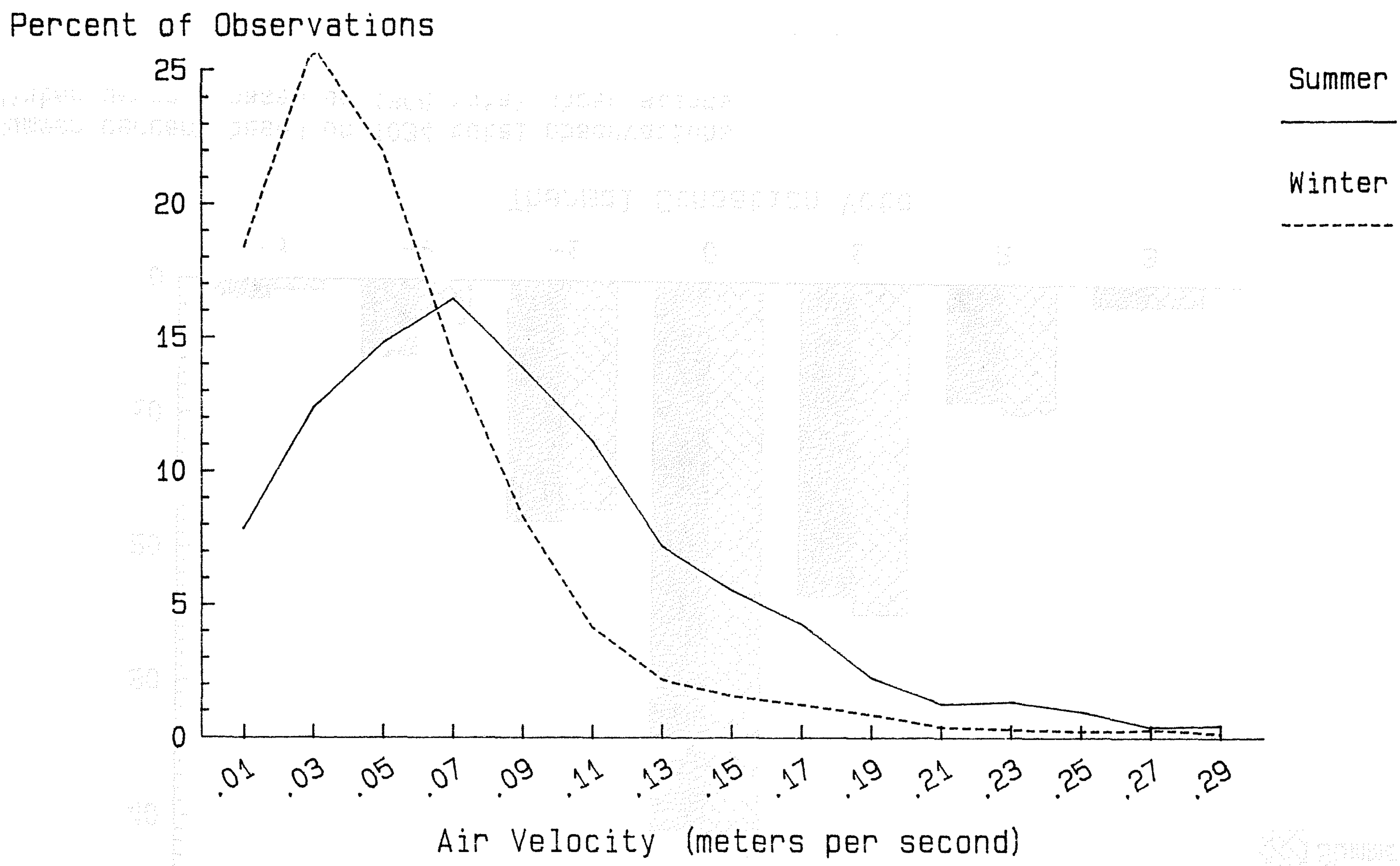


*Figure 4 Frequency distribution of ET**



Summer percent based on 1034 total observations
Winter percent based on 1308 total observations

Figure 5 Frequency distribution of air velocity

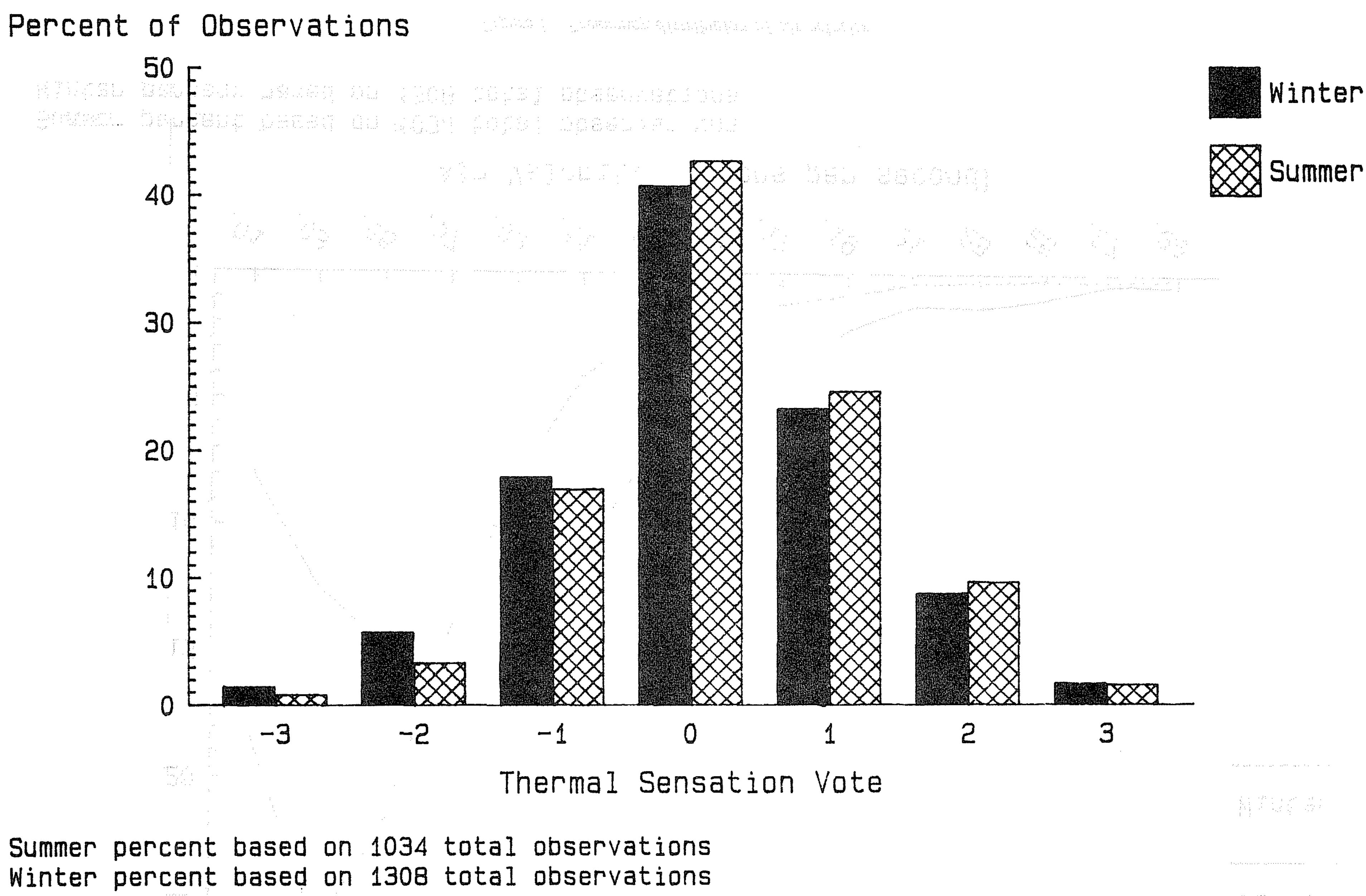
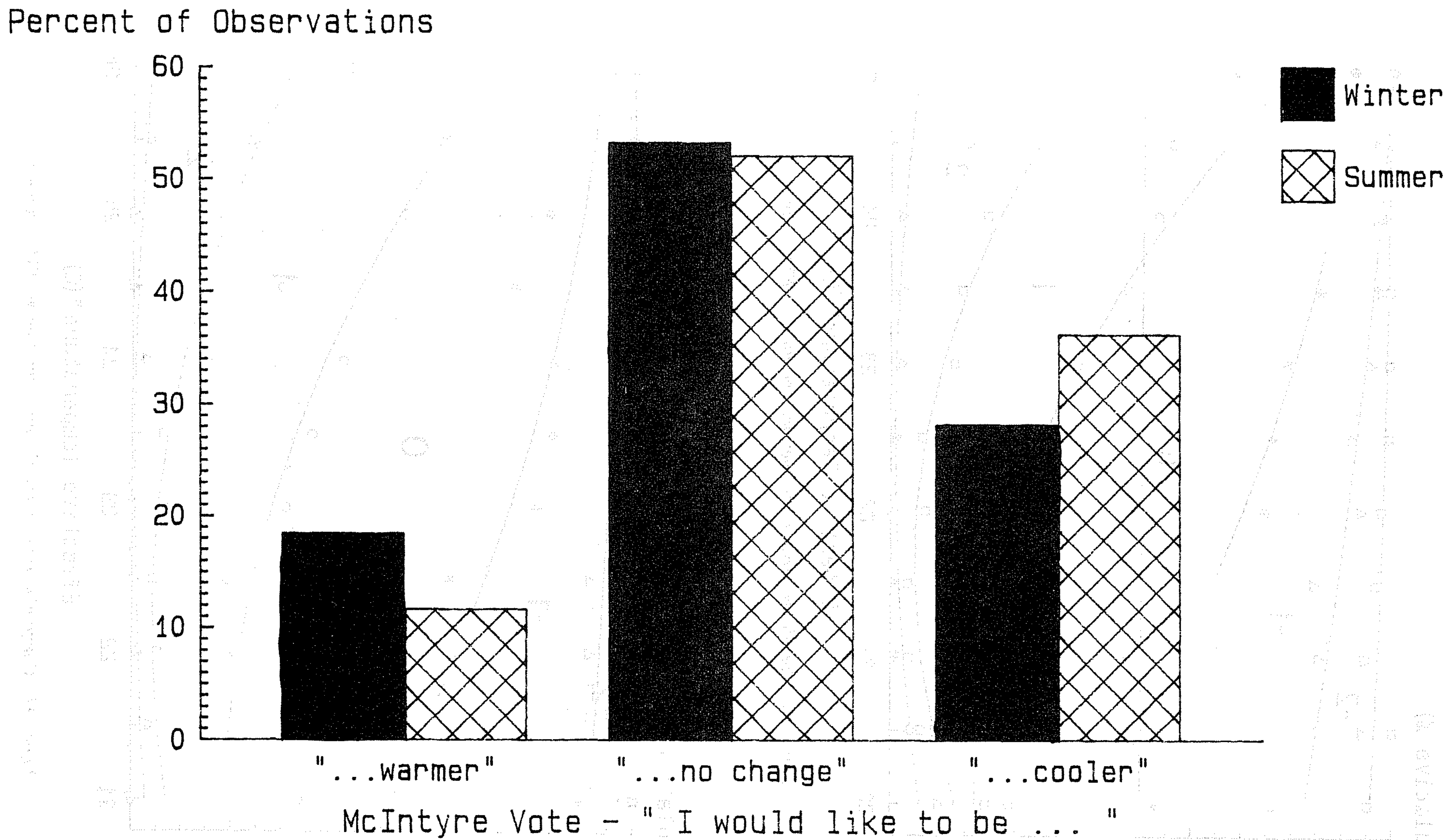


Figure 6 Frequency distribution of thermal sensation votes



Summer percent based on 1034 total observations
Winter percent based on 1297 total observations

Figure 7 Frequency distribution of McIntyre votes

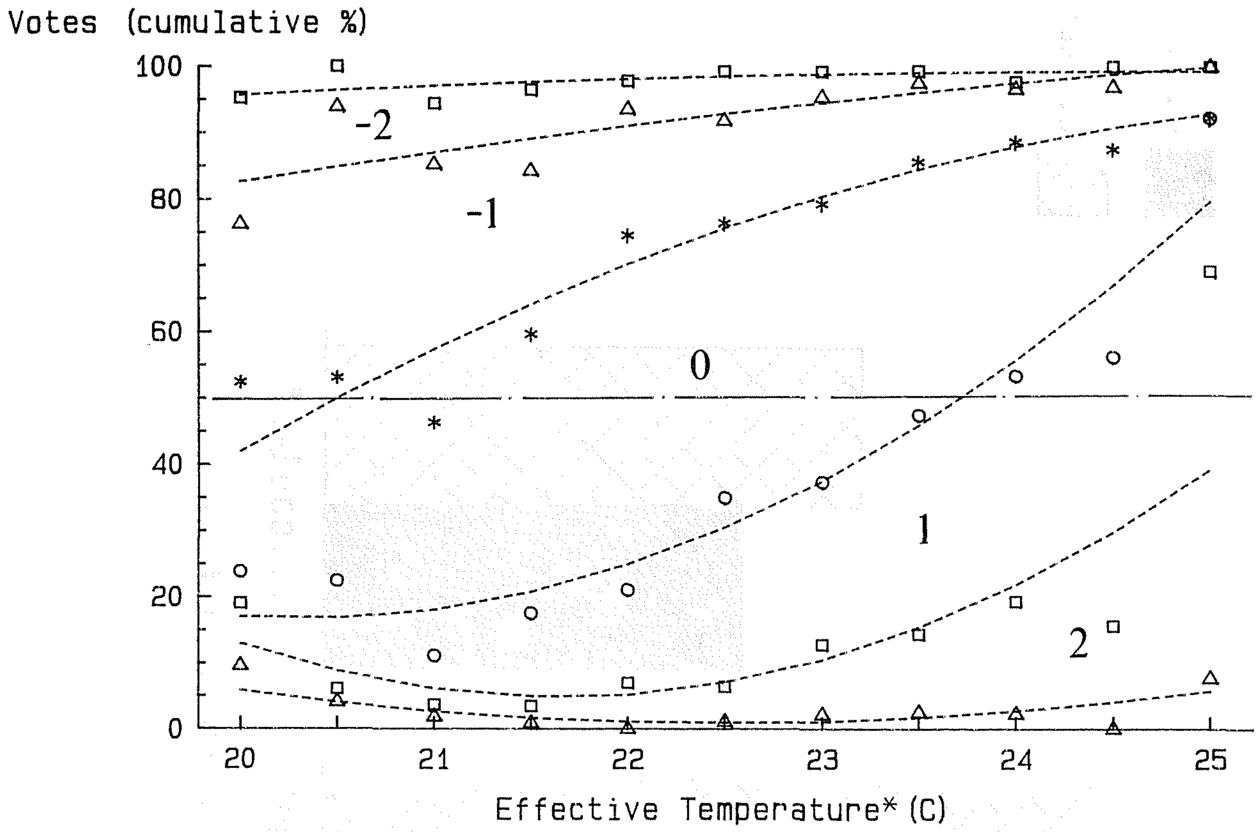


Figure 8a Cumulative frequencies, thermal sensation vs. ET: winter*

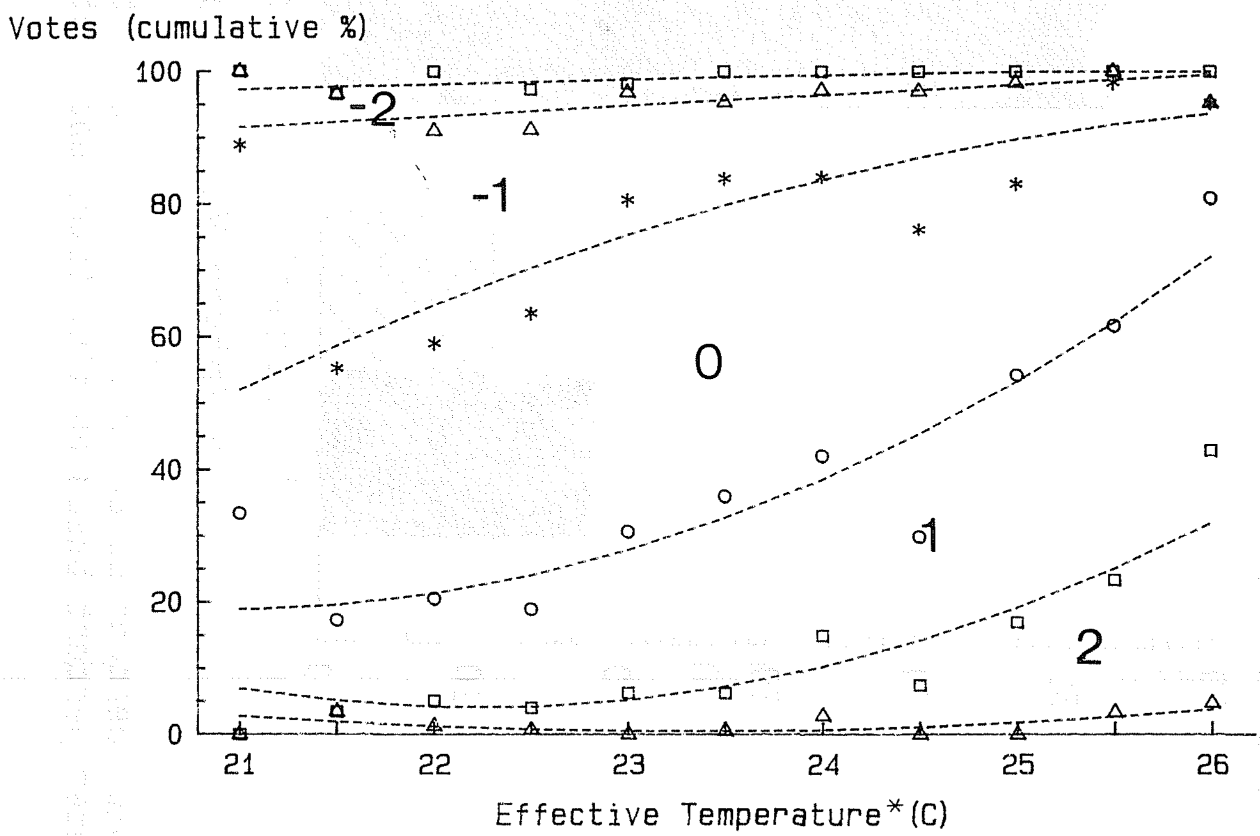


Figure 8b Cumulative frequencies, thermal sensation vs. ET: summer*

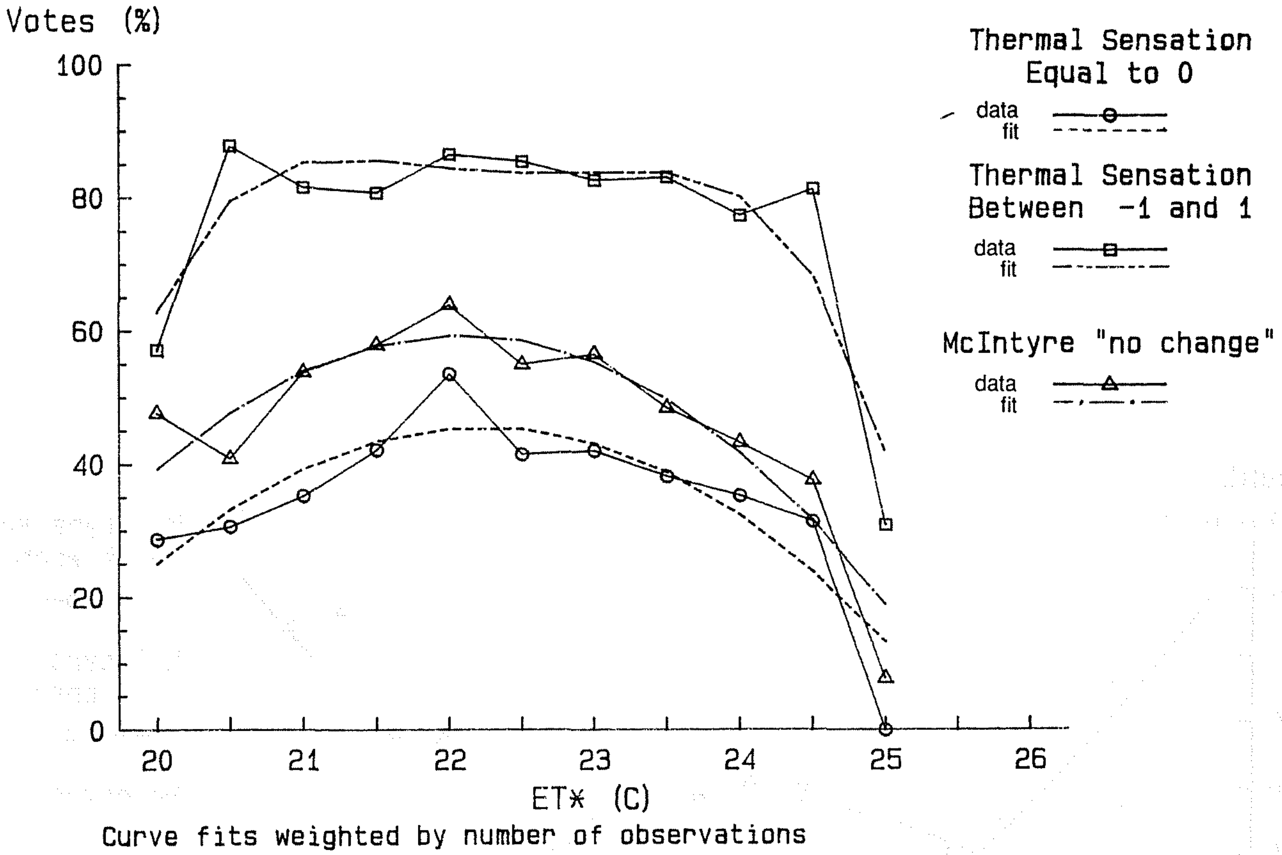


Figure 9a Thermal acceptability: winter

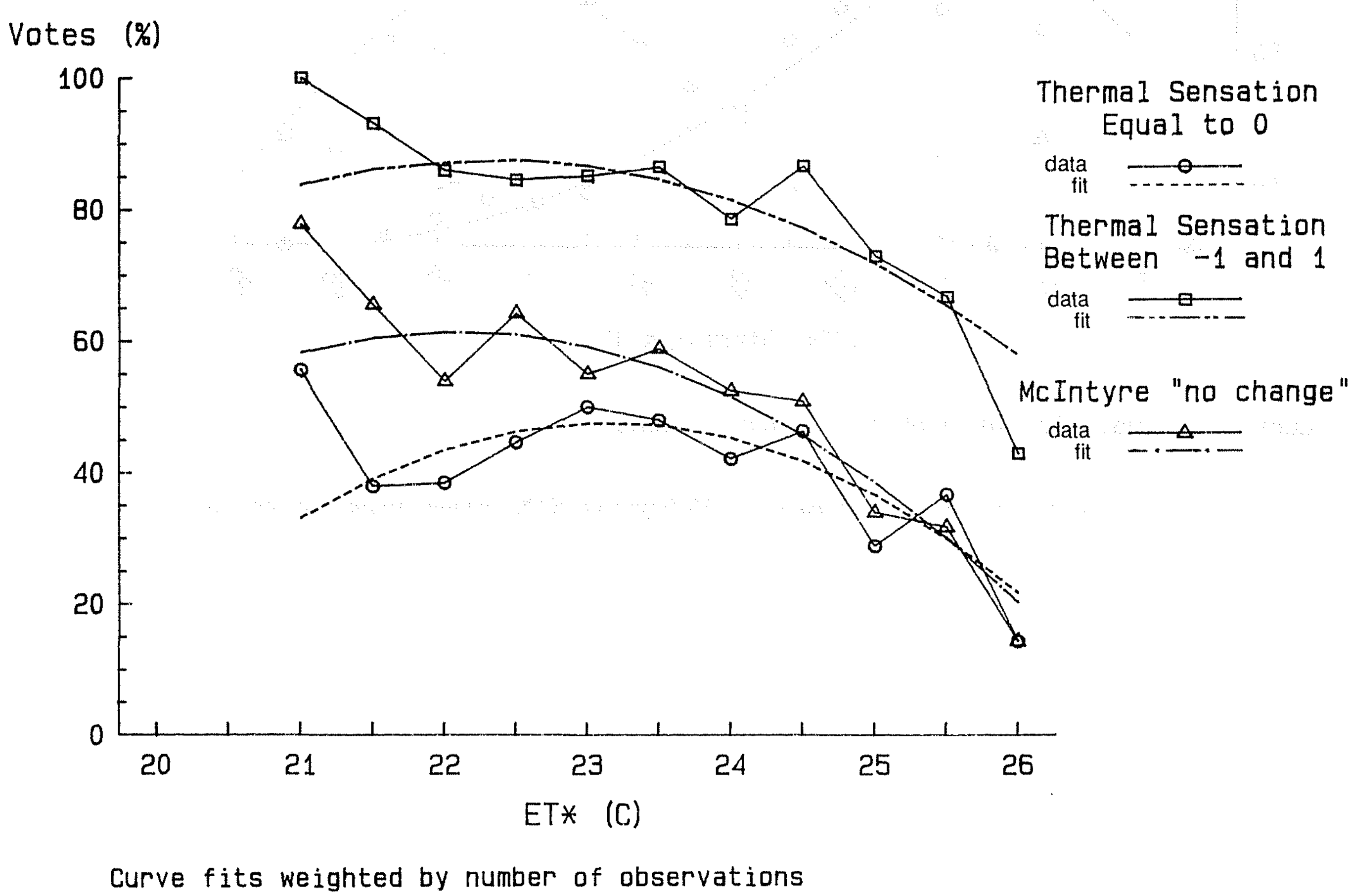


Figure 9b Thermal acceptability: summer

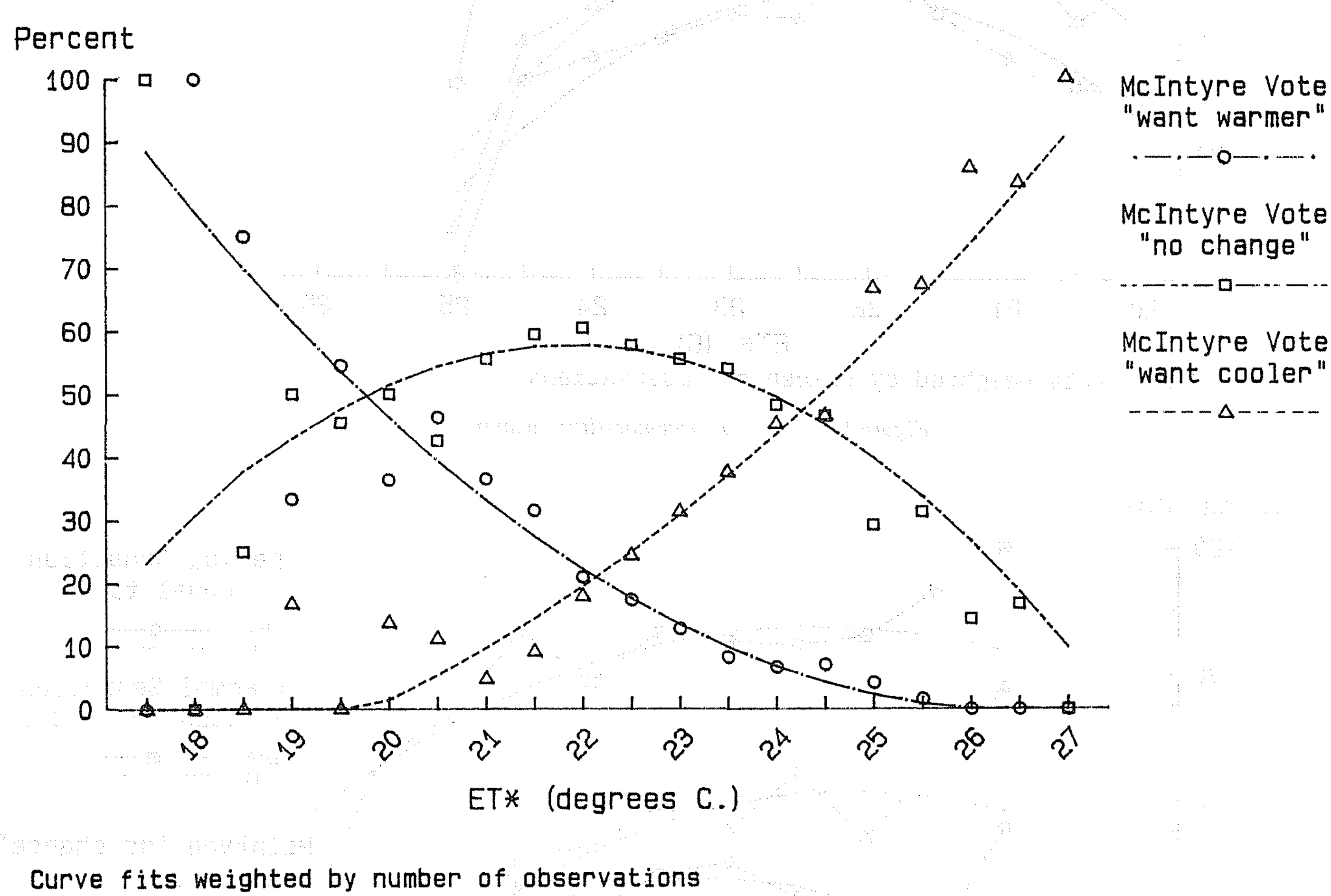


Figure 10 Relative frequencies, McIntyre vs. ET: winter/summer combined*

DISCUSSION

G.S. Kochhar, Lecturer, University of the West Indies, Trinidad: Did the study take into account the ethnic background of the subjects or were all subjects of one ethnic background? If you did account for it, were there any variations in response of subjects?

G.E. Schiller: We were able to collect data on ethnic background for 259 of the 304 subjects. Of these 259, the ethnic backgrounds were: 81.5% Caucasian, 7.3% Asian American, 6.2% Black, and 5% Hispanic. Except for gender, we have not yet analyzed the data for variations based on demographics such as ethnic background, age, or occupation.

A. Meier, Lawrence Berkeley Laboratory, Berkeley, CA: Have you compared or correlated thermal comfort to job satisfaction?

Schiller: We are currently conducting analyses to compare ratings of job satisfaction to thermal responses from the repetitive survey, as well as to other questions from the background survey related to office description, work area satisfaction, and health characteristics. Results will be forthcoming in a future paper.

B.W. Jones, Kansas State University, Manhattan: Your paper indicates that an activity checklist was used to estimate the metabolic rate of the participants and also that the resulting data were used in correlation and regression analyses. However, no information is presented describing the distribution or even the mean of the metabolic rates. Since metabolic rate is as important as clothing insulation, air temperature, air velocity, etc., in determining thermal sensation and comfort, it would be useful to have information on this variable. Are data, comparable to that presented in Tables 3a and 3b for other variables, available for metabolic rate?

Your "sampling period" for metabolic rate and environmental variables was only 15 minutes. The thermal response time of the human body is typically several hours and the thermal state of the body at a point in time will depend on the activity level and environmental conditions experienced during this longer response time. What was done to determine whether or not the estimated metabolic rates and the measured environmental conditions were representative of the subjects' experiences for the longer time period? Is it possible that the low correlation between thermal sensation and physical, personal, and demographic parameters is due in part to random variations between metabolic rates during the 15-minute period and earlier time periods? Likewise, is it possible that the preference for cooler than expected temperatures is due to bias in measuring the metabolic rate? The nature of the study tended to require measurements at a desk or similar work station. A person who performed a variety of tasks may have a higher average metabolic rate than would be indicated by a "desk activity."

Schiller: Approximately 50% of the activity levels were at 1.0 met, 38% at 1.2 met, and 12% at 1.4 met. Activity patterns were similar between men and women, and no significant seasonal differences were observed.

The 15-minute sampling period for our activity questions was based on a member of the research team's experience with physiological testing in which 15 to 30 minutes was the standard control period and the body consistently came to steady state with the first 15 minutes, except for conditions of very heavy exercise. The sampling period is also supported by results of Rohles and Wells (ASHRAE Transactions 1977, Vol. 83, Pt. 2), where it was found that subjects' votes after 15 minutes were representative of their votes over a much longer time period. The objective of the field study was to measure conditions at the immediate workstation. Although we attempted to visit people only after they had been sitting at their desk for an extended period, we sampled up to 40 people in a single day, and it was not possible to collect measurements of their experiences over a long time period.

It's difficult to assess the exact reason(s) for the low correlation between thermal sensation and selected measured parameters. It could be a combination of fluctuating conditions, psychological influences, or individual variations in environmental sensitivity or scale interpretation.

There are at least a couple of possible explanations for people's preference for cooler than expected temperatures in our study. Although clothing was lighter than levels assumed by ASHRAE Standard 55-81, half of the subjects had activity levels higher than the sedentary level assumed by the Standard. Another possible explanation is found by comparing the thermal sensation and thermal preference scale responses. The data indicate that more people prefer a sensation of "slightly cool" as opposed to "slightly warm," and many people experiencing a neutral thermal sensation still preferred to be cooler. The combination of higher activity levels, and a preference by many people for a "slightly cool" thermal state, could explain the cooler neutral temperatures found in our study.