THE EFFECTS OF CLOTHING INSULATION AND TEMPERATURE ON THERMAL COMFORT

BY

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INTRODUCTION

During the 1970s, citizens of the United States experienced a major energy crisis. It became painfully evident that there were limited energy resources and an immediate need to conserve dwindling supplies. Mandatory and voluntary government guidelines were enacted to ease and extend limited supplies. The government's goal was to ease current shortages and create a stable transition period until more plentiful and reliable energy sources could be developed. Energy sources can be expensive, nonrenewable, hazardous to obtain, and inconsistent in supply. The need to conserve and use energy wisely is unlikely to diminish in the future, and few can deny the possibility of future energy crises.

To encourage voluntary energy conservation, the National Energy Act of 1978 made available tax credits and utility loans. A federal tax credit of 15% can be deducted for the first $2,000 spent on specified energy cost saving equipment.[1,2] Utility companies are required to inform consumers about ways to save energy in addition to offering small and large scale loans to fund the purchase and installation of specified conservation measures. Clock thermostats, devices to increase the efficiency of furnaces, and load management devices (mainly meters) qualify for large scale loans of more than $300.[2]

Manipulating indoor thermostats is an immediate, effective, and inexpensive means of conserving energy. An indoor winter temperature setback from 22.2°C (72 F) to 20.0°C (68 F) can result in a 9-14% cost savings on a family's energy bill,[3] although savings potential depends on the thermal characteristics of the building, its internal load, and climatic conditions. Increased summer thermostat settings from 22.2°C (72 F) to 26.7°C (80 F) can save up to 47% of energy used.[2] The federal government enacted strong guidelines in the Emergency Building Temperature Restriction Plan on July 16, 1979.[4] This plan, no longer in effect, required owners of most non-residential government and non-government buildings to maintain thermostats at settings no higher than 18.3°C (65 F) for winter heating and no lower than 26.7°C (80 F) for summer cooling. Many federal, state, and local government officials have realized the importance and potential for saving energy and money through indoor temperature control.

When restricting temperatures, the thermal comfort of all occupants should be of paramount concern. Thermal comfort has been defined as "that condition of mind which expresses satisfaction with the environment."[5] Environmental factors which contribute to thermal comfort are air temperature, mean radiant temperature, water vapor pressure (relative humidity), and air velocity. Activity level, exposure time, and clothing are personal factors which determine thermal comfort.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE, Inc.) has been sponsoring thermal comfort research for many years. Thermal comfort charts (Fig. 1) based on the above environmental and personal factors in the ASHRAE

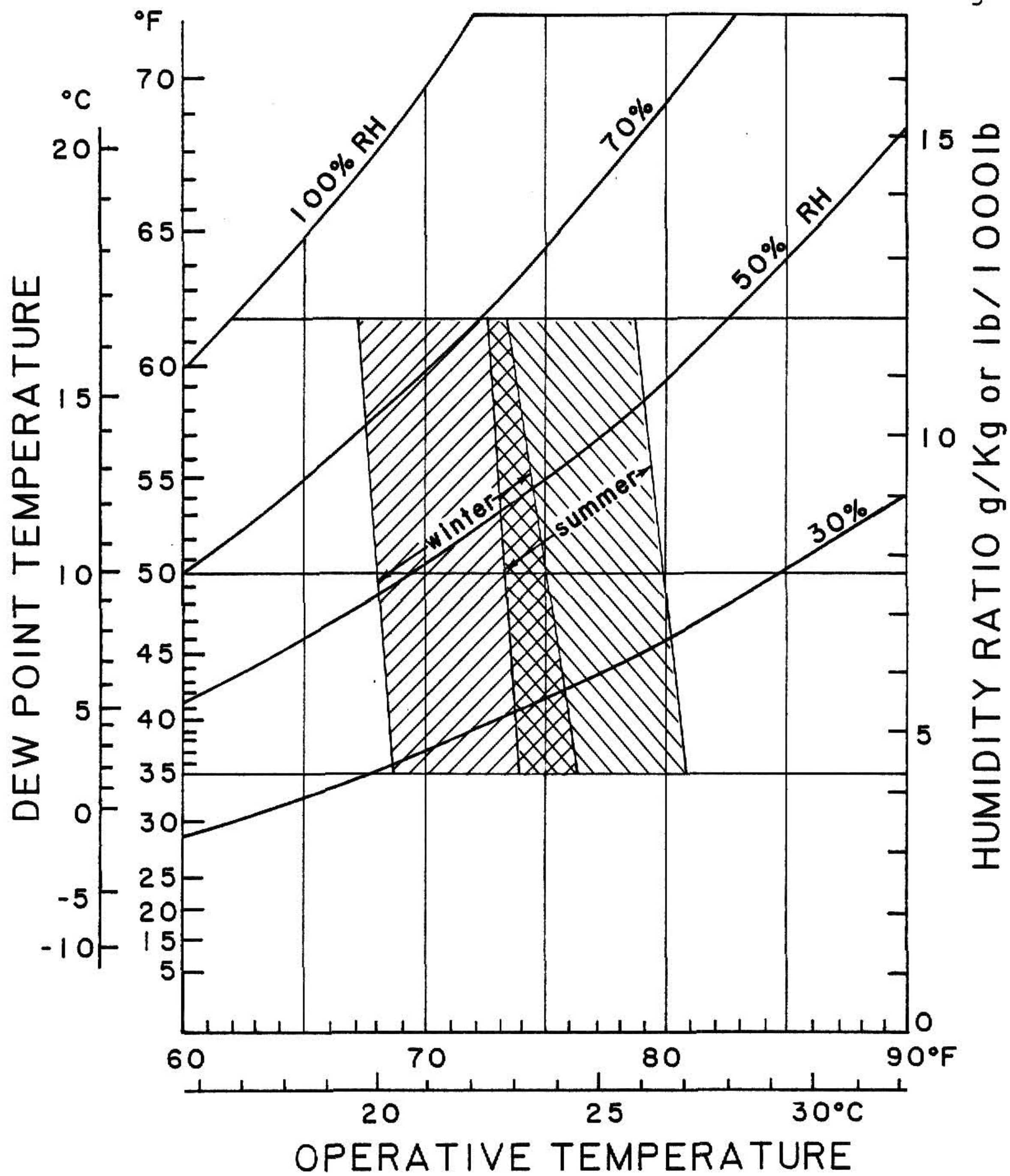


Figure 1 Acceptable ranges of operative temperature and humidity for persons clothed in typical summer and winter clothing, at light, mainly sedentary, activity (≦ 1.2 met).

Source: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., ASHRAE Standard 55 - 1981 Thermal Environmental Conditions for Human Occupancy, ASHRAE, Atlanta, GA, January 29, 1981, p. 5.

Standard, Thermal Environmental Conditions for Human Occupancy,[5] are used by researchers, engineers, administrators, physiologists, and others to establish optimum temperature/humidity combinations for efficient energy usage and occupant thermal acceptability. The above thermal comfort factors can be modified to expand the thermal comfort zone. Most factors, however, have limitations for occupant thermal acceptability and energy savings. For example, increased air velocity may compensate for higher thermostat settings in the summer, but not without increasing noise, drafts, or the blowing of dust, hair, and light weight objects. Dehumidification at high thermostat settings would increase comfort as well, but since requiring additional energy for the dehumidification, it would be infeasible in terms of saving energy or money. Decreased occupant activity may also compensate for higher temperature settings in the summer, but this solution is not appropriate or possible in most work or school environments. Clothing, on the other hand, can be easily and inexpensively controlled in warm or cool environments for personal comfort and energy savings.[6]

Surprisingly, little research using clothing as an independent variable with human subjects in controlled test conditions has been undertaken to validate given clothing insulation values (as measured in clo units). Guidelines are given in the 1981 ASHRAE Standard, Thermal Environmental Conditions for Human Occupancy,[5] for lower, upper, and optimum human thermal acceptability limits which are charted according to clo units and operative temperatures (Fig. 2). Research is lacking in the use of clothing as an independent variable

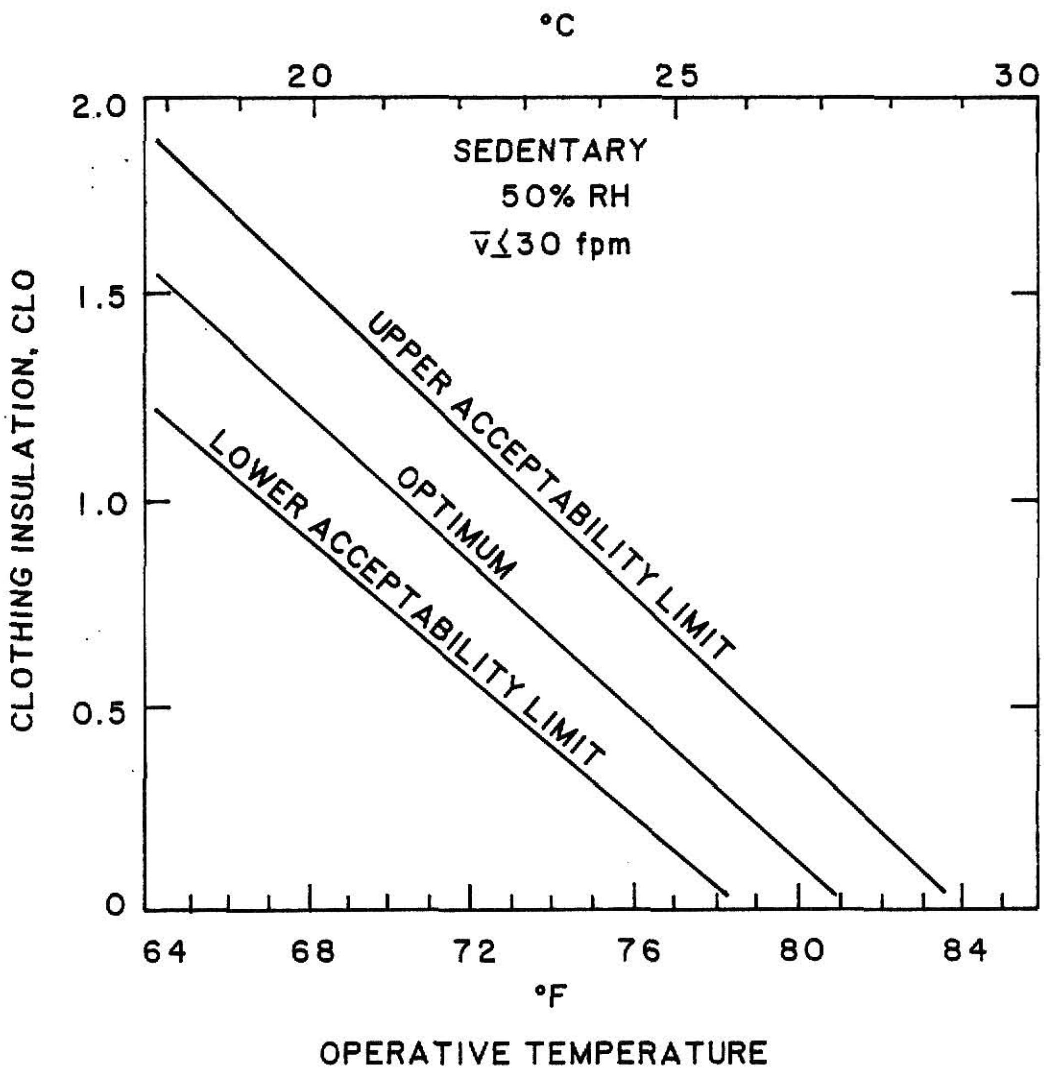


Figure 2 Clothing insulation necessary for various levels of comfort at a given temperature.

Source: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., <u>ASHRAE Standard 55 - 1981 Thermal Environmental Conditions for Human Occupancy</u>, ASHRAE, Atlanta, GA, January 29, 1981, p. 3.

due to the expense and time involved in purchasing, fitting, and measuring the thermal insulation of individual ensembles. When clothing has been varied, the clo values of each ensemble have usually been estimated rather than measured accurately. Extrapolations of temperatures and clo units can be made from the ASHRAE thermal comfort chart (Fig. 1), but the validity and accuracy of this approach has not yet been thoroughly researched or tested.

In view of increasing long-term energy conservation, accurate, refined, and reproducible research is needed to specify amounts of clothing insulation or clo units for indoor temperatures. Research validating occupant thermal acceptability or refining human individual differences with clothing as an independent variable has rarely been undertaken in the past. Summer indoor temperatures and clothing ensembles are the focus of this study since energy usage is generally greater for summer than winter indoor environments and therefore offers the most potential for energy cost savings and conservation.

The purpose of this study was to measure the effect of clothing insulation and effective temperature on the thermal sensation, thermal comfort, and weighted mean skin temperatures of male and female college students. An additional purpose was to determine if 80% of the subjects were satisfied with the thermal environment specified as the summer envelope in the the 1981 ASHRAE Standard, Thermal Environmental Conditions for Human Occupancy.[5]

Hypotheses

1. There will be no significant difference in the thermal response of students when exposed to 22.8°CET* (72.7 FET*), 24.3°CET* (75.7 FET*), and 26.0°CET* (78.8 FET*) while wearing the same amount of clothing insulation.

2. There will be no significant difference in the thermal response of students when exposed to the same temperature while wearing ensembles representing 0.54 clo units or 0.95 clo units of clothing insulation.

3. There will be no significant difference in the thermal response of male and female students when exposed to the same temperature while wearing the same amount of clothing insulation.

4. There will be no significant difference in the thermal response of students when exposed to 22.8°CET* (72.7 FET*), 24.3°CET* (75.7 FET*), and 26.0°CET* (78.8 FET*) while wearing ensembles representing 0.54 clo units or 0.95 clo units of clothing insulation.

5. There will be no significant difference in the thermal response of male and female students when exposed to 22.8°CET* (72.7 FET*), 24.3°CET* (75.7 FET*), 26.0°CET* (78.8 FET*) while wearing the same amount of clothing insulation.

6. There will be no significant difference in the thermal response of male and female students when exposed to the same temperature while wearing ensembles representing 0.54 clo units or 0.95 clo units of clothing insulation.

7. There will be no significant difference in the thermal response of male and female students when exposed to 22.8°CET* (72.7 FET*), 24.3°CET* (75.7 FET*), 26.0°CET* (78.8 FET*) while wearing ensembles representing 0.54 clo units or 0.95 clo units of clothing insulation.

Definitions

1. Clothing area factor (f_{cl}): the ratio of the surface area of the clothed body to the nude body.[7]
2. Effective temperature (ET*): the dry bulb temperature of a uniform enclosure at 50% relative humidity in which humans would have the same heat exchange by radiation, convection, and evaporation as they would in the varying humidities of the test environment.[8]
3. Intrinsic clo value (I_{cl}): resistance to heat transfer provided by clothing.
5. Operative temperature (t_o): the numerical average weighted by respective heat transfer coefficients ($h_c + h_r$), of the air and mean radiant temperatures.[5]
5. Thermal comfort: that condition of mind which expresses satisfaction with the environment.[5]
6. Thermal comfort score: a rating derived from responses for each of six pairs of adjectives on a thermal comfort ballot:[9] referred to as percent comfort satisfaction.
7. Thermal response: the physiological and psychological reaction to the environment as measured by thermal comfort and thermal sensation ballots and weighted mean skin temperature.

8. Thermal sensation: a conscious feeling commonly graded into the categories of cold, cool, slightly cool, neutral, slightly warm, warm, and hot.[5]

9. Thermal sensation rating: the response from a 9-point thermal sensation scale with the adjectives very cold (1) and very hot (9) added to those for thermal sensation.[10]

10. Total clo value (I_T): resistance to heat transfer provided by clothing and the external layer of air surrounding the clothed body.

11. Weighted mean skin temperature: the mean of skin temperatures measured with thermistors taped to the chest, arm, and leg and assigned a weighted value using the following formula:

$$t_{wmsk} = 0.50\ t_{skc} + 0.36\ t_{skl} + 0.14\ t_{ska} \qquad (1)$$

where t_{skc} = skin temperature of chest

t_{skl} = skin temperature of leg

t_{ska} = skin temperature of arm

t_{wmsk} = weighted mean skin temperature

Limitations

This study was limited to students largely from general psychology classes, but also general home economics and engineering classes at Kansas State University in September 1981.

Since most heating/cooling systems and building structures do not provide as precise an environmental control as the KSU-ASHRAE Chamber used for this study, occupants at lower or higher temperatures may experience drafts or assymetrical temperatures within various rooms. These conditions would affect discomfort as compared to students tested in the chamber under highly controlled conditions.

Assumptions

Students at Kansas State University are a representative sample of the mid-western United States population between the ages of 18 and 24.

The indoor clothing chosen is representative of typical ensembles worn indoors by people throughout the United States.

September temperatures in Kansas are representative of summer temperatures.

Chapter 2

REVIEW OF LITERATURE

Thermal comfort research is based on factors necessary for occupant satisfaction in man-made environments. Measured factors controlled during research consist of environmental and personal parameters. Environmental parameters include 1) air or dry bulb temperature; 2) mean radiant temperature or the uniform surface temperature of a radiantly black enclosure; 3) relative humidity or water vapor pressure (the latter term is preferred to describe the moisture content of the air because it is independent of the air temperature); and 4) air velocity. Personal parameters include 1) level of physical activity measured in met units which refers to man's metabolic rate; 2) clothing insulation which is defined in terms of a clo value that represents a clothing ensemble's thermal resistance; and 3) exposure time which was identified by Rohles[11] and refers to the amount of time occupants spend in an environmental condition.

The establishment of thermal comfort zones by Houghten and Yaglou[12] in 1923 laid the foundation for today's thermal comfort research. Their study was based on the effective temperature (ET) at which 50% or more of the occupants were satisfied. The resulting comfort zone ranged from 16.7-20.6^{o}CET (62-69 FET) with a comfort line at 17.8^{o}CET (64 FET). A variety of ages, occupations, and self-selected clothing ensembles was represented by subjects.

Since the 1920s, clothing habits and indoor temperature preferences have changed. People have gradually begun to wear less clothing and consequently prefer warmer indoor temperatures. More efficient heating/cooling systems, an abundance of cheap energy, and a preference for clothing ensembles which are lighter and more seasonally uniform have led to temperature preferences from 20°C (68 F) for winter to the year-round range of 22.0-25.2°C (72-78 F).[5]

The majority of thermal comfort studies have focused on variables of temperature, relative humidity, activity level of subjects, and air movement. Comparatively little research has examined the effect of clothing insulation on thermal comfort of occupants. In fact, the clo values specified in the 1981 ASHRAE Thermal Comfort Standard[5] for winter and summer comfort zones have not actually been validated in controlled comfort zone conditions, but determined through extrapolations from other studies.[7,13] Research is needed to accurately validate clo values if the above standard is to be effectively used to determine optimal thermal comfort conditions for occupant satisfaction.

The Effect of Temperature on Thermal Acceptability

Temperature is a major parameter affecting one's thermal comfort. As a general rule people most often seek to control thermal comfort by regulating the thermostat in their homes or offices. Efficient temperature regulation results in energy savings. Consequently, the Federal Energy Administration in 1968 and a Presidential mandate in 1979 called for thermostat guidelines when fuel shortages and spiraling costs were a serious problem.[4,14]

Temperature was the most basic parameter in early thermal comfort research conducted by Houghten and Yaglou[12,15] as mentioned earlier. They developed the effective temperature index which combined dry bulb temperature, humidity, and air motion in relation to the sensation of warmth or cold felt by man. Yaglou and Miller[16] modified the comfort zone to 17.2-21.7°CET (63-71 FET) with the comfort line at 18.9°CET (66 FET). Their study was based on subjects wearing a medium weight business suit. Yaglou and Drinker[17] further modified the comfort zone to 17.8-26.1°CET (64-79 FET) with a comfort line at 21.7°CET (71 FET) when determining the effect of summer climate on the comfort zone. When Koch, Jennings, and Humphreys[18] re-evaluated the then current ASHRAE thermal comfort zone in 1960, the comfort line was established at a higher dry bulb temperature of 25.6°C (78 F) at 30% relative humidity.

Nevins[19] in 1966 cited the need for correction tables or charts to show the effect of clothing, thermal radiation, air motion, and activity on thermal comfort. He largely attributed differences between comfort lines of 1923 and 1960 to a change in clothing habits among Americans. A difference in experimental procedures was also cited since early effective temperature tests were based on immediate impressions of the environment and later tests were long-term impressions. Early tests by Houghten and Yaglou[12,15] were conducted under dynamic conditions with subjects walking from one controlled room to another instead of remaining in the same room.

Rohles[11] indicated the need to consider more factors pertaining to comfort and organized these into an ecosystem. Three major groups in the ecosystem include 1) physical environmental factors (air movement, temperature, etc.); 2) personal or organismic factors (age, diet, rhymicity, etc.); and 3) adaptive factors (activity, clothing, exposure, social, etc.). Major factors from the ecosystem to be controlled or varied in thermal comfort research are air temperature, water vapor pressure, mean radiant temperature, air movement, clothing, activity level, and time exposure.

Nevins et al.[20] undertook their classic study to modify the then current 1961 ASHRAE thermal comfort zones[21] with Rohles's factors in mind. They established a comfort zone from 22.8-28.9^{o}C (73-84 F) dry bulb temperature with a comfort line at 25.6^{o}C (78 F) for a relative humidity of 40%. This generally agrees with the comfort zones of Koch, Jennings, and Humphreys.[18]

The 1974 ASHRAE thermal comfort zone[22] was based on the results of Nevins et al.,[20] Rohles and Nevins,[23] and Fanger's comfort equation.[7] In addition to temperature and humidity, Fanger considered mean radiant temperature, air movement, clothing, and activity level as important factors to be controlled. These were formulated into a complex comfort equation which gives tables and charts to be used for extrapolating data. The comfort line for light office work in the 1974 ASHRAE standard is 23.9^{o}C (75 F) at relative humidities between 20-40%.[22]

In 1971 Gagge, Stolwijk, and Nishi[24] updated the effective temperature index established earlier by Houghten and Yaglou[15] since the effects of humidity in current research and real life situations seemed to be overestimated at low temperatures and underestimated at high temperatures. They developed the new effective temperature index (ET*) often used in current thermal comfort research. The index is based on a subject normally clothed (0.6 clo) at sedentary activity, and a measure of constant wetness caused by regulatory sweating. The new effective temperature index uses the dry bulb temperature at the intersection of its loci with the 50% relative humidity curve found on an ASHRAE psychrometric chart, rather than by the saturated temperature or 100% relative humidity curve used before. This index is believed to be more realistic, accurate, and usable for building engineers and laymen in public use.

The Effect of Sex on Thermal Acceptability

Significant differences for preferred thermal conditions between males and females have been reported in thermal comfort research, although findings have not been consistent. No consideration to sex of subject has been made in the 1981 ASHRAE Thermal Comfort Standard.[5]

Fanger[7] reported no significant differences according to sex of subject for the comfort equation. He stated that Danish males preferred a warmer environment than females, but it was not statistically different at the 5% level. However, he reported American females preferred a significantly higher temperature than males. Since his data treated Danish and American subjects together, he derived that females preferred a temperature that is 0.3°C higher than that of males, a difference he felt was too small to be of engineering significance.

Rohles et al.[23] reported a significant difference among males and females in time of adaptation over a three-hour period and preferred temperature at one-hour periods. Males felt warmer than females during the first hour of exposure at a given temperature and humidity, but little difference occured after a three-hour exposure. He reported that such a difference should be reflected in the standards of thermal comfort for facilities requiring exposure of one hour or less.

Rohles, Woods, and Nevins[25] reported a significant difference between sex and clothing insulation for ensembles measuring 0.4 clo, 0.6 clo, and 0.8 clo units. In their analysis the thermal sensation vote was correlated with the clothing ensemble for men and women separately and for men and women combined. The correlations were statistically significant at the 0.01 level of confidence. They attributed this to the clothing worn which created insulation and comfort differences due to the permeability index, pumping coefficient, and snugness of fit.

Munson,[26] Gonzalez and Nishi,[27] and Wyon et al.[28] reported significant differences between males and females in cool conditions. Munson found that females were significantly cooler than males who responded neutral at 18.3°CET* (65 FET*) while wearing the recommended 1.6 clo of insulation after a one-hour exposure. Gonzalez and Nishi reported that in young females it is not a lessening in whole body discomfort solely that occurs, but rather an unequal distribution in thermal input possibly from cold sensation of legs or feet which diverts a person's attention toward other factors that make an environment unacceptable. Local sensation from cold arms and legs was greatest in the female group. They partially attributed this to low weight-to-surface area ratio, increased local air movement around extremeties while walking, and increased dry heat loss around these specific body parts. They cited the need to consider appropriate comfort charts for different ages and sex groups. Wyon et al. reported that males were significantly warmer in 0.6 clo and 1.15 clo ensembles than females. However, there were no significant differences in preferred temperatures for males and females. Beshir and Ramsey,[29] on the other hand, reported significant differences in preferred temperatures for males and females wearing 0.6 clo units. Linear regression equations showed the preferred wet bulb temperature for females was 25°C (77 F) and for males was 22°C (71.6 F). Females in all of the above studies generally preferred warmer temperatures than males.

Nevins, Gonzalez, Nishi, and Gagge[30] in their summer chamber study reported a mean preferred temperature for comfort of males at 24.7°C (76.5 F) and females at 25°C (77 F) which agrees with Rohles and Nevins[23] and Fanger[7] for a three-hour exposure. However, there were significant differences between males and females, and between age groups within the females in thermal sensation regression lines and optimal ambient temperatures judged as neutral.

Clothing Insulation and Thermal Acceptability

Clothing can be personally and easily controlled for optimum thermal comfort. It can be removed or added when one feels warm or cold. A major function of clothing is to insulate the human body against heat loss and help maintain a constant body temperature. Two factors which influence clothing insulation and thermal comfort are measured by the permeability index and pumping coefficient. The permeability index refers to the evaporative heat transfer permitted by a garment. The pumping coefficient refers to body motion which increases the heat exchange between a person and the environment. Pumping accelerates the rate of evaporative cooling and convective heat transfer for a sweating person. These two factors generally have little effect on clothing insulation when temperatures are comfortable and body activity is sedentary.

Clothing insulation involves the resistance of heat transfer from the body through clothing by convection and radiation in air spaces and conduction through the cloth itself. Azer[31] explained the heat transfer mechanism from the body through the clothing in detail and stated that it is dependent on style, fit, and thickness of the fabric or ensemble.

The insulation of clothing is quantitatively defined in terms of a clo unit[6,32] which represents the total thermal resistance from the skin to the outer surface of the clothed body. Fabric properties which influence the clo value have been studied extensively using small scale devices.[33,34] The clo value depends more on thickness than porosity of individual textile layers since most textiles commonly worn vary little in porosity. The greater the thickness of the textile or textile composite the greater the amount of trapped air and the greater the insulation value.[34] The relationship of

1.57 clo/cm (4 clo/in.) of thickness applies to most conventional fabrics, regardless of fiber content or construction.[35]

A clothing ensemble's design, fit, and layering affect insulation. These factors influence the air layer between the body surface and the clothing which provides thermal insulation. The thermal insulation is also influenced by the surface area of the clothing since an ensemble with a large surface area normally allows less heat transfer. Extremely loose fitting or hanging clothing results in a 'chimney effect' where air flow between the clothing and the body creates lower thermal insulation values.[7] If a belt is worn with a loose fitting bodice, a shirt is tucked in, or garment openings are snug fitting, the trapped air results in a higher thermal insulation value. Fabric layering within an ensemble or garment affects the insulation by increasing thickness and reducing heat transfer. Air is immobilized between the fabrics which increases the insulative value.

Clo values are affected by the position and surroundings of a subject. The clo value of an ensemble worn by a seated subject is less than when he/she is standing due to the compressed clothing layers which decrease thermal insulation.[7] However, the supplementary insulation provided by an upholstered chair often compensates for the sitting effect.

<u>Clothing insulation and environmental factors</u>. For optimal comfort the temperature and clothing insulation should be within the summer and winter comfort zone guidelines specified in the 1981 ASHRAE Thermal Comfort Standard.[5] For winter, 0.9 clo units and an

operative temperature range of 20.0-23.6°C (68-74.5 F) and for summer, 0.5 clo units and 22.8-26.1°C (73-79 F) have been specified. When the air temperature rises beyond the comfort zone, the body depends more on evaporation from the clothing and evaporation/perspiration from the skin to be comfortable and maintain a constant body temperature.[36] Absorbed wetness in the fabric lowers the thermal insulation value. On the other hand, when air temperature falls below the comfort zone, unless the rate of heat loss by conduction, convection, and radiation through the fabric is restricted, clothing insulation becomes insufficient.

Increased air movement results in lower thermal insulation values which depend on the open or closed fabric structure. Under high windspeeds, the air circulated in the fabric interstices of loosely woven fabrics results in a greater heat loss than in a closely woven fabric.[37]

Relative humidity results in an increased heat loss, but is generally of minor significance.[37] While the humidity increases heat loss, the effect of a 33-88% humidity increase in actual use (provided there is no evaporation of perspiration from the insulated body) would be small.[37]

Measurement of Clothing Insulation

The thermal insulation of an ensemble can be tested in several ways.

The single hot plate method measures the heat or moisture transfer through a textile sample. Multiple or single textile layers may be placed on the plate's surface.[38] The disadvantage of this method is that the thermal resistance of a flat piece of fabric does not take into account the air layer between the body and the clothing surface, and between fabric layers. In addition, the surface area of the clothing cannot be considered. The factors which partially determine the clothing surface area including fit, design, and drape of an ensemble or garment cannot be accounted for in this method.

Another method is based on the I_{cle} or the direct measurement of mean skin temperature (t_{sk}), temperature of clothing surface (t_{cl}), and operative temperature (t_o) taken from live subjects.[8] The ratio of $t_{cl} - t_o/t_{sk} - t_o$ is related to the effective insulation (I_{cle}) of clothing worn. Breckenridge[38] used this method after using a copper manikin to detect differences due to body movement and design/fabric details of a garment. However, the use of subjects may become expensive, tedious, and time consuming when testing a large number of garments while measuring the necessary physiological variables.

The third method involves using a copper manikin--a method which takes into account the ensemble's design, drape, fit, and layering. The manikin measurements also reflect the uneven distribution of insulation over the body surface, indicating the net effect and areas of higher heat loss.[6] Unfortunately, a limited number of manikins exist in the United States. The manikin at Kansas State University consists of a black anodized copper skin constructed in the physical form and size of an average man.[6] When the electrical power to the circuits equals the rate at which thermal energy leaves the manikin via conduction, convection, and radiation the manikin is in equilibrium and ready for clothing insulation testing.

The total thermal insulation (I_T) includes the insulation provided by the clothing and the external air around the clothed body. This is measured when the manikin is in equilibrium in an environmentally controlled chamber.[6]

The intrinsic clo value (I_{cl}) is the thermal insulation of the clothing itself. The clothing area factor (f_{cl}) and the clo value of the air layer (I_a) are needed to calculate I_{cl}. The clothing area factor (f_{cl}) may be determined using tables in literature based on photographic or shadow projection methods.[7,13] Equations used for determining I_{cl} and I_T are given in Chapter 3.

Thermal insulation (clo) values for everyday individual garments and ensembles using the copper manikin are given in an index compiled by Sprague and Munson.[13] They developed the linear regression equations below to find the clo values of ensembles from individual garments for men and women.

$$\text{men:} \quad I_{cl} = 0.727 \, \Sigma \, I_i + 0.113 \qquad (1)$$

$$\text{women:} \quad I_{cl} = 0.770 \, \Sigma \, I_i + 0.050 \qquad (2)$$

where

ΣI_i = sum of intrinsic thermal insulation values of individual clothing items (clo)

I_{cl} = estimate of intrinsic clo value for an ensemble (clo)

The difference between the two equations were attributed to the difference in minor design details or the thickness of men's and women's garments which is a linear function of insulation. The 1981 ASHRAE Thermal Comfort Standard[5] has combined the two equations into the formula below.

$$I_{cl} = 0.82 (\Sigma I_i) \quad (3)$$

Azer[31] investigated individual textile properties which influence the clo value and then utilized the Sprague and Munson linear regression formula to determine the I_{cl}.

Extropolations based on Fanger's comfort equation can be made from tables giving comfort lines for subjects in light, medium, and heavy clothing which vary according to air temperature, mean radiant temperature, and either sedentary, medium, or high activity levels.[7] Extrapolating clo values from the above sources is quicker, less expensive, and more convenient than formulating or measuring clothing insulation values.

Clothing Insulation and Thermal Comfort Research

Early thermal comfort research rarely described or quantified the clothing insulation of ensembles worn by subjects. Yaglou and Miller[16] based their research on ordinary garments of medium thickness and mesh. They stated, "any reasonable departure from this average in actual practice will not affect the results to any great extent" (p. 90). Rohles, Woods, and Nevins,[25] however reported that subjects could detect a difference of 0.2 clo which is comparable to removal of a light sweater or vest. Subjects in the Yaglou and Miller study wore light weight cotton underwear, a madras shirt with collar attached, a three-piece medium weight woolen suit of medium size mesh, cotton socks, and shoes. No quantitative data or visual pictures were given; consequently, validation of their results in a similar ensemble would be difficult today.

Houghten and Yaglou[15] based their comfort zone and line on male and female subjects wearing widely different types of clothing. Validation would again be difficult due to regional differences in clothing and changes in fashion and fabrics since the 1920s. Yaglou and Drinker[17] modified the comfort chart for summer conditions with men wearing two piece light woolen suits and women wearing silk, linen, or cotton dresses. The range in clo values among ensembles worn and compared to those today also would be difficult to validate. In addition, little attention was given to the fact that women in wearing dresses would have less clothing insulation. Female responses on thermal comfort ballots may have been different from male's wearing a business suit. This was determined to be the case in a study conducted by Yaglou and Messer in 1941.[39] A major reason for not supplying uniform ensembles to the subjects was probably the time and expense required.

Nevins, Rohles, Springer, and Feyerherm[20] first controlled the clothing insulation in their classic study to validate the then current ASHRAE Thermal Comfort Standard in 1966. Male and female college students were issued an ensemble of 0.6 clo units as tested by a copper manikin. It was composed of a gray twill trouser and shirt and woolen socks. No shoes, belt, tie, or undershirt were included. Since clothing insulation was controlled the possibility of poor internal validity due to varying clo values was eliminated. Later research using the same ensemble for all subjects would most likely improve the validity.

In 1971, Rohles, Woods, and Nevins[25] conducted a study to determine the influence of clothing and temperature on sedentary comfort. Three ensembles measuring 0.4 clo, 0.6 clo, and 0.8 clo units were worn and furnished by male and female college students. Ensembles were visually checked by a trained observer to see that they were comparable to those tested on the copper manikin. Subjects were not tested at random by wearing all three ensembles in one test, which may have allowed for significant differences in responses due to replication of an individual test. Women wearing a mini-skirt in the light weight ensemble may have accounted for significant differences between the sexes wearing the same clo units due to the amount of skin surface area covered, however the literature search revealed no studies which reported significant differences in this area. They reported that subjects were able to perceive the difference in clo value between each ensemble. They attributed this to a garment's permeability, snugness of fit, and pumping coefficient. However, the permeability and pumping coefficient of a garment have little affect during sedentary activity in comfort zone conditions. Snugness of fit could be a major factor since ensemble fit most likely varied from subject to subject. In addition, small design differences may also have accounted for the perceived differences among subjects.

Studies[26,27,28,40] examining the effect of clothing insulation on thermal comfort in cool environments produced inconsistent results for the subject's sex, discomfort of extremities, and acceptance of cool temperature.

McIntyre and Griffiths[40] investigated the effects of added clothing on thermal comfort in cool conditions. The mean insulation of the standard ensemble was 0.74 clo with a standard deviation of 0.1 clo. A sweater added to this ensemble was estimated to be 0.3 clo. The addition of the long-sleeve woolen sweater was compared to a 2°C drop in temperature for sedentary activity. While addition of the sweater increased feelings of warmth at 19°C (66 F), it did not compensate for discomfort of cold extremities.

Wyon et al.[28] reported on the mental performance of subjects clothed for comfort at self-selected air temperatures of 18.7°C (65.6 F) for a 1.15 clo ensemble and 23.2°C (73.8 F) for a 0.6 clo ensemble. The heavy 1.15 clo ensemble consisted of three pairs of cotton tracksuit trousers over cotton underpants, two cotton tracksuit tops, one thick woolen sweater, three pairs of woolen socks, and a pair of light moccasins. Clo values were measured using a copper manikin. Results showed no difference in the mental performance of subjects wearing either ensemble at the preferred temperature.

Gonzalez and Nishi[27] and Munson[26] researched the ability of subjects to select clothing for cool environments which would result in thermal comfort and a neutral thermal sensation. Gonzalez and Nishi based their research on the Federal Energy Administrations' guideline of 20°C (68 F) and Munson based hers on the 1979 presidential mandate of 18.3°C (65 F) for winter thermostat settings. Studies indicated that subjects were unable to select ensembles which resulted in comfort at either temperature. In the Munson study, a supplied 1.6 clo ensemble recommended for 18.3°C included the KSU uniform and a heavy pair of insulated coveralls. Females were slightly cool in the recommended 1.6 clo while males were not. It was recommended that apparel designers and manufacturers be encouraged to develop non-bulky or non-cumbersome ensembles for people which were more suitable for a school or office environment.

Berglund and Gonzalez[41] researched to what extent occupants react to summer temperature drifts and under what conditions do they find them acceptable. Subjects provided their own clothing which was selected to conform to a list. The insulation values were 0.5 clo, 0.7 clo, and 0.9 clo and based on methods developed by Sprague and Munson[13] and Nishi et al.[42] A 0.5°C/hr change in temperature was indistinguishable to subjects for temperatures ranging from 25-27°C (77-80.6 F) and 23-25°C (73.4-77 F) in the 0.7 clo ensemble, from 25-27°C in the 0.5 clo ensemble, and from 23-25°C in the 0.9 clo ensemble. Thermal acceptability in the 0.9 clo ensemble remained above 80% down to 20°C. In the 0.5 clo ensemble, 80% or more judged the environment acceptable at temperatures above 22°C.

<u>Research Elements for Thermal Acceptability</u>

Thermal acceptability is determined through objective and subjective measures. Subjective measures consist of psychophysical scales which include thermal sensation and thermal comfort ballots. The objective measure most commonly used is the physiological response of mean skin temperature. By utilizing both types of measures or research elements the effects of environmental and personal parameters on thermal acceptability are meaningful, accurate, and reliable. Environments for optimum thermal acceptability can then be better predicted and controlled.

Thermal sensation. Thermal sensation refers to a conscious feeling of warmth or coolness. The 1981 ASHRAE Standard, Thermal Environmental Conditions for Human Occupancy,[5] defined categories in the 7-point thermal sensation scale as cold, cool, slightly cool, neutral, slightly warm, warm, and hot. Early thermal comfort research by Houghten and Yaglou[15] based responses on a 3-point scale including warmer, comfortable, and cooler. Yaglou and Drinker[17] were one of the first to use a 5-point scale including adjectives of cold, comfortably cool, very comfortable, comfortably warm, and too warm. Winslow et al.[43] also used a 5-point scale, but with the categories of very pleasant, pleasant, indifferent, unpleasant, and very unpleasant. Bedford[44] in 1933 was the first to report using a 7-point scale which was the forerunner to that given in the ASHRAE Standard.[5] He included terms of much too warm, too warm, comfortably warm, comfortable, comfortably cool, too cool, and much too cool. Rohles[10] recently proposed and recommended a 9-point scale with the terms very cold, cold, cool, slightly cool, neutral, slightly warm, warm, hot, and very hot. The reasons for including very hot and very cold were to increase sensitivity by spreading the overall distribution of ratings. Furthermore, since raters tend to avoid terminal categories, the 7-point scale is actually a 5-point scale. Researchers testing in extreme cold or hot conditions consider the terminal categories essential.

Thermal sensation responses are used to determine the acceptability of an environmental condition. ASHRAE defines an acceptable thermal environment as one in which at least 80% of the occupants find acceptable by voting slightly warm, neutral, or slightly cool on a 7-point scale.[5] This is the basis for the winter and summer comfort zones plotted on a psychrometric chart in the 1981 ASHRAE Therml Comfort Standard.[5] Early studies had no standard level of acceptability. Houghten and Yaglou[15] based thermal acceptability on a 50% occupant response of 'comfortable'. Yaglou and Drinker[17] using a 5-point scale based thermal acceptability on all votes indicating comfort which included 3 points on a 5-point scale.

Thermal sensation measurements can be used in three types of situations. The most common involves exposing a group of subjects to controlled conditions in an environmental chamber. Thermal sensation ballots are filled out periodically or at the end of the test period. A second situation involves exposing a group of subjects to uncontrolled conditions in an indoor or outdoor field situation. This type has less reliability due to the wider range of a neutral temperature for a group of subjects and the influence of unwanted environmental variables. The third situation involves determination of a preferred temperature from a small group or single subject in an environmental chamber. The temperature is changed to suit the subjects' preferences. This provides information on the preferred temperature among subjects according to the age, sex, activity level, clothing insulation, or other environmental parameters. Since it normally includes more physiological measurements than the two above, it offers the highest reliability.

Thermal comfort. The measurement and prediction of thermal comfort refers to a condition of mind which expresses satisfaction with a thermal environment.[5] It was synonomous with thermal sensation until being defined and distinguished in the ASHRAE Comfort Standard 55-74.[22] The previous definition of thermal comfort in ASHRAE standards was a sensation that is neither slightly warm or slightly cool which now relates more to thermal sensation. The current term 'condition of mind' refers to the psychological value assessment in terms of satisfaction or dissatisfaction towards the thermal environment.[45] The psychological assessment is important due to changes in the non-thermal aspects of the environment which affect how we respond to the thermal aspect. Rohles[45] tested such non-thermal aspects as embellished environments, misinformation or information given to subjects prior to testing, and Teichner[46] tested the influence of incentives to participate.

Several thermal comfort scales have been proposed and recommended, but no standard or widely used scale presently exists, due to the difficulty in psychological assessment. McNall[47] was one of the first to use separate ballots for thermal sensation and thermal comfort measurements in 1970. In studying the effect of assymetric radiant fields on thermal comfort he used the adjectives comfortable, slightly warm, uncomfortable, very uncomfortable, and intolerable. Separate thermal comfort and thermal sensation scales were needed since the comfortable category corollated with slightly cool, more so than slightly warm. Rohles[48] has developed and recommended a semantic differential scale originated by Osgood et al.[49] and refined by Mehrabian and Russell,[50] where a person is asked to rate his/her impression of the environment. Rohles's scale originally included 14 bipolar adjective pairs with a 9-point rating scale for each pair. A current scale by Rohles in use at the Institute for Environmental Research includes seven bipolar adjective pairs with comfortable-uncomfortable, bad temperature-good temperature, pleasant-unpleasant, unacceptable-acceptable, warm-cool, comfortable temperature-uncomfortable temperature, and satisfied-dissatisfied. He identified ten steps in developing a semantic differential scale which can be adapted to a variety of testing situations.[9]

In using the older definition of thermal comfort two classic thermal comfort prediction models have been developed which were based on the 7-point thermal sensation scale and can be related to the 80% level of thermal acceptance specified in the ASHRAE Thermal Comfort Standard.[5]

Fanger[7] developed the most widely used model for estimating occupant satisfaction at a given dry bulb temperature. By using his comfort equation, one can calculate all combinations of air temperature, mean radiant temperature, air velocity, and humidity according to activity level and clothing insulation which will create optimal comfort. After developing the comfort equation based on 1600 Kansas State University students and Danish subjects, he developed a method for predicting the mean thermal sensation called the Predicted Mean Vote (PMV). By employing a probit analysis he then developed a nomogram from which he could estimate the percentage of people dissatisfied (PPD). Based on this he compiled tables and figures which relate PPD to the percent distribution of thermal sensation votes, ambient temperature, PMV, and cold/warm dissatisfaction.

Rohles et al.[51] using the dissatisfaction criteria of Fanger and similar methods for 1600 Kansas State University students based their model on the new effective temperature scale (ET*). They developed the following regression equation to determine the mean thermal sensation (TS) for environments between 20°C (68 F) and 32°C (90 F).

$$TS = 0.325\ CET^* - 8.444 \tag{4}$$

Their results compare favorably to Fanger's. Rohles et al.[25] then developed the following equation for predicting the amount of clothing required for comfort at various effective temperatures which is referred to as the Lower Thermal Comfort Threshold (LTCT) and expressed in CET*.

$$CET^* = 29.75 - 7.28\ I_{cl} \tag{5}$$

The 1981 ASHRAE Thermal Comfort Standard's summer and winter comfort zones and specifications for clothing insulation were largely based not only on Fanger's comfort equation, but also numerous research studies conducted at the Kansas State University's Institute for Environmental Research.

Skin temperature. The mean skin temperature is a measurement obtained through thermistors taped to the skin's surface. Numerous researches have used mean skin temperatures as an indication of thermal comfort or thermal sensation.[7,39,43] Skin temperatures are an indication of heat balance in the body which is a thermal regulatory process necessary for comfort. This is based on a normal balance between production and loss of heat at a normal body temperature.

Yaglou and Messer[39] reported subjects were comfortable when mean skin temperatures ranged between 33-34°C (91.4-93.5 F) under a wide range of environmental temperatures from 13-28°C (55-83 F) and when wearing suitable clothing. This range has been used as a comfort reference for subjects at a sedentary activity level.[26,39,52]

Fanger developed the heat balance equation which must be satisfied for thermal comfort to occur.[7] He identified skin temperature and sweat secretion as basic variables influencing heat balance. When sweat secretion is zero and mean skin temperature is between 33-34°C thermal comfort is satisfied at a sedentary activity level.[7] Activity levels greater than one met or sedentary activity lower mean skin temperature due to the evaporation of sweat which acts as a cooling mechanism in the body's thermal regulatory process. Beyond the point of perspiration and sweating, skin temperature raises slowly and can not be used as a satisfactory index of thermal comfort without considering pulse rate, rectal temperature, and sweat secretion and evaporation.

Skin temperatures can be based on a measurement from several or a few body locations. Measurements requiring sensitive skin temperatures based on 14 or more body locations are used with fewer test subjects.[7,28,39] Burton[53] suggested a method for measuring skin temperatures from three locations when it is not possible or desirable to use several locations. It is based on the surface temperatures of the body trunk, lower leg, and lower arm using the following formula.

$$t_{wmsk} = 0.50\ t_{skc} + 0.36\ t_{skl} + 0.14\ t_{ska} \qquad (6)$$

<u>where</u>

t_{skc} = skin temperature of chest

t_{skl} = skin temperature of leg

t_{ska} = skin temperature of arm

t_{wmsk} = weighted mean skin temperature

This formula weights the respective temperatures according to the mass of tissue beneath them. Weighting the temperatures according to area would give relatively more weight to the leg and forearm.

In summary, major factors controlled in thermal comfort research have been well defined and quantitatively determined in the 1981 ASHRAE Thermal Comfort Standard,[5] with the exception of clothing insulation. The clothing insulation values recently specified for thermal comfort have not been validated, but determined by extrapolations from previous research. If the ASHRAE Standard is to be used for a precise prediction and control of optimal thermal comfort accurate and valid clothing insulation guidelines for the given comfort zones are needed. Inconsistent results for males and females in comfort zone conditions presently exist for thermal sensation and skin temperature responses. Again, if the comfort standard is to be effective and reliable, research which determines the significance of sex in comfort zone conditions is needed.

Chapter 3

METHODOLOGY

Research Design

A 3 x 2 x 2 factorial design with six replications was used to analyze the effects of clothing insulation and effective temperature (ET*) on the thermal response of male and female college students over a period of 90 minutes. The independent variables selected for study were 1) three effective temperatures 22.8°CET* (72.7 FET*), 24.3° CET* (75.7 FET*), and 26.0°CET* (78.8 FET*); 2) two levels of clothing insulation (0.54 clo units and 0.95 clo units); and 3) sex (male and female). The dependent variables of thermal response were measured using the 1) thermal sensation ballot for the body as a whole and for the hands, face, and feet; 2) thermal comfort ballot; and 3) weighted mean skin temperature. Thermistors were taped to the chest, arm, and leg of subjects.

Clothing Selection

Clothing chosen was representative of that typically worn indoors during the summer by men and women in office or school environments. The insulation values as measured in clo units determined specific garment selections. Thermal insulation values of 0.5 clo units and 0.95 clo units for ensembles were estimated using a clothing index compiled by Sprague and Munson.[13] A clo unit of 0.5 was chosen from the specification in the ASHRAE Standard[5] for summer comfort zone temperatures. The medium weight ensemble of 0.95 clo units was recommended by Rohles et al.[51] for optimal satisfaction from their model for predicting the amount of clothing required for various effective temperatures.

An assortment of casual office clothing ensembles estimated to be 0.5 clo units and 0.95 clo units was ordered and purchased from Sears and Penney's department stores. Ensembles represented what an average person might select, buy, and wear. Clothing was based on styles that stay in fashion and on commonly woven fabrics of both natural and manmade fibers. Ensembles were selected with fitting ease in mind and included features such as elastic waist band, basic design, and fabric which may stretch and be comfortable when worn. Ensembles for men and women were as similar as possible in fit, design, fabric, fiber, and color. In other words, women were wearing pant ensembles similar to those worn by men.

Testing of Clothing Insulation

Clothing items were selected, combined in ensemble form, and tested using an electrically-heated copper manikin. The copper manikin at Kansas State University consisted of a black anodized copper skin formed according to the physical form of a typical man and is described by Rohles and McCullough.[6] The copper manikin's thermistor locations are shown in Fig. 3. Experimental conditions in the manikin test chamber included an ambient temperature of 26.7^{o}C (80 F), mean radiant temperature equal to the ambient temperature, relative humidity of 50%, and air velocity of 0.15 m/s (30 fpm). The test chamber was 3.20 m (8½ ft) x 1.52 m (5 ft) in size. A matrix of four thermistors on a wooden stick support placed at 15 cm (6 in.), 76 cm (30 in.), 102 cm (40 in.), and 183 cm(72 in.) above the floor

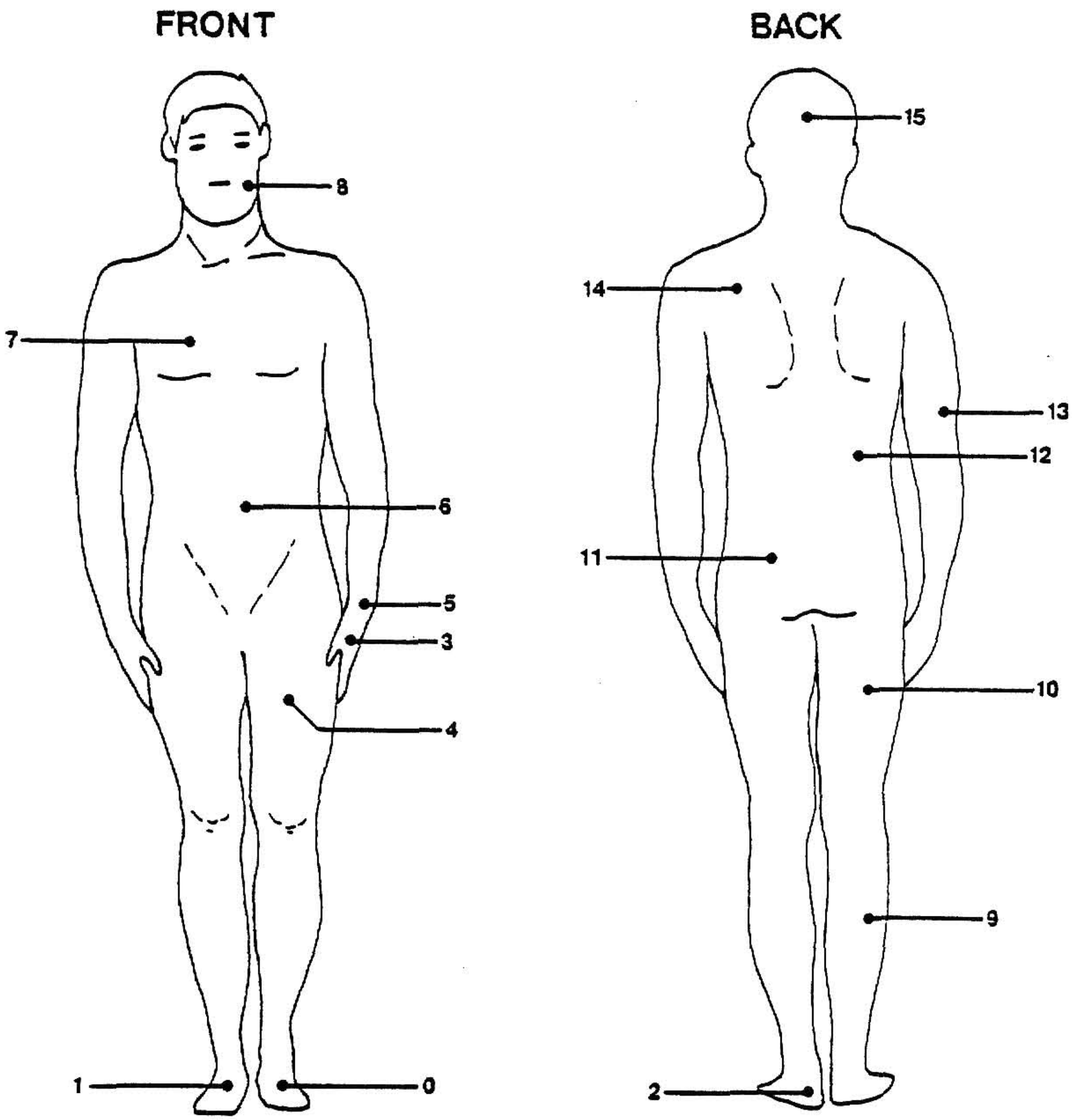


Figure 3 Location of thermistors of the copper manikin.

were used to determine the average ambient temperature which was recorded on a channel of the data logger kept in the manikin control room.

The manikin control room was located next to the manikin chamber and contained the data acquisition system. The system included a proportional temperature controller, power reducer for the extremities, digital power monitor, watt-hour meter, timer, data logger, and hygrometer.

A single pen chart recorder next to the data acquisition system determined when the power to the manikin was stable and equilibrium had been reached. Chart readings were kept for each replication to varify power stability for the manikin.

Emsemble testing was conducted for a period of one hour with temperature readings monitored and recorded every 10 minutes. A complete test consisted of three replications for one ensemble. The garment description and method of dressing were recorded on an ensemble test data sheet. Power and temperature were recorded after each replication on the data sheet and used in calculating the intrinsic clo value (I_{cl}). The average power (H) used during a replication was determined by the equation below.[6]

$$H = \frac{60 \text{ x watt hours}}{14 \text{ x minutes}} \qquad (1)$$

The average power (H) was multiplied by 0.985 to account for power loss in the cable running from the manikin to the data acquisition system.

Total thermal insulation (I_T) includes the insulation provided by the external air layer and clothing. It was determined using the following equation.[38]

$$I_T = \frac{K\,(\bar{T}_s - T_a)\,A_s}{H} \tag{2}$$

<u>where</u>

$\bar{T}_s$ = mean skin temperature (^oC)

T_a = air temperature (^oC)

A_s = body surface area (m^2)

H = power input (w)

I_T = total thermal insulation (clo)

K = constant = 6.45 clo · w/m^2 · ^oC

The KSU uniform, consisting of a gray twill workshirt and workpant, cotton socks, and leather shoes was tested initially for calibration of the manikin (I_T = 1.25 clo).

The intrinsic clo value (I_{cl}) is the insulation of clothing, excluding the external air layer surrounding the clothed manikin. The I_{cl} is the basis for the ASHRAE clothing insulation guidelines.[5] The I_{cl} was determined by subtracting the insulation provided by the air layer around the clothed body from the total clo value (I_T) according to the formula below.

$$I_{cl} = I_T - \frac{I_a}{f_{cl}} \tag{3}$$

<u>where</u>

I_{cl} = intrinsic thermal insulation of clothing (clo)

I_T = total thermal insulation of clothing plus external iar layer (clo)

I_a = thermal insulation of air layer around nude manikin (clo)

f_{cl} = clothing area factor

The clothing area factor (f_{cl}) was estimated from the literature giving composite ensemble values derived from individual garment values.[13] Values may vary according to the design, fit, number of exposed garments, and layering in the ensemble. Better methods of estimating values are needed due to the sensitivity of the I_{cl} to the f_{cl} and the influence of ensemble characteristics. Intrinsic clo values for this study were based on an estimate of 1.19 f_{cl} for the light weight ensembles and 1.30 f_{cl} for the medium weight ensembles.

Final ensembles for men and women resulted in values of 0.54 clo units for the light weight and 0.95 clo units for the medium weight ensembles. Although 0.5 clo units is recommended in the ASHRAE Standard[5] for the summer envelope, 0.54 clo units was the lowest practical amount of insulation obtainable. The 0.54 clo unit ensemble included a light weight short-sleeve shirt, light weight pant, underwear, and sandals without socks. The medium weight ensemble meeting the 0.95 clo units included a medium weight fully-lined suit jacket, medium weight pant, long-sleeve shirt, underwear, cloth covered shoes, and cotton socks. The women's long-sleeve shirt was medium weight compared to the men's light weight shirt to compensate for the lower insulation value of the women's suit jacket. Multiple sizes of the light and medium weight ensembles were ordered for human subject testing.

Tabs. 1 and 2 give fabric information for garments including construction, count, weight, fiber content, finish, and thickness. ASTM Standard Test Method 1910[54] was used for fabric count and D 1777[55] for fabric thickness. Tabs. 3 and 4 give garment

Table 1

Fabric Characteristics of Men's Garments[a]

Garment Code	Garment Type	Fabric Construction	Count Warp x Weft/cm2 (Warp x Weft/in2)	Weight g/m2 (oz/yd2)	Fiber Content	Thickness cm (in.)
111	lightweight men's shirt, short-sleeve, broadcloth	plain weave	44.84 x 29.71 (113.8 x 75.4)	0.566 (2.87)	65% polyester 35% cotton	0.0183 (0.007)
112	lightweight men's pant, kettle cloth	plain weave	25.77 x 19.94 (65.4 x 25.8)	1.085 (5.51)	50% polyester 50% cotton	0.0508 (0.020)
211	lightweight men's shirt, long-sleeve, broadcloth	plain weave	46.26 x 29.79 (117.4 x 46.2)	0.606 (3.08)	65% polyester 35% cotton	0.0203 (0.008)
212	medium weight men's pant, gabardine	twill weave	25.14 x 23.72 (63.6 x 25.1)	1.221 (6.20)	100% polyester	0.0630 (0.025)
213	medium weight men's blazer, gabardine	twill weave	19.45 x 23.48 (49.4 x 58.6)	1.202 (6.11)	100% polysester	0.0508 (0.020)
	socks	filling knit	*	*	100% cotton	*

[a]Subjects supplied their own underwear.

*Varied throughout garment so measurement was not taken.

Table 2

Fabric Characteristics of Women's Garments[a]

Garment Code	Garment Type	Fabric Construction	Count Warp x Weft/cm2 (Warp x Weft/in2)	Weight g/m2 (oz/yd2)	Fiber Content	Thickness cm (in.)
111	lightweight women's shirt, short-sleeve broadcloth	plain weave	43.81 x 35.38 (111.2 x 89.8)	0.626 (3.19)	65% polyester 35% cotton	0.0183 (0.007)
112	lightweight women's pant, poplin	plain weave	40.98 x 19.70 (104.0 x 50.0)	0.954 (4.85)	65% polyester 35% cotton	0.0300 (0.012)
211	medium weight women's shirt, long-sleeve oxford cloth	basket weave	35.76 x 16.71 (90.8 x 42.4)	0.774 (3.93)	40% polyester 60% cotton	0.0361 (0.014)
212	medium weight women's pant, gabardine gabardine	twill weave	25.14 x 23.72 (57.4 x 60.2)	1.221 (6.84)	100% polyester	0.0630 (0.027)
213	medium weight women's blazer, gabardine	twill weave	21.75 x 23.09 (55.2 x 58.6)	1.381 (7.02)	100% polyester	0.0691 (0.027)
	socks	filling knit	*	*	100% cotton	*

[a]Subjects supplied their own underwear.

*Varied throughout garment so measurement was not taken.

Table 3

Men's Garment Characteristics

Garment Code	Design Description	Garment Weight[a] g (oz)	Retailer
111	men's dress shirt, short-sleeve, long point collar, button front, chest pocket, long tuck in tails	144.4 (5.09)	Penney's
112	men's dress pant, plain front elastic waistband, 2 side pockets, 1 back pocket	314.2 (11.08)	Penney's
211	men's dress shirt, long-sleeve, long point collar, button front, chest pocket, long tuck in tails, 1 button barrel cuff	181.8 (6.41)	Penney's
212	men's dress pant, belt loop and stretch waist band, 2 back pockets	390.6 (13.78)	Penney's
213	men's blazer, 2 button front, notched lapels, center vent, 2 lower patch pockets, patch chest pocket, 1 inside pocket, acetate lined	598.3 (21.10)	Sears

[a]Garment weights for men's size 15½ x 33 shirt, 15½ shirt, 32 waist, 33 inseam pant, and 40 blazer.

Table 4

Women's Garment Characteristics

Garment Code	Design Description	Garment Weight[a] g (oz)	Retailer
121	women's dress shirt, short-sleeve, long point collar, button front, long tuck in tails, bodice pocket	109.6 (3.87)	Penney's
122	women's dress pant, eleastic waistband, 2 front pockets, straight legs	250.9 (8.85)	Penney's
221	women's dress shirt, long-sleeve, button down collar, button front, long tuck in tails, chest pocket 1 button cuff, back yoke and pleat	177.8 (6.27)	Sears
222	women's dress pant, stretch waistband (elastic in back), zip-fly front, front-back darts	317.8 (11.21)	Sears
223	women's blazer, 2 button front, notched lapels, mock breast pocket, 2 lower patch pockets acetate lined, slightly padded shoulders	448.9 (15.83)	Sears

[a]Garment weights for women's size 12 blouse, 12 pant, and 12 blazer.

information including the retailer, design, and weight. Tab. 5 gives thermal insulation values for each ensemble used in human subject testing. Fig. 4 presents photographs of the ensembles selected for subjects to wear.

Environmental Chamber and Pretest Room

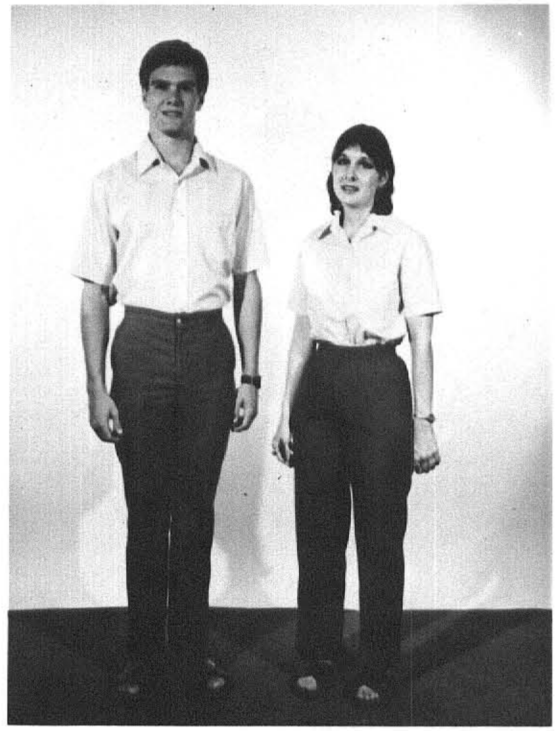
All human subject testing was conducted in the KSU-ASHRAE Environmental Chamber located at Kansas State University in the Institute for Environmental Research. The chamber was 3.45 m x 7.3 m (11 ft 4 in. x 23 ft) with a ceiling height of 3.2 m (10 ft 6 in.). Controlled environmental factors included effective temperatures for the ASHRAE summer zone[5] of 22.8°CET* (72.7 FET*), 24.3°CET* (75.5 FET*), and 26.0°CET* (78.8 FET*). Temperature within the chamber did not normally vary more than 0.6°CET* (1.0 FET*) at any location. Air velocity was less than 0.15 m/s (30 ft/min.) for all testing. Lighting was from two sources including task lighting from a single fluorescent 46 cm (18 in.) 15 w study lamp and wall valence fluorescent lighting from four 1.2 m (4 ft) 30 w fluorescent bulbs. The foot candle measure varied from 78-65 f.c. for readings directly under the study lamps on the table surface and 55-30 f.c. on the table surface edge.

The chamber was furnished to simulate a school or office environment. Furnishings included dark grain wood paneling on the walls, short loop carpeting on the floor, six study tables, 12 study lamps, and 12 cushioned straight-back chairs.

Table 5

Thermal Insulation Values of Clothing Ensembles

Ensemble Code	Ensemble Components	Total Clo (I_T)	Clothing Factor Area (f_{cl})	Intrinsic Clo (I_{cl})
11	men's light weight ensemble: short-sleeve shirt pants underwear sandals	1.15	1.19	0.54
21	men's medium weight ensemble: long-sleeve shirt pants, blazer underwear shoes, socks	1.51	1.30	0.96
12	women's light weight ensemble: short-sleeve shirt pants underwear sandals	1.15	1.19	0.54
22	women's medium weight ensemble: long-sleeve shirt pants, blazer underwear shoes, socks	1.50	1.30	0.95



light weight ensemble

medium weight ensemble

Figure 4 Photographs of light weight ensemble (0.54 clo) and medium weight ensemble (0.95 clo).

Orientation conditioning was accomplished in an adjoining 2.74 x 5.48 m (9 ft x 18 ft) room furnished with 12 classroom desks, carpeting, paneling, and overhead fluorescent lighting. The temperature was 24.3°CET* (76 FET*) and other environmental factors represented a comfortable indoor environment. Subjects were in this room for roughly 20 minutes while being readied for a test.

Sample Selection

Subjects for the study were college student volunteers largely from general psychology classes with a small number from general home economics and engineering classes. They were assigned to experimental groups in a random manner. Subjects were recruited in September 1981. Students between the ages of 18 and 24 were allowed to participate. A designated number of 108 male and 108 female subjects were tested. Twelve subjects signed up for each test. Additional testing included one makeup test for each condition. A total of 245 subjects were actually tested. Fig. 5 gives the testing plan. Testing consisted of seven replications each week for three weeks. A pretest required 12 additional subjects. Two hours of research experimental or extra credit was given to all subjects participating for a complete test.

During the sign-up period of three weeks, all subjects who decided to participate were asked to read an orientation statement describing the purpose of the study, risks that subjects might incur, subjects' right, obligations, and research credit hours (Appendix A). They were then asked to sign-up for a test time/date and complete a

Effective Temperature*	Clothing Insulation				Test Replication Number
	0.54 clo		0.95 clo		
	male(N)	female(N)	male(N)	female(N)	
22.8°CET* (72.7 FET*)	3	3	3	3	1
	3	3	3	3	2
	3	3	3	3	3
	3	3	3	3	4
	3	3	3	3	5
	3	3	3	3	6
	3	3	3	3	7
24.3°CET* (75.7 FET*)	3	3	3	3	1
	3	3	3	3	2
	3	3	3	3	3
	3	3	3	3	4
	3	3	3	3	5
	3	3	3	3	6
	3	3	3	3	7
26.0°CET* (78.8 FET*)	3	3	3	3	1
	3	3	3	3	2
	3	3	3	3	3
	3	3	3	3	4
	3	3	3	3	5
	3	3	3	3	6
	3	3	3	3	7
Subject Subtotals	54	54	54	54	
	108		108		

Note: Data from 6 replications were used in the final analysis (i.e., 216 total subjects).

Figure 5 Testing plan.

clothing size information form (Appendix A). The exact testing conditions were not mentioned to subjects, only that they would be in a testing room at an ordinary indoor temperature for a period of 10 minutes.

Procedure

Human subject testing was scheduled for September 1981. Testing was conducted in five afternoon sessions (3 p.m. - 4:30 p.m.) and two evening sessions (7 p.m. - 8:30 p.m.) each week for three weeks. This resulted in a total of 21 tests. A researcher and technician were present during all testing. Two assistants helped in preparing subjects for testing.

All subjects were called by telephone the night before testing to remind them of their test appointment, to wear or bring the proper items, and not to consume alcohol or drugs 12 hours prior to testing.

Upon arriving for a test, subjects were given their predetermined clothing ensemble and asked to change clothes. They were checked for an acceptable clothing fit to avoid variation in thermal response and assure personal comfort.

Subjects were seated in the conditioning room and oral temperatures were taken. Meanwhile, the researcher and assistants were taping thermistors on subjects using micropore surgical tape. Eight subjects out of 12 in each test were assigned thermistors. Three Yellow Springs Instrument Thermistors were used which terminated at a Digitec Automatic Temperature Data Acquisition System in the control room. Thermistors were taped to the right pectoral regions of the chest, radial surface of the left arm, and fibular surface of the right leg. Arm and leg thermistors were taped on the opposite limb if the subject was left-handed. Each subject had his/her oral temperature checked to see if he/she was in good health ($98.6 \pm 1^{o}F$). Subjects with oral temperatures outside of this range participated, but their data were not used in the final results. Subjects were given clipboards with papers to identify subject, test, and skin thermistor numbers and asked to sign the Agreement and Release Form (Appendix B). Thermal comfort and sensation ballots for the complete test were also attached to the clipboard (Appendix B). Subjects were read an orientation statement and asked to study or read during the entire period and not to talk or communicate in anyway with each other, sleep, or move about while in the chamber. Directions for the completion of thermal comfort and sensation ballots were given (Appendix B).

Subjects entered the test chamber and seated themselves in chairs assigned for a random arrangement of sex and clothing ensembles. The researcher was seated at a table and remained through the test. Two subjects were seated at each table. Subjects were studying or reading at a sedentary activity level of one met. Ballots were collected by the researcher every 30 minutes of the 90-minute test period after the test began. Skin temperature readings were taken and monitored by the technician as ballots were completed.

After the experiment, subjects removed the thermistors and changed into their own clothing. They were asked to fill out a computer experimental class credit card upon returning the provided clothing ensembles. They were also asked to sign a form acknowledging they had been given research credit and had returned all clothing provided for the test. Subjects were told not to discuss the test with other class members.

Data Treatment

Data of subjects' thermal responses for the 90-minute response only were recorded and analyzed. The purpose for having subjects respond at 30 and 60 minutes was to familiarize them with the ballot rating categories and minimize the error factor at the final response. Analysis of Variance, Fisher's Least Significant Difference, and Duncan's Multiple Range tests were used to determine significant effects and interactions in responses. Statistical tests were conducted at a 0.05 level of significance. A description of the statistical analysis for each thermal response is given in Chapter 4.

In addition to statistical analysis of thermal responses, the percent distribution of thermal sensation votes was compiled for each of the nine ballot categories for thermal sensation of body. Percentages for categories of slightly cool (4), neutral (5), and slightly warm (6) were totaled for a composite percentage of subjects finding the environment thermally acceptable. This is expressed as a thermal acceptance frequency response. According to the ASHRAE Standard[5] the environment is thermally acceptable if 80% or more of the subjects respond in the above three categories.

Chapter 4

RESULTS AND DISCUSSION

A three-way analysis of variance was used to test for differences in the main effects and interactions of three factors, (1) temperature, (2) clothing insulation, and (3) sex, on the thermal responses of college students. Thermal response was measured by six dependent variables including thermal sensation of the body, face, hands, and feet, as well as thermal comfort score and weighted mean skin temperature. Post hoc analysis using the Duncan's Multiple Range Test indicated where significant differences existed between means of main factors. Additional analysis, Fisher's Least Significant Differences Test, was used to locate and determine significant differences in two-way and three-way interactions. Results and discussion concerning the hypotheses will serve as the summary of this chapter. Results and discussion related to the validation of clothing-insulation levels for the summer comfort envelope as given in the 1981 ASHRAE Standard, Thermal Environmental Conditions for Human Occupancy,[5] will be given at the end of this chapter.

In selecting the final data to be used, an analysis of variance was performed on the data for each replication for each temperature. Since replication data did not significantly differ at each temperature, one replication for each temperature condition was designated as a make-up test. Subjects' data were taken from the make-up test to substitute for unusable data in other replications of the same temperature. Data were considered unusable due to abnormal body temperatures, poor clothing fit, or questionable behavior by subjects. Data from 216 subjects, based on 12 subjects in each replication, were used in the final analysis. Data from the final 90-minute response were used for analysis, although response data for 30 and 60-minute responses were collected. The reason for collecting 30 and 60-minute responses was to provide data for future analysis related to time of exposure, to familiarize subjects with ballot categories, and to avoid subject errors in the final response.

Results will be discussed according to the dependent variables of thermal sensation, thermal comfort score, and weighted mean skin temperature.

Thermal Sensation of Body

Means of subjects' responses for thermal sensation of body, face, hands, and feet were treated similarly and subjected to the ANOVA, Duncan's Multiple Range, and Fisher's LSD tests. Thermal sensation ballots providing subjects' means were based on a 9-point scale including very cold - 1, cold - 2, cool - 3, slightly cool - 4, neutral - 5, slightly warm - 6, warm - 7, hot - 8, and very hot - 9. Responses of slightly cool, neutral, and slightly warm are considered thermally acceptable according to the ASHRAE Standard.[5]

Significant differences occurred in main effects of temperature, clothing insulation, and sex for thermal sensation of body (Tabs. 6 and 7). These differences were further explained by a two-way interaction between temperature and sex, which were in turn given additional support by a significant three-way interaction between temperature, clothing insulation, and sex (Tabs. 6, 8, and Fig. 6).

Table 6

Analysis of Variance for Thermal Sensation of the Body and Face

		Thermal Sensation of the Body		Thermal Sensation of the Face	
Source	df	ss	F value	ss	F value
Temperature	2	30.01	8.75**	10.75	3.01
Clothing Insulation	1	31.13	31.21**	7.78	9.82**
Sex	1	9.80	9.82**	6.34	8.00**
Temperature x Clothing Insulation	2	0.62	0.31	1.18	0.74
Temperature x Sex	2	7.34	3.68*	7.12	4.49**
Clothing Insulation x Sex	1	1.19	1.19	4.45	5.61*
Temperature x Sex x Clothing Insulation	2	8.40	4.21*	3.06	1.93
Replication	5	5.09	0.59	1.26	0.14
Error Term (chamber)	10	17.16		17.86	
Error Term (subject)	189	188.53		149.82	

* Indicates significance at the 0.05 level.

**Indicates significance at the 0.01 level.

Table 7

Duncan's Multiple Range Test for the Mean Thermal Sensation Ratings of the Body, Face, Hands, and Feet

		Body		Face		Hands		Feet	
Main Effects	N	mean	grouping[1]	mean	grouping[1]	mean	grouping[1]	mean	grouping[1]
Temperature									
22.8°CET* (72.7 FET*)	72	4.35	A	4.88	A	4.79	A	4.81	A
24.3°CET* (75.7 FET*)	72	4.97	B	5.08	B	5.39	B	5.50	B
26.0°CET* (78.8 FET*)	72	5.24	B	5.42	B	5.39	B	5.85	B
Clothing Insulation									
0.54 clo ensemble	108	4.47	A	4.94	A	4.98	A	4.86	A
0.95 clo ensemble	108	5.23	B	5.31	B	5.40	B	6.09	B
Sex									
male	108	5.06	A	5.30	A	5.34	A	5.49	A
female	108	4.64	B	4.95	B	5.04	B	5.28	B

[1]Means with the same letter designations are not significantly different from one another at the 0.05 level.

Table 8

Results of Fisher's Least Significant Differences for Thermal Sensation of Body at a Given Temperature, Clothing Insulation Level, and Sex

22.8°CET* (72.7 FET*)	0.54 clo Males	0.54 clo Females	0.95 clo Females	0.95 clo Males
N	18	18	18	18
Mean	3.89	4.00	4.11	5.39

24.3°CET* (75.7 FET*)	0.54 clo Females	0.95 clo Females	0.54 clo Males	0.95 clo Males
N	18	18	18	18
Mean	4.17	5.00	5.17	5.56

26.0°CET* (78.8 FET*)	0.54 clo Males	0.54 clo Females	0.95 clo Males	0.95 clo Females
N	18	18	18	18
Mean	4.78	4.83	5.61	5.72

Means not underlined are significantly different at the 0.05 level.
LSD = 0.659

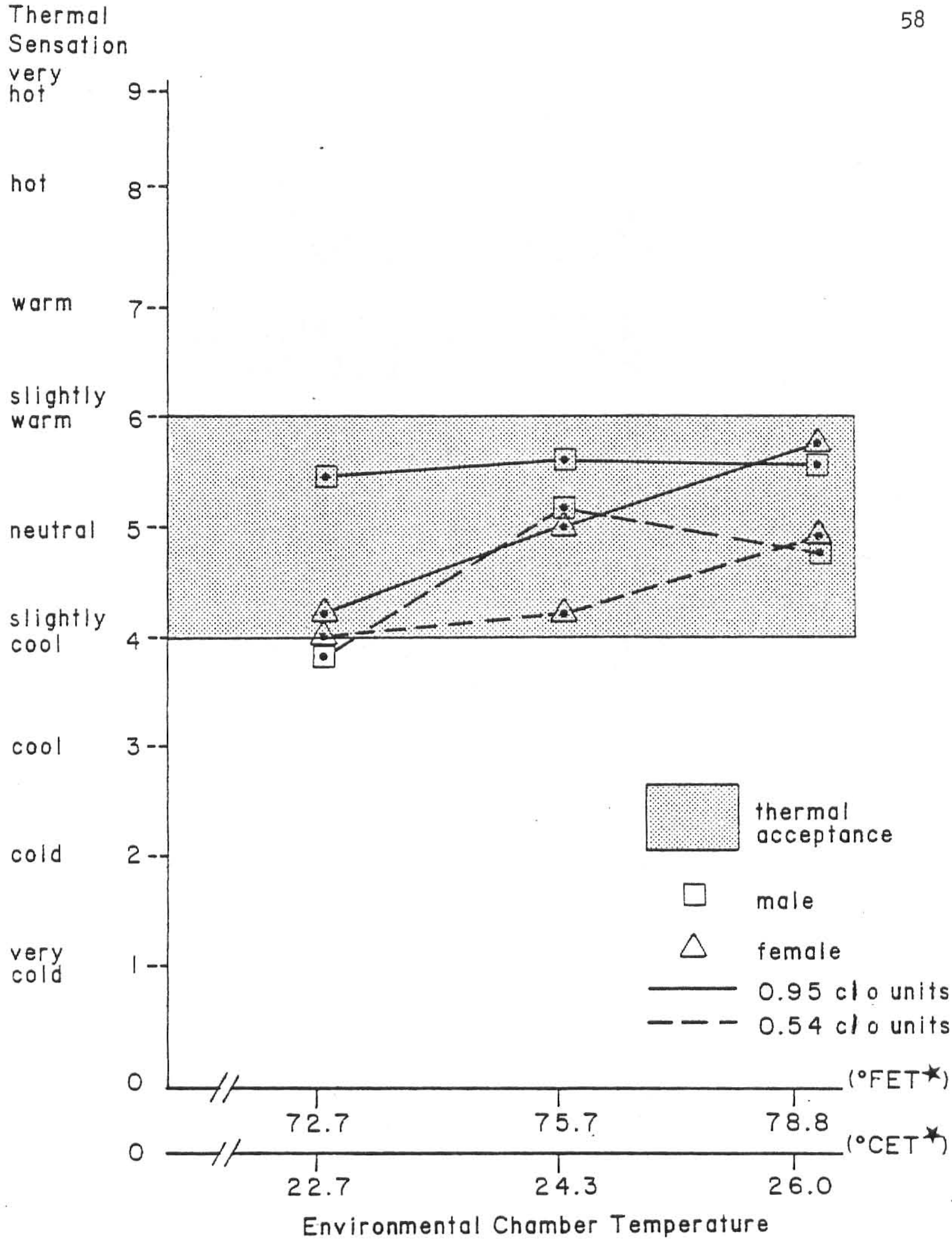


Figure 6 Mean thermal sensations of body at three environmental temperatures for males and females wearing two levels of clothing insulation.

In the three-way interaction at 22.8°CET* (72.7 FET*), males in the medium weight ensemble (0.95 clo) were warmer and responded closer to neutral than females in the same ensemble or subjects of either sex in the light weight ensemble (0.54 clo) (Tab. 8). Mean thermal sensation of body responses for males of 3.89 (cool) indicated this temperature was slightly thermally unacceptable, however not significantly less than females' response of 4.00 (slightly cool). Females at 24.3oCET* (75.7 FET*) in the light weight ensemble responded cooler than males who responded closer to neutral in the same ensemble. More clothing insulation than 0.54 clo is needed for females to respond closer to neutral and similar to males at this temperature. Males and females at 26.0°CET* (78.8 FET*) in the medium weight ensemble were warmer than those in the light weight ensemble who responded closer to neutral. The light weight ensemble at this temperature was highly and similarly acceptable to both sexes.

In summary, the light weight ensemble was minimally inadequate for male thermal acceptance at 22.8°CET* (72.7 FET*), but adequate at all three temperatures for females. Females at 22.8°CET* (72.7 FET*) in the medium weight ensemble and at 24.3°CET* (75.7 FET*) in the light weight ensemble were cooler than males who responded more neutral. Females appear to need more clothing insulation in these instances than males to respond similarly after 90 minutes of exposure. At 26.0°CET* (78.8 FET*) males and females responded similarly and close to neutral in the light weight ensemble, but were significantly warmer in the medium weight ensemble.

Thermal Sensation of Face

The analysis of variance indicated that the mean responses for thermal sensation of face were significantly different in main effects for clothing insulation and sex (Tab. 6). The Duncan's Multiple Range Test indicated significant main effects for clothing insulation, sex, and temperature (Tab. 7). Significant two-way interactions between temperature and sex in addition to clothing insulation and sex further explained the main effects (Tabs. 6, 9, 10, Figs. 7 and 8).

In the temperature and sex interaction (Tab. 9 and Fig. 7), at 24.3°CET* (75.7 FET*), females' faces with a mean response of 4.69 were cooler than males' at 5.47.

In the clothing insulation and sex interaction, males' faces in the medium weight ensemble were warmer than females' in the same ensemble and warmer than both sexes in the light weight ensemble. Males' faces appear more sensitive to the amount of clothing insulation in the medium weight ensemble than do females' faces.

Thermal Sensation of Hands

Mean responses for thermal sensation of hands were significant for the main effects of temperature, clothing insulation, and sex (Tabs. 7 and 11). Temperature and sex differences were further explained by a significant two-way interaction (Tabs. 7, 12, and Fig. 9).

In general, subjects in the light weight ensemble had cooler hands than those in the medium weight ensemble. Responses for thermal sensation of hands were most neutral in the light weight ensemble.

Table 9

Results of Fisher's Least Significant Differences for Thermal Sensation of Face at a Given Temperature and Sex

22.8°CET* (72.7 FET*)	Female	Male
N	36	36
Mean	4.69	5.06

24.3°CET* (75.7 FET*)	Female	Male
N	36	36
Mean	4.69	5.47

26.0°CET* (78.8 FET*)	Male	Female
N	36	36
Mean	5.36	5.47

Means not underlined are significantly different at the .05 level.
LSD = 0.416

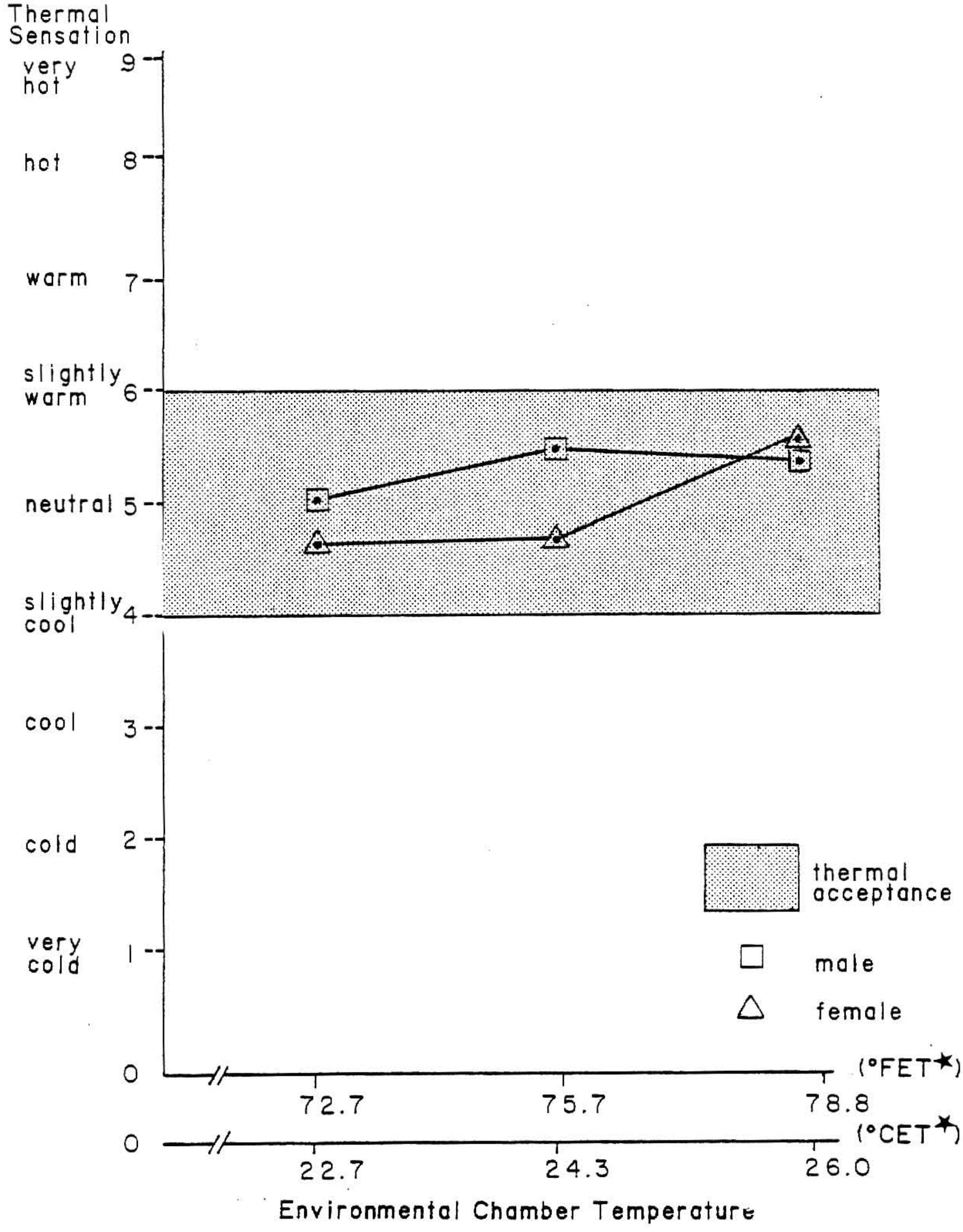


Figure 7 Mean thermal sensations of face at three environmental temperatures for males and females.

Table 10

Results of Fisher's Least Significant Differences for Thermal Sensation of Face at a Given Clothing Insulation Level and Sex

	0.54 clo Female	0.54 clo Male	0.95 clo Female	0.95 clo Male
N	54	54	54	54
Mean	4.91	4.96	5.00	5.63

Means not underlined are significantly different at the 0.05 level.
LSD = 0.339

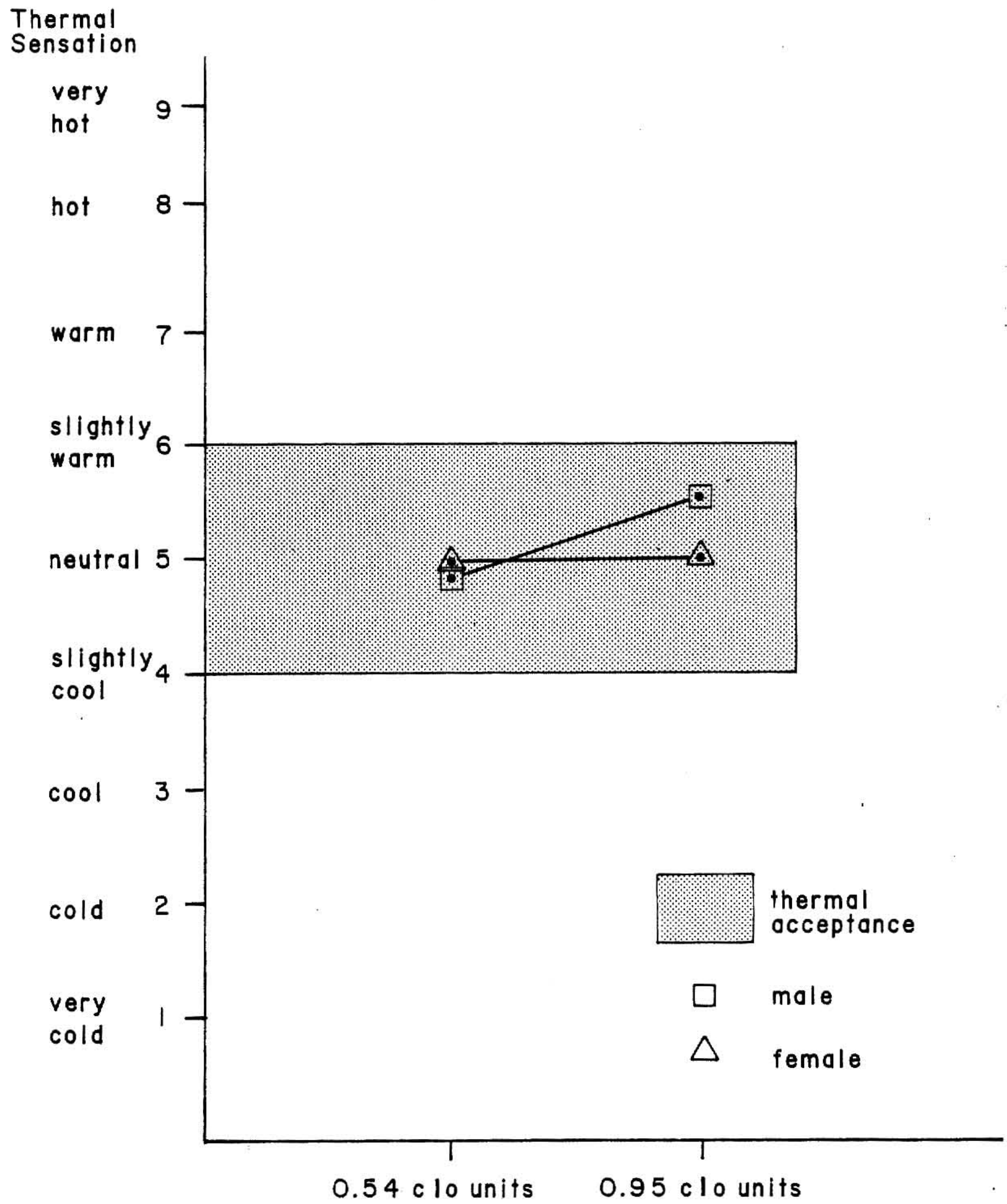


Figure 8 Mean thermal sensations of face at two levels of clothing insulation for males and females.

Table 11

Analysis of Variance for Thermal Sensation of the Hands and Feet

		Thermal Sensation of the hands		Thermal Sensation of the feet	
Source	df	ss	F value	ss	F Value
Temperature	2	17.12	7.99**	40.51	11.09**
Clothing Insulation	1	9.38	9.99**	108.38	68.50**
Sex	1	5.04	5.37**	2.45	1.55
Temperature x Clothing Insulation	2	0.19	0.10	0.58	0.18
Temperature x Sex	2	9.25	4.93**	5.73	1.81
Clothing Insulation x Sex	2	0.78	0.83	0.00	0.00
Temperature x Sex x Clothing Insulation	2	1.18	0.63	3.40	1.07
Replication	5	10.13	1.89	14.75	1.61
Error Term (Chamber)	10	10.71		18.27	
Error Term (subject)	189	177.43		299.04	

* Indicates significance at the 0.05 level.

**Indicates significance at the 0.01 level.

Table 12

Results of Fisher's Least Significant Differences for Thermal Sensation of Hands at a Given Temperature and Sex

22.8°CET* (72.7 FET*)	Female	Male
N	36	36
Mean	4.47	5.11

24.3°CET* (75.7 FET*)	Female	Male
N	36	36
Mean	5.11	5.67

26.0°CET* (78.8 FET*)	Male	Female
N	36	36
Mean	5.25	5.33

Means not underlined are significantly different at the 0.05 level.
LSD = 0.452

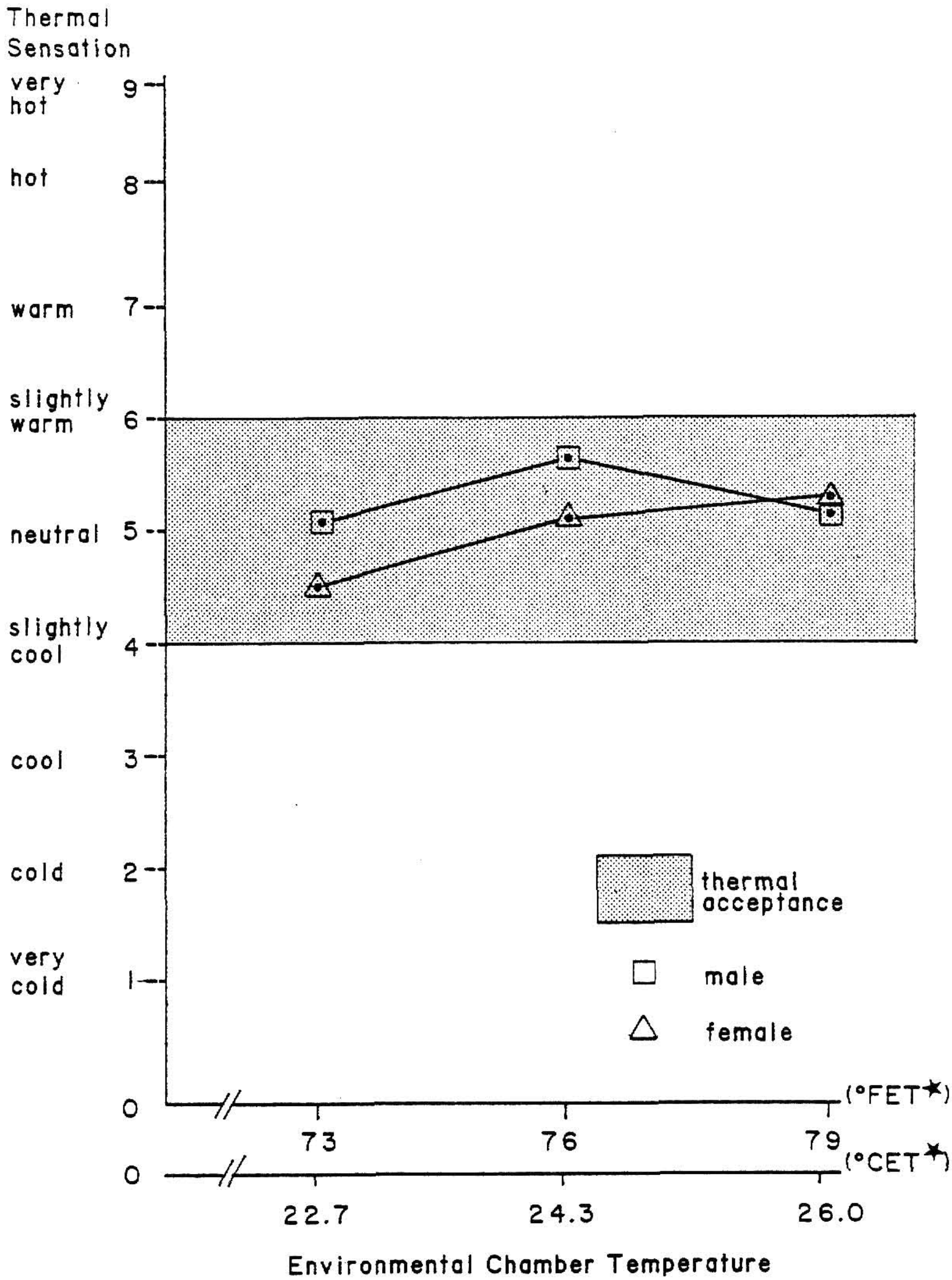


Figure 9 Mean thermal sensations of hands at three environmental temperatures for males and females.

In the two-way interaction for temperature and sex, females' hands were cooler than males' at 22.8°CET* (72.7 FET*) and 24.3°CET*, (75.7 FET*) but similar at 26.0°CET* (78.8 FET*).

Thermal Sensation of Feet

Mean responses for thermal sensation of feet were significant only in mean effects of temperature and clothing insulation (Tabs. 11 and 2).

Subjects' feet were significantly cooler at 22.8°CET*, (72.7 FET*) regardless of which ensemble they were wearing.

Subjects' feet in the medium weight ensemble were warmer with a response of 6.09 (warm) which is above the thermal acceptance range of slightly cool (4.00) to slightly warm (6.00) given in the ASHRAE Standard.[5] Those in the light weight ensemble had a mean response of 4.68 which is slightly cool, but much closer to a neutral response (5.00). The thermal unacceptability of socks and shoes at 24.3°CET* (75.7 FET*) and 26.0°CET* (78.8 FET*) is not a problem for females in the summer who generally wear open-toed shoes or sandals in an office or school environment, but may be a problem for males who cannot normally wear sandals in similar summer environments.

Thermal Comfort Score

Thermal comfort scores were compiled from a ballot based on a semantic differential scale developed by Rohles.[9] A list of six bi-polar adjectives including comfortable-uncomfortable, good temperature-bad temperature, pleasant-unpleasant, acceptable-unacceptable, comfortable temperature-uncomfortable temperature, and satisfied-dissatisfied were included in the ballot. Subjects checked one of nine spaces which indicated their level of thermal comfort between each adjective pair. Responses of data concerning the adjectives of cool-warm and those at the bottom of the ballot for thermal preferance were not included in the analysis. A rating of one was considered least desirable and nine most desirable. Each rating was multiplied by a loading. Loadings formulated by Rohles[9] from a broad category of thermal comfort adjectives were used. The loadings for the adjective pairs used in this study are as follows: comfortable-uncomfortable, 0.555; bad temperature-good temperature, 0.693; pleasant-unpleasant, 0.628; unacceptable-acceptable, 0.521; uncomfortable temperature-comfortable temperature, 0.726; satisfied-dissatisfied, 0.568. The products of the ratings multiplied by their loadings were summed and expressed as a percent for a subject's thermal comfort score. Means of subjects' thermal comfort scores were statistically analyzed by the ANOVA, Duncan's Multiple Range, and Fisher's LSD tests.

Significant differences in thermal comfort scores occurred for the main effect of clothing insulation (Tabs. 13 and 14). Additional evidence was given in a significant two-way interaction between clothing insulation and temperature (Tabs. 13, 15, and Fig. 10). The highest comfort score (82%) occurred for subjects in the light weight ensemble at 26.0°CET* (78.8 FET*). The lowest comfort score (60%) occurred for subjects in the medium weight ensemble at the same temperature. Subjects wearing a normal summer suit indoors at this temperature should lessen or adapt their level of clothing to be more

Table 13

Analysis of Variance for Thermal Comfort Scores and Weighted Mean Skin Temperatures

	Thermal Comfort			Weighted Mean Skin Temperature	
Source	df	ss	F value	ss	F value
Temperature	2	692.22	0.44	105.11	30.62**
Clothing Insulation	1	3868.35	6.85**	99.36	119.14**
Sex	1	864.52	1.53	5.60	6.72**
Temperature x Clothing Insulation	2	4906.26	4.34**	1.21	0.73
Temperature x Sex	2	663.24	0.59	8.14	4.88**
Clothing Insulation x Sex	1	3628.10	6.43	0.14	0.17
Temperature x Sex x Clothing Insulation	2	1110.15	0.98	0.47	0.28
Replication	5	3924.90	1.00	15.63	1.82
Error Term (chamber)	10	7847.92		17.16	
Error Term (subject)	189	106,724.75		97.58	

* Indicates significance at the 0.05 level.

**Indicates significance at the 0.01 level.

Table 14

Duncan's Multiple Range Test for the Mean Thermal Comfort Scores
and Weighted Mean Skin Temperatuers

Main Effects	Thermal Comfort N	Thermal Comfort mean	Thermal Comfort grouping[1]	Weighted Mean Skin Temperature °C (F) N	Weighted Mean Skin Temperature °C (F) mean	Weighted Mean Skin Temperature °C (F) grouping[1]
Temperature						
22.8°CET* (72.7 FET*)	72	70.63%	A	48	32.76 (90.96)	A
24.3°CET* (75.7 FET*)	72	74.64	A	48	33.40 (92.12)	B
26.0°CET* (78.8 FET*)	72	71.10	A	48	33.92 (93.05)	C
Clothing Insulation						
0.54 clo ensemble	108	76.35	A	72	32.90 (91.22)	A
0.95 clo ensemble	108	67.89	B	72	33.82 (92.88)	B
Sex						
male	108	70.12	A	72	33.47 (92.24)	A
female	108	74.12	A	72	33.25 (91.85)	B

[1]Means with the same letter designations are not *significantly* different from one another at the 0.05 level.

Table 15

Results of Fisher's Least Significant Differences for Thermal Comfort Scores at a Given Temperature and Clothing Insulation Level

22.8°CET* (72.7 FET*)	0.54 clo	0.95 clo
N	36	36
Mean	69.90	71.88

24.3°CET* (75.7 FET*)	0.95 clo	0.54 clo
N	36	36
Mean	71.88	77.40

26.0°CET* (78.8 FET*)	0.95 clo	0.54 clo
N	36	36
Mean	60.44	81.77

Means not underlined are significantly different at the 0.05 level.
LSD = 11.090

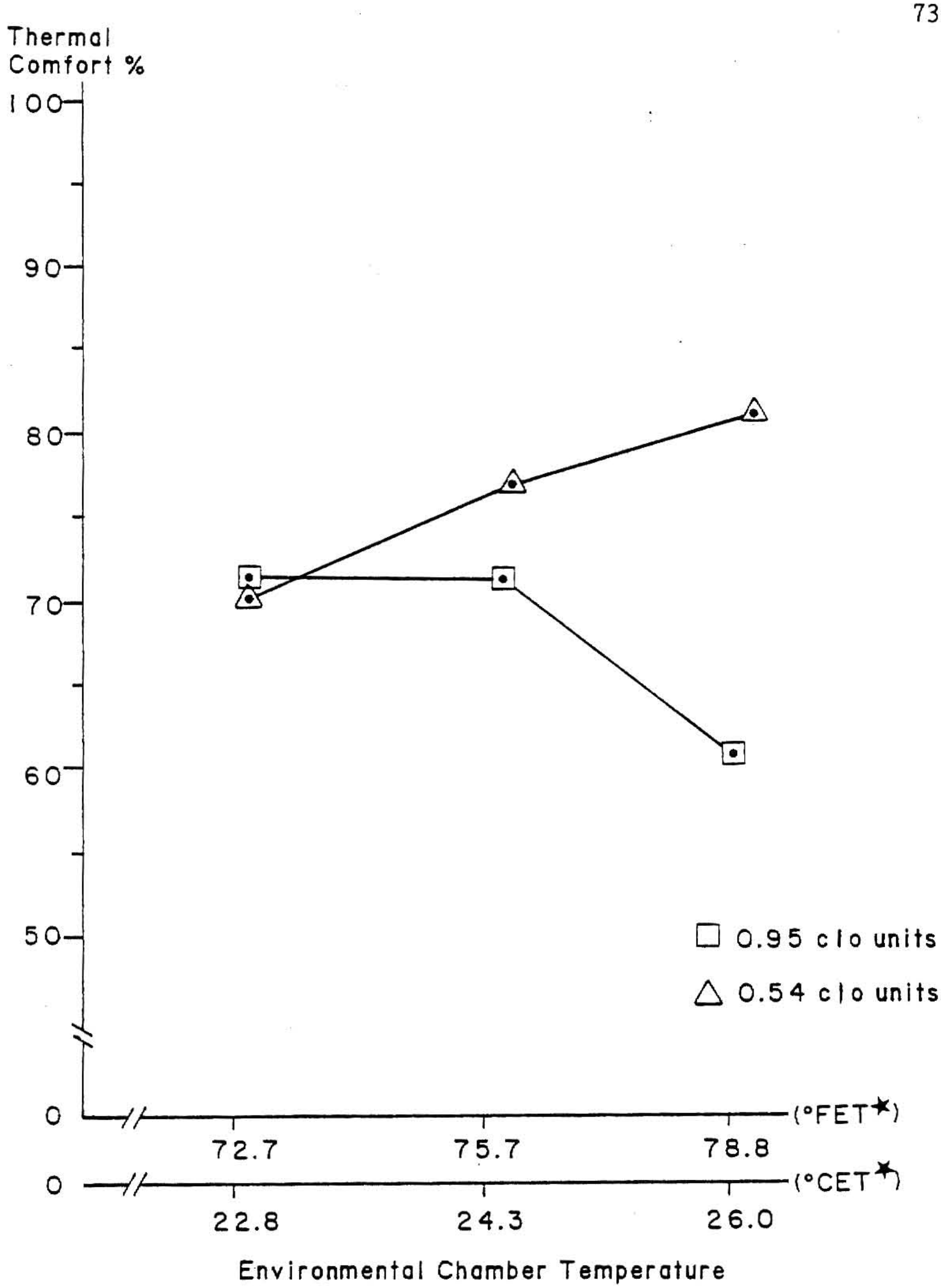


Figure 10 Mean thermal comfort scores at three environmental temperatures for two levels of clothing insulation.

comfortable. Subjects were similarly comfortable at 24.3°CET* (75.7 FET*) and 22.8°CET* (72.7 FET*) in either ensemble (Tab. 15).

Weighted Mean Skin Temperature

Weighted mean skin temperature represents the average skin temperature of the body. Thermistors were taped to the chest, arm, and leg to obtain three skin temperatures. Each temperature was multiplied by a weighting and then totaled with other skin temperatures to produce a subject's weighted mean skin temperature. A standard skin temperature comfort zone of 33-34°C (91.4-93.2 F) was used as a basis for thermal acceptance.[39] Significant differences were obtained with the ANOVA, Duncan's Multiple Range, and Fisher's LSD tests.

Subjects' mean responses for weighted mean skin temperature were significantly different for the three factors of temperature, clothing insulation and sex (Tabs. 13 and 14). Differences in the main effects of temperature and sex were further clarified by a significant two-way interaction (Tabs. 7, 13, 16, and Fig. 11).

In the significant main effect of clothing insulation, subjects' skin temperatures were unacceptably cool in the light weight clothing ensemble and most thermally comfortable in the medium weight ensemble (Tab. 14). Their weighted mean skin temperature of 32.9°C (91.22 F) was minimally below the standard skin temperature comfort zone of 33-34°C.

The two-way interaction between temperature and sex resulted in different weighted mean skin temperatures for males and females at 22.8°CET* (72.7 FET*) (Tab. 16 and Fig. 11); females responded cooler

Table 16

Results of Fisher's Least Significant Differences for Weighted Mean Skin Temperatures at a Given Temperature and Sex

22.8°CET* (72.7 FET*)	Female	Male
N	24	24
Mean °C	32.46	33.06
(F)	(90.43)	(91.50)

24.3°CET* (75.7 FET*)	Female	Male
N	24	24
Mean °C	33.37	33.42
(F)	(92.09)	(92.15)

26.0°CET* (78.8 FET*)	Male	Female
N	24	24
Mean °C	33.92	33.93
(F)	(93.05)	(93.08)

Means not underlined are significantly different at the 0.05 level.
LSD = 0.522

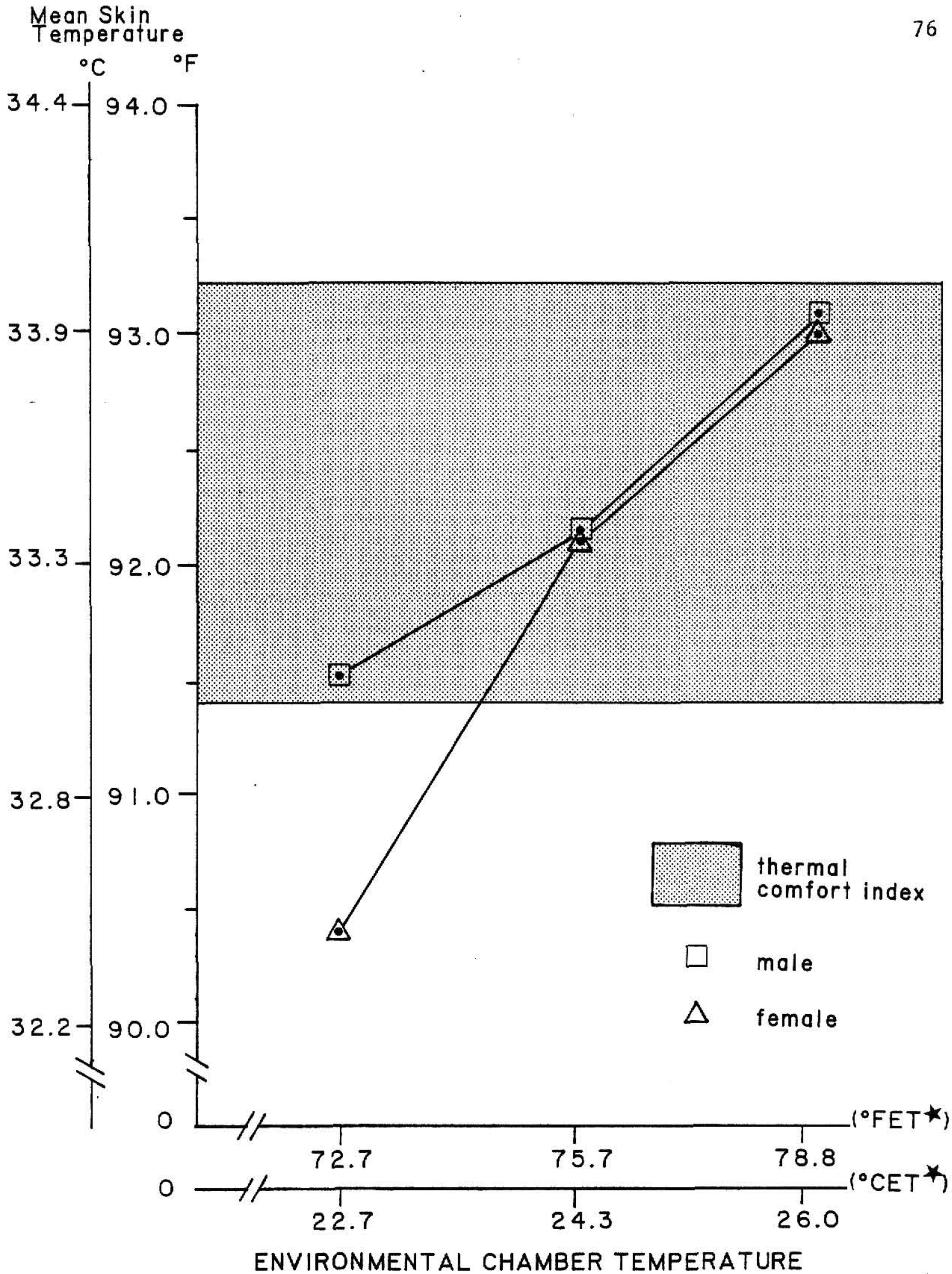


Figure 11 Weighted Mean skin temperatures at three environmental temperatures for males and females.

than males. The weighted mean skin temperature of females was 32.45°C (90.43 F) and for males was 33.06°C (91.50 F). Females responded unacceptably cool and below the skin temperature comfort zone of 33-34°C. More clothing insulation or a higher air temperature is needed for females to have an acceptable weighted mean skin temperature.

Null Hypotheses

Null hypotheses were rejected for some dependent variables due to the resulting significant differences (Fig. 12). The independent variables, temperature, sex, and clothing insulation, significantly affected the thermal responses of college students for a 90-minute exposure. However, not all thermal responses were significantly different for each independent variable (Fig. 12).

Hypothesis 1 stated that there will be no significant difference in the thermal response of students when exposed to 22.8°CET* (72.7 FET*), 24.3°CET* (75.7 FET*), and 26.0°CET* (78.8 FET*) while wearing the same amount of clothing insulation. This was rejected because significant differences occurred within temperatures for thermal sensation of body, face, hands, and feet, and for weighted mean skin temperature. In general, subjects' thermal sensation responses were cooler at 22.8°CET* (72.7 FET*) than at 24.3°CET* (75.7 FET*) or 26.0°CET* (78.8 FET*) (Tabs. 7 and 14). Weighted mean skin temperatures were also significantly different between all three temperatures (Tab. 14).

Hypothesis 2 stated that there will be no significant difference in the thermal response of students when exposed to the same

Hypothesis	Thermal Sensation					
There will be no significant differences in the thermal response of students due to:	Body	Face	Hands	Feet	Thermal Comfort Score	Weighted Mean Skin Temperature
1. Temperature	**		**	**		**
2. Clothing Insulation	**	**	**	**	**	**
3. Sex	**	**	**			**
4. Temperature x Clothing Insulation					**	
5. Temperature x Sex	*	**	**			**
6. Clothing Insulation x Sex		*				
7. Temperature x Clothing Insulation x Sex	*					

*Indicates significance at the 0.05 level.
**Indicates significance at the 0.01 level.

Figure 12 Summary of significant differences for each hypothesis by each dependent variable.

temperature while wearing ensembles representing 0.54 clo units or 0.95 clo units. This hypothesis was rejected due to significant differences for all six dependent variables (Tabs. 7 and 14). Subjects were cooler and found the light weight ensemble more thermally acceptable. In general, the light weight ensemble is the most acceptable choice for the summer envelope temperatures used in this study. Occupants wearing a summer medium weight ensemble as used in this study should remove the jacket and include a short sleeve shirt and sandals to be more comfortable in summer indoor environments.

Hypothesis 3 stated that there will be no significant difference in the thermal response of male and female students when exposed to the same temperature while wearing the same amount of clothing insulation. This was rejected since significant differences resulted between males and females for thermal sensation of body, face, hands, and feet, and for weighted mean skin temperature (Tabs. 7 and 14). In general, females were cooler in thermal sensation and skin temperature than males when at the same temperature and wearing the same clothing. This finding agrees with past studies[25,28] that have reported differences in thermal sensation and weighted mean skin temperature responses due to sex of subject for short exposure periods.

Hypothesis 4 stated that there will be no significant difference in the thermal response of students when exposed to 22.8°CET* (72.7 FET*), 24.3°CET* (75.7 FET*), and 26.0°CET* (78.8 FET*) while wearing ensembles representing 0.54 clo units or 0.95 clo units of clothing insulation. Hypothesis 4 was rejected since significant differences for temperature and clothing insulation occurred for thermal comfort scores. Subjects found the light weight ensemble more thermally acceptable at 26.0^{o}CET* (78.8 FET*) than the medium weight ensemble (Tab. 15). Subjects perceived the least difference between the light and medium weight ensembles at 22.8^{o}CET* (72.7 FET*). Occupants wearing the medium weight ensemble at 26.0^{o}CET* (78.8 FET*) clearly needed to lessen their clothing insulation to respond more neutral.

Hypothesis 5 stated that there will be no significant difference in the thermal response of male and female students when exposed to 22.8^{o}CET* (72.7 FET*), 24.3^{o}CET* (75.7 FET*), and 26.0^{o}CET* (78.8 FET*) while wearing the same amount of clothing insulation. This was rejected due to the significant differences between temperature and sex for thermal sensation of body, face, and hands, and for weighted mean skin temperature (Tabs. 6, 11, and 13). Females' thermal sensation responses were cooler than males at 24.3^{o}CET* (75.7 FET*) after a 90-minute exposure (Tabs. 9 and 12). Less difference occurred for thermal sensation responses between males and females at 22.8^{o}CET* (72.7 FET*) with the exception of females having cooler hands. Females had unacceptable and cooler weighted mean skin temperatures than males at 22.8^{o}CET* (72.7 FET*), but differed little at 24.3^{o}CET* (75.7 FET*) and 26.0^{o}CET* (78.8 FET*) (Tab. 16). Responses at 22.8^{o}CET* (72.7 FET*) indicating that females were generally more sensitive to cold than males have been reported in other thermal comfort studies after a 90-minute exposure.[25,28]

Hypothesis 6 stated that there will be no significant difference in the thermal response of male and female students when exposed to the same temperature while wearing ensembles representing 0.54 clo units or 0.95 clo units of clothing insulation. This was rejected due to significant differences between clothing insulation and sex for thermal sensation of face (Tab. 10). Males in the medium weight ensemble had warmer faces than females in the same ensemble or both sexes in the light weight ensemble. Males' faces therefore appear more sensitive to the amount of clothing insulation in the medium weight ensemble than females'. Males should reduce the amount of clothing worn in the medium weight ensemble for a more acceptable sensation of face response.

Hypothesis 7 concerned the three-way interaction and stated that there will be no significant difference in the thermal response of male and female students when exposed to 22.8°CET* (72.7 FET*), 24.3°CET* (75.7 FET*), and 26.0°CET* (78.8 FET*) while wearing ensembles representing 0.54 clo units or 0.95 clo units of clothing insulation. This was rejected due to significant differences in the three-way interaction for thermal sensation of body (Tab. 8). Males in the medium weight ensemble at 22.8°CET* (72.7 FET*) were warmer than females in the same ensemble or either sex in the light weight ensemble at 22.8°CET* (72.7 FET*). Males in the medium weight ensemble responded between neutral and slightly warm. Females, however, responded cool or slightly cool. Females at 24.3°CET* (75.7 FET*) were cooler than males in the light weight ensemble. Females need more clothing insulation than 0.54 clo to respond similar to males at 24.3°CET* (75.7 FET*). Males and females found the light weight ensemble acceptable at 26.0°CET* (78.8 FET*) according to all responses.

Validation of the ASHRAE Summer Envelope

The second purpose of this study was to validate or suggest modifications for the thermal acceptability of the ASHRAE summer comfort envelope. The 1981 ASHRAE Standard, Thermal Environmental Conditions for Human Occupancy,[5] defined an acceptable environment as one which at least 80% of the occupants find thermally acceptable by voting 3 to 5 on a 7-point thermal sensation ballot. The 80% level of acceptance is the basis for determining the summer envelope boundary temperatures, 22.8°CET* (72.7 FET*) and 26.0°CET* (78.8 FET*). Responses from a 9-point or 7-point thermal sensation scale can be used, although a 9-point scale creates more variability and sensitivity in responses by adding adjectives of very cold and very hot at each end of the scale. Occupants voting 4 to 6 (slightly cool to slightly warm) on a 9-point scale find the environment thermally acceptable.

Thermal acceptability frequency tables were used to determine the level of acceptability for males and females at each temperature in the light weight and medium weight ensembles. The distribution of thermal sensation responses in each of the nine ballot rating categories was determined and expressed as a response frequency in percentage figures. Percentages for slightly warm, neutral, and slightly cool categories were totaled to reveal the percentage of respondents who indicated thermal acceptance of the environment.

The ASHRAE Standard[5] specifies that 80% of the subjects in a light weight ensemble of 0.5 clo units should find the summer envelope temperatures thermally acceptable. However, only 75% of the subjects found 22.8°CET* (72.7 FET*) acceptable (Tab. 17). Responses indicated that 72% of the males and 78% of the females found 22.8°CET* (72.7 FET*) thermally acceptable. More clothing insulation is needed at 22.8°CET* (72.7 FET*) for 80% of the subjects to be satisfied or 'comfortable'. At 24.3°CET* (75.7 FET*) 86% of the subjects found the temperature thermally acceptable. The percentage of males increased to 94% at this temperature while females remained the same as at 22.8°CET* (72.7 FET*). Thermal acceptability was indicated by 89% of the subjects at 26.0°CET* (78.8 FET*) with the same percentage of males and females finding the temperature acceptable. Males (94%) found the light weight ensemble most acceptable at 24.3°CET* (75.7 FET*) and females (89%) at 26.0°CET* (78.8 FET*).

The medium weight ensemble was minimally unacceptable to 80% of the subjects at each of the three temperatures. Subjects (78%) responded similarly for each temperature. The same percentage of females and males responded in thermally acceptable categories at 22.8°CET* (72.7 FET*). At 24.3°CET* (75.7 FET*), males (72%) decreased and females (83%) increased in percentage of thermal acceptability. A greater difference occurred between males and females at 26.0°CET* (78.8 FET*) where 89% of the males and 67% of the females found the condition thermally acceptable. It is unexplainable why more males found the medium weight ensemble acceptable at 26.0°CET* (78.8 FET*) which is incongruous with the

Table 17

Frequency Responses for Thermal Sensation of Body

	Percentage of subjects that found the environment thermally acceptable[1]	
Temperature	0.54 clo	0.95 clo
22.8°CET* (72.7 FET*)		
male	72.22	77.78
female	77.78	77.78
both	75.00	77.78
24.3°CET* (75.7 FET*)		
male	94.45	72.22
female	77.78	83.34
both	86.11	77.78
26.90°CET* (78.8 FET*)		
male	88.89	88.89
female	88.89	66.67
both	88.89	78.78

[1] As indicated by a response of 4, 5, or 6 on the thermal sensation of body ballot.

thermal responses discussed earlier. Females (83%) found the medium weight ensemble most acceptable at 24.3^{o}CET* (75.7 FET*) which agrees with weighted mean skin temperatures and thermal sensation of body and hand responses mentioned earlier.

In summary, the light weight ensemble was thermally acceptable to at least 80% of the subjects at 24.3^{o}CET* (75.7 FET*) and 26.0^{o}CET* (78.8 FET*), but slightly unacceptable at 22.8^{o}CET* (72.7 FET*). The medium weight ensemble was equally acceptable to subjects at any of the three temperatures, but slightly unacceptable to 80% of the subjects at any temperature. This slight unacceptance may be due to experimental error or the 9-point thermal sensation ballot. A 9-point thermal sensation ballot may spread the responses over a wider rating due to the addition of adjectives on either end of the scale. If a 7-point thermal sensation ballot were used 80% of the subjects might have found the condition acceptable. It is recommended that subjects wear more than 0.5 clo of insulation at 22.8^{o}CET* (72.7 FET*) to meet an 80% level of subject thermal acceptability. Results indicate the optimum temperature to be at 26.0^{o}CET* (78.8 FET*), not 24.3^{o}CET* (75.7 FET*) as reported in the ASHRAE Standard.[5] It appears the clothing insulation units or the upper air temperature in the standard are conservative. The temperature could most likely be extended upward 1.6^{o}C (3 F) while keeping within a thermally acceptable range.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this research was to measure the effect of clothing insulation and effective temperature on the thermal sensation, thermal comfort, and weighted mean skin temperature of male and female college students. A second purpose was to determine if 80% or more of the subjects were satisfied with the thermal environment specified as the summer envelope in the 1981 ASHRAE Standard, Thermal Environmental Conditions for Human Occupancy.[5] Based on the results of this study the following conclusions were drawn.

ANOVA and Duncan's Multiple Range tests indicated 1) subjects responded differently to 22.8°CET* (72.7 FET*) than 24.3°CET* (75.7 FET*) and 26.0°CET* (78.8 FET*) in thermal sensation responses and weighted mean skin temperatures; 2) subjects perceived the difference in clothing insulation of the medium weight (0.95 clo units) and light weight (0.54 clo units) ensembles according to thermal sensation responses, thermal comfort score, and weighted mean skin temperature; 3) males responded differently than females in thermal sensation responses and weighted mean skin temperature.

The Fisher's LSD Test yielded more specific results in two-way and three-way interactions. The light weight ensemble was generally more acceptable than the medium weight ensemble in the summer envelope temperatures. An exception occurred at 22.8°CET* (72.7 FET*) where subjects responded unacceptably cool for weighted mean skin temperature. Females had a cooler weighted mean skin temperature than males. The medium weight ensemble was more acceptable at this temperature to males and females. More insulation than 0.54 clo units as provided by the light weight ensemble is needed for subjects to find 22.8°CET* (72.7 FET*) thermally acceptable.

The greatest difference in male and female responses occurred at 24.3°CET* (75.7 FET*) where females were cooler than males and more neutral in thermal sensation of hands, face, and body. Males in the light weight ensemble responded warmer, but more neutral than females.

Subjects preferred the light weight ensemble at 26.0°CET* (78.8 FET*) in all thermal responses. Females and males responded similarly and slightly warm in the light weight ensemble. The light weight ensemble had the greatest level of acceptance over the medium weight ensemble at this temperature. Subjects' feet in the medium weight ensemble responded unacceptably warm at 24.3°CET* (75.7 FET*) and 26.0°CET* (78.8 FET*) since wearing shoes and socks as opposed to sandals which resulted in a more neutral response for the light weight ensemble.

The 80% level of thermal acceptance required by the ASHRAE Standard[5] was not reached by subjects in either ensemble at 22.8°CET* (72.7 FET*), although the unacceptance was minimal. The light weight ensemble was acceptable to 75% of the subjects and the medium weight ensemble to 78% of the subjects. More clothing insulation than 0.54 clo units is probably needed for 80% of the subjects to find 22.8°CET* (72.7 FET*) thermally acceptable. At 24.3°CET*

75.7 FET*), 94% of the males and 78% of the females found the light weight ensemble acceptable. This agrees with thermal sensation of body responses which indicated that females in the light weight ensemble were cooler than males. A higher percentage of females (83%) found the medium weight ensemble acceptable at 24.3°CET* (75.7 FET*) where a lower percentage of males (72%) found this ensemble less acceptable. The light weight ensemble was similarly and highly acceptable at 26.0°CET* (78.8 FET*) to 89% of the male and female subjects. Females (67%) found the medium weight ensemble least acceptable at this temperature.

Recommendations

Since the ASHRAE Standard, Thermal Environmental Conditions for Human Occupancy,[5] specifies that subjects wearing 0.5 clo units will find 22.8°CET* (72.7 FET*), 24.3°CET* (75.7 FET*), and 26.0°CET* (78.8 FET*) thermally acceptable, the following recommendations were made based upon the results of this research for a 90-minute exposure.

1. The clo value of 0.5 units should be increased for a more thermally acceptable response at 22.8°CET* (72.7 FET*) for males and females.

2. Females have been found to be generally more sensitive to cold than males at 22.8°CET* (72.7 FET*) and 24.3°CET* (75.7 FET*) so they should wear more clothing insulation.

3. Occupants should be encouraged to wear sandals instead of socks and shoes when summer indoor temperataures are 24.3°CET* (75.7 FET*) or higher.

4. Dress codes should be relaxed to discourage wearing summer suits in temperatures above 24.3°CET* (75.7 FET*). Companies or schools should examine more closely the wearing apparel of occupants in summer indoor environments to assure thermal comfort which will in turn foster work productivity and comfortable working conditions.

5. The ASHRAE summer comfort envelope temperatures should be extended upward for an 0.5 clo ensemble since subjects generally found 26.0°CET* (78.8 FET*) as an optimal temperature, not 24.3oCET* (75.7 FET*) as specified in the ASHRAE Standard.[5] This will clearly result in more energy savings for summer indoor temperatures.

Recommendations for Future Research

1. Examine the relationship of clothing insulation and temperature to the thermal comfort of male and female subjects in ASHRAE winter comfort envelope conditions.

2. Research how perceptive subjects are to the amount of clothing insulation worn in increments of 0.1 clo units, 0.2 clo units, etc.

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APPENDICES

APPENDIX A

MATERIALS USED TO RECRUIT AND ASSIGN TEST SUBJECTS

Recruitment Orientation Statement

The purpose of this study is to determine how people respond to their thermal environment. You should be fully aware that the conditions to which you will be exposed entail no physical risks. Second, you have volunteered to act as a subject and are participating on your own volition. Third, you may stop participating in the experiment if necessary. Fourth, your identity as a subject will not be disclosed and anonymity will be maintained.

Your participation will include 2 hours of your time on one occasion. During the first 30 minutes, you will dress in a clothing ensemble that will be provided for you. In the following 1½ hours, you will be seated in a test room, where you will be able to study or read. You can bring reading materials with you, although some will be provided. You may not sleep, walk about, or leave the room during the tests. At certain intervals you will be asked to complete ballots evaluating the temperature of the environment and your comfort. You also may be wearing 3 skin temperature sensors on your chest, calf, and arm to measure your skin temperature. You will be given 2 hours of experimentation credit for your participation.

If you decide to participate, fill out a yellow form which will be given to you by Institite personnel. Then sign up for a date and time when you can participate.

Announcement for Psychology Notice Board

Volunteers for an environmental research study are needed. Your participation will involve about 2 hours of your time. If you choose to participate in this study, you will receive 2 hours of experimentation credit in your general psychology class. You will be a volunteer and may stop participating in the experiment if necessary. Your identity as a subject will not be disclosed and anonymity will be maintained.

Come to the Institute for Environmental Research in Seaton Hall. Enter through the doorway by room 67, walk through the narrow corridor, turn left, and go up the stairs to the Institute office on the 2nd floor. Sign-up will be from 9:00 a.m. to 11:30 a.m. and 1:00 p.m. to 4:30 p.m. beginning August 31, 1981. Approximately 126 men and 126 women will be needed for this study. To insure your participation at a convenient time, sign up immediately.

PLEASE DON'T SIGN UP FOR THIS STUDY UNLESS YOU WILL COME TO THE TESTING SESSION. IT IS IMPERATIVE TO THE EXPERIMENT THAT YOU ARE PROMPT AND KEEP YOUR TESTING APPOINTMENT.

If you have questions, please call Amy Holzle at 539-2339 or 532-5620 or Dr. E. A. McCullough at 532-6993.

Female Subject Information Form

Please fill out this form and give it to the person in charge of registration. It is important that you give us complete and accurate information so that we may contact you before your tet appointment and assign you a clothing ensemble that will fit.

Test number________________________________ (filled out by researcher)

Subject number ____________________________ (filled out by researcher)

Name ____

Address (current) ____

Phone (current) ____

Garment Sizing Information:

Height _______________ Feet _____________ Inches

Weight _______________ Pounds

Shirt Size ___________ Misses

Slack Size ___________ Misses

Foot Length __________ Inches (a ruler to measure your bare foot may be found on the table)

Blazer _______________ Misses

If you have any questions or need help in sizing, please ask the person in charge of registration. Thank you for your cooperation.

To be filled out by researcher:

Shirt __________ Pant __________ Blazer __________ Sandal ___________

Male Subject Information Form

Please fill out this form and give it to the person in charge of registration. It is important that you give us complete and accurate information so that we may contact you before your test appointment and assign you a clothing ensemble that will fit.

Test number____________________ (filled out by researcher)

Subject number ____________________ (filled out by researcher)

Name ____

Address (current) ________________________________

Phone (current) __________________________________

Garment Sizing Information:

Height __________ Feet __________ Inches

Weight __________ Pounds

Shirt Size in Inches: Neck ________ Sleeve ________

Pant Size in Inches: Waist ________ Inseam ________

Blazer in Inches: Chest ________

Foot Length ________ Inches (a ruler to measure your bare foot may be found on the table)

If you have any questions or need help in sizing, please ask the person in charge of registration. Thank you for your cooperation.

To be filled out by researcher:

Shirt ________ Pant ________ Blazer ________ Sandal ________

Take-home Slip

Thank you for volunteering to participate in this study. You are scheduled to report to the Institute for Environmental Research for testing on the following day and time:

____________________ 1981 at ____________________

You will be tested in an environment maintained at an ordinary indoor temperature and will wear an ensemble of clothing which will be given to you at that time. You are to <u>wear your own tennis or track shoes and underwear</u> with the ensemble. It is important that you do not consume alcohol or drugs within 12 hours prior to the time you are scheduled for testing. You should plan to bring study or reading materials for the 1½-hour test.

APPENDIX B

MATERIALS USED DURING PRECONDITIONING PERIODS

Subject Identification Information

Test Number ____________________ Subject Number ____________________

Name ____

Thermistor Numbers

Chest ____________

Arm ______________

Leg ______________

Comments regarding ensemble fit:

Agreement and Release

1. I, ____

volunteer to participate in a project in connection with research studies to be conducted by Kansas State University.

2. I realize that participation may impose physical and/or mental stresses upon me and/or the other subjects. I believe that I am physically and mentally fit to withstand any such stresses.

3. I understand that I will be observed during my participation and that my conduct and/or voice may be recorded by photographic and/or recording devices. I may have attached to my person sensors to measure temperature. I also realize that public reports and articles may be made of the experiments and all of the observations, and I consent to publication of such, including the use of photographs.

4. I hereby authorize the Kansas State University to remove me from the evaluation exercise at any time and for any reason. I agree to leave the exercise willingly when asked to do so.

5. I understand that I will be permitted to leave the evaluation exercise at any time that I find that I am unable to withstand the conditions and request to be relieved.

6. I hereby agree, under penalty of forfeiture of all compensation due me, not to give information regarding these studies to any public news media not to publicize any articles or other accounts thereof without prior written approval by Kansas State University.

I have signed the herein Agreement and Release, this ________ day of ________________________, 1981.

____
Signature

Instruction to Subjects

On the opposite page are several pairs of adjectives that can be used to describe how the environment in this room feels to you. Look over the list of adjectives; then take a few minutes to get into the mood of the situation and then complete the ratings according to the following instructions:

If you feel that the environment can be described very closely by the adjective at one end of the scale you should place your checkmark as follows:

fair _✓_:____:____:____:____:____:____:____:____unfair
or
fair ____:____:____:____:____:____:____:____:_✓_unfair

If you feel that the environment can be described quite closely by the adjective at one or the other end of the scale (but not extremely) you should place your checkmark as follows:

strong ____:_✓_:____:____:____:____:____:____:____weak
or
strong ____:____:____:____:____:____:____:_✓_:____weak

If you feel that the environment can be described somewhat closely by the adjective at one or the other end of the scale you should make your checkmark as follows:

near ____:____:_✓_:____:____:____:____:____:____far
or
near ____:____:____:____:____:____:_✓_:____:____far

If you feel that the environment can be described only slightly by the adjective at one or the other end of the scale you should make your checkmark as follows:

active ____:____:____:_✓_:____:____:____:____:____passive
or
active ____:____:____:____:____:_✓_:____:____:____passive

If you feel that the environment can be described as neutral, or if the scale is completely irrelevant or unrelated to the environment, then you should place the checkmark as follows:

safe ____:____:____:____:_✓_:____:____:____:____dangerous

PLEASE:
1) Place your checkmark in the middle of the spaces.
2) Do not omit any.
3) Do not put more than one checkmark to a question.

Thermal Comfort Scale

Test Number ____________________ Subject Number ____________________

Name ____

According to the instructions on the previous page, place a check between each pair of adjectives at the location that describes how you feel.

___comfortable ___:___:___:___:___:___:___:___:___ uncomfortable___

bad ___temperature ___:___:___:___:___:___:___:___:___ good temperature___

___pleasant ___:___:___:___:___:___:___:___:___ unpleasant___

___cool ___:___:___:___:___:___:___:___:___ warm___

___unacceptable ___:___:___:___:___:___:___:___:___ acceptable___

uncomfortable ___temperature ___:___:___:___:___:___:___:___:___ comfortable temperature___

____satisfied ___:___:___:___:___:___:___:___:___ dissatisfied___

Would you like to be:

warmer cooler no change

Thermal Sensation Scale

Test Number ____________________ Subject Number ____________________

Name ____

Circle the number beside the adjective that best describes how you feel.

9 very hot
8 hot
7 warm
6 slightly warm
5 neutral
4 slightly cool
3 cool
2 cold
1 very cold

Circle the number beside the adjective that best describes how the following poarts of your body feel.

Hands	Feet	Face
9 very hot	9 very hot	9 very hot
8 hot	8 hot	8 hot
7 warm	7 warm	7 warm
6 slightly warm	6 slightly warm	6 slightly warm
5 neutral	5 neutral	5 neutral
4 slightly cool	4 slightly cool	4 slightly cool
3 cool	3 cool	3 cool
2 cold	2 cold	2 cold
1 very cold	1 very cold	1 very cold
Hands	Feet	Face

Orientation Statement in Preconditioning Room

The purpose of this study is to determine how people respond to their thermal environment. You should be fully aware that the conditions which you will be exposed to entail no physical risks. Second, you have volunteered to act as a subject and are participating on your own volition. Third, your identity as a subject will not be disclosed and anonymity will be maintained.

The way the test will proceed is this: Soon you will be taken into the test room next to us where you will remain for 1½ hours. While there you will be studying or reading and filling out test ballots. You may not talk, communicate with each other in any manner, sleep, walk about, or leave the room during the test. I will be present throughout the test to announce when to fill out ballots and collect them. Water, kleenex and magazines are available on a table in the test room.

Now, let's look on your clipboards. You should have signed the gold Agreement and Release form. You have examples of the two test ballots you will be using on your clipboard. Let's read the directions and look at the sample ballots now. (Read directions and first example, wait, and read last pointers.) Do you have any questions? Turn to the yellow practice ballots. You have a thermal comfort ballot and thermal sensation ballot. Let's read directions of the thermal sensation ballot. Fill out the yellow thermal comfort and thermal sensation practice ballots now. Are there any questions? You will be completing a thermal comfort and thermal sensation ballot every one-half hour. When you complete the third or last set of ballots, the test will be finished.

When you follow me or an assistant into the test room, you will be shown where to sit and how to connect your own thermistor cables to the color coded sockets on the wall next to your chair. When everyone has started studying the test will start. Do you have any questions?

Now the first 6 will come with me into the test room. The second 6 will follow the assistant who will show you where to sit.

APPENDIX C

THERMAL RESPONSE DATA

Table 18

Mean Thermal Sensations of Body, Face, Hands, and Feet

	N	Body	Face	Hands	Feet
Main Effects					
Temperature					
22.8°CET* (72.7 FET*)	72	4.35	4.88	4.79	4.81
24.3°CET* (75.7 FET*)	72	4.97	5.08	5.39	5.50
26.0°CET* (78.8 FET*)	72	5.24	5.42	5.39	5.85
Clothing Insulation					
0.54 clo ensemble	108	4.47	4.94	4.98	4.68
0.95 clo ensemble	108	5.23	5.31	5.40	6.09
Sex					
male	108	5.05	5.30	5.34	5.49
female	108	4.64	4.95	5.04	5.28

Table 19

Mean Thermal Comfort Scores and Weighted Mean Skin Temperatures

	N(TC)	Thermal Comfort	N(WMST)	Weighted Mean Skin Temperature °C (F)
Main Effects				
Temperature				
22.8°CET* (72.7 FET*)	72	70.63%	48	32.76 (90.96)
24.3°CET* (75.7 FET*)	72	74.64	48	33.40 (92.12)
26.0°CET* (78.8 FET*)	72	71.10	48	33.92 (93.05)
Clothing Insulation				
0.54 clo ensemble	108	76.35	72	32.90 (91.22)
0.95 clo ensemble	108	67.89	72	33.82 (92.88)
Sex				
male	108	70.12	72	33.47 (92.24)
female	108	74.12	72	33.25 (91.85)

Table 20

Mean Thermal Sensations of Body, Face, Hands, and Feet for First Order Interactions

	N	Body	Face	Hands	Feet
First Order Interactions					
Temperature x Clothing Insulation					
22.8°CET* (72.7 FET*) x 0.54 clo ensemble	36	3.94	4.78	4.61	4.03
22.8°CET* (72.7 FET*) x 0.95 clo ensemble	36	4.75	4.97	4.97	5.58
24.3°CET* (75.7 FET*) x 0.54 clo ensemble	36	4.67	4.89	5.19	4.81
24.3°CET* (75.7 FET*) x 0.95 clo ensemble	36	5.28	5.28	5.58	6.19
26.0°CET* (78.8 FET*) x 0.54 clo ensemble	36	4.81	5.14	5.14	5.19
26.0°CET* (78.8 FET*) x 0.95 clo ensemble	36	5.67	5.69	5.64	6.50
Temperature x Sex					
22.8°CET* (72.7 FET*) x male	36	4.64	5.06	5.11	4.83
22.8°CET* (72.7 FET*) x female	36	4.06	4.69	4.47	4.78
24.3°CET* (75.7 FET*) x male	36	5.36	5.47	5.67	5.83
24.3°CET* (75.7 FET*) x female	36	4.58	4.69	5.11	5.17
26.0°CET* (78.8 FET*) x male	36	5.19	5.36	5.25	5.81
26.0°CET* (78.8 FET*) x female	36	5.28	5.47	5.53	5.89
Clothing Insulation x Sex					
0.54 clo ensemble x male	54	4.61	4.96	5.07	4.78
0.54 clo ensemble x female	54	4.33	4.91	4.89	4.57
0.95 clo ensemble x male	54	5.52	5.63	5.61	6.20
0.95 clo ensemble x female	54	4.94	5.00	5.19	5.98

Table 21

Mean Thermal Comfort Scores and Weighted Mean Skin Temperatures for First Order Interactions

	N(TC)	Thermal Comfort	N(WMST)	Weighted Mean Skin Temperature ^{o}C (F)
First Order Interactions				
Temperature x Clothing Insulation				
22.8°CET* (72.7 FET*) x 0.54 clo ensemble	36	69.90%	24	32.23 (90.02)
22.8°CET* (72.7 FET*) x 0.95 clo ensemble	36	71.36	24	33.28 (91.91)
24.3°CET* (75.7 FET*) x 0.54 clo ensemble	36	77.40	24	32.94 (91.29)
24.3°CET* (75.7 FET*) x 0.95 clo ensemble	36	71.88	24	33.86 (92.95)
26.0°CET* (78.8 FET*) x 0.54 clo ensemble	36	81.77	24	33.52 (92.34)
26.0°CET* (78.8 FET*) x 0.95 clo ensemble	36	60.44	24	34.32 (93.77)
Temperature x Sex				
22.8°CET* (72.7 FET*) x male	36	66.19	24	33.05 (91.50)
22.8°CET* (72.7 FET*) x female	36	75.06	24	32.46 (90.43)
24.3°CET* (75.7 FET*) x male	36	73.47	24	33.42 (92.15)
24.3°CET* (75.7 FET*) x female	36	75.81	24	33.38 (92.01)
26.0°CET* (78.8 FET*) x male	36	70.71	24	33.93 (93.02)
26.0°CET* (78.8 FET*) x female	36	71.49	24	33.91 (93.03)
Clothing Insulation x Sex				
0.54 clo ensemble x male	54	78.45	36	33.02 (91.44)
0.54 clo ensemble x female	54	74.26	36	32.77 (90.99)
0.95 clo ensemble x male	54	61.79	36	33.91 (93.04)
0.95 clo ensemble x female	54	73.99	36	33.73 (92.71)

Table 22

Mean Thermal Sensations of Body, Face, Hands and Feet
for Second Order Interactions

	N	Body	Face	Hands	Feet
Second Order Interactions					
Temperature x Clothing Insulation X Sex					
22.8°CET* (72.7 FET*) x 0.54 clo x male	18	3.89	4.67	4.78	3.89
22.8°CET* (72.7 FET*) x 0.54 clo x female	18	4.00	4.89	4.44	4.17
22.8°CET* (72.7 FET*) x 0.95 clo x male	18	5.39	5.78	5.44	5.78
22.8°CET* (72.7 FET*) x 0.95 clo x female	18	4.11	5.39	4.50	5.39
24.3°CET* (75.7 FET*) x 0.54 clo x male	18	5.17	5.28	5.50	5.28
24.3°CET* (75.7 FET*) x 0.54 clo x female	18	4.17	4.33	4.89	4.33
24.3°CET* (75.7 FET*) x 0.95 clo x male	18	5.56	6.39	5.83	6.39
24.3°CET* (75.7 FET*) x 0.95 clo x female	18	5.00	6.00	5.33	6.00
26.0°CET* (78.8 FET*) x 0.54 clo x male	18	4.78	5.17	4.94	5.17
26.0°CET* (78.8 FET*) x 0.54 clo x female	18	4.83	5.22	5.33	5.22
26.0°CET* (78.8 FET*) x 0.95 clo x male	18	5.61	6.44	5.56	6.44
26.0°CET* (78.8 FET*) x 0.95 clo x female	18	5.72	6.56	5.72	6.56

Table 23

Mean Thermal Comfort Scores and Weighted Mean Skin Temperatures for Second Order Interactions

	N(TC)	Thermal Comfort	N(WMST)	Weighted Mean Skin Temperature °C (F)
Second Order Interactions				
Temperature x Clothing Insulation X Sex				
22.8°CET* (72.7 FET*) x 0.54 clo x male	18	70.33%	12	32.51 (90.51)
22.8°CET* (72.7 FET*) x 0.54 clo x female	18	69.46	12	31.96 (89.53)
22.8°CET* (72.7 FET*) x 0.95 clo x male	18	62.04	12	33.60 (92.48)
22.8°CET* (72.7 FET*) x 0.95 clo x female	18	80.67	12	32.96 (91.34)
24.3°CET* (75.7 FET*) x 0.54 clo x male	18	82.63	12	33.01 (91.41)
24.3°CET* (75.7 FET*) x 0.54 clo x female	18	72.17	12	32.86 (91.16)
24.3°CET* (75.7 FET*) x 0.95 clo x male	18	64.30	12	33.83 (92.89)
24.3°CET* (75.7 FET*) x 0.95 clo x female	18	79.46	12	33.90 (93.02)
26.0°CET* (78.8 FET*) x 0.54 clo x male	18	82.39	12	33.56 (92.40)
26.0°CET* (78.8 FET*) x 0.54 clo x female	18	81.14	12	33.48 (92.27)
26.0°CET* (78.8 FET*) x 0.95 clo x male	18	59.03	12	34.31 (93.76)
26.0°CET* (78.8 FET*) x 0.95 clo x female	18	61.85	12	34.32 (93.78)

Table 24

Results of Fisher's Least Significant Differences for Thermal Sensation of Body at a Given Temperature and Sex

22.8°CET* (72.7 FET*)	Female	Male
N	36	36
Mean	4.06	4.64

24.3°CET* (75.7 FET*)	Female	Male
N	36	36
Mean	4.58	5.36

26.0°CET* (78.8 FET*)	Male	Female
N	36	36
Mean	5.19	5.28

Means not underlined are significantly different at the 0.05 level.
LSD = 0.466

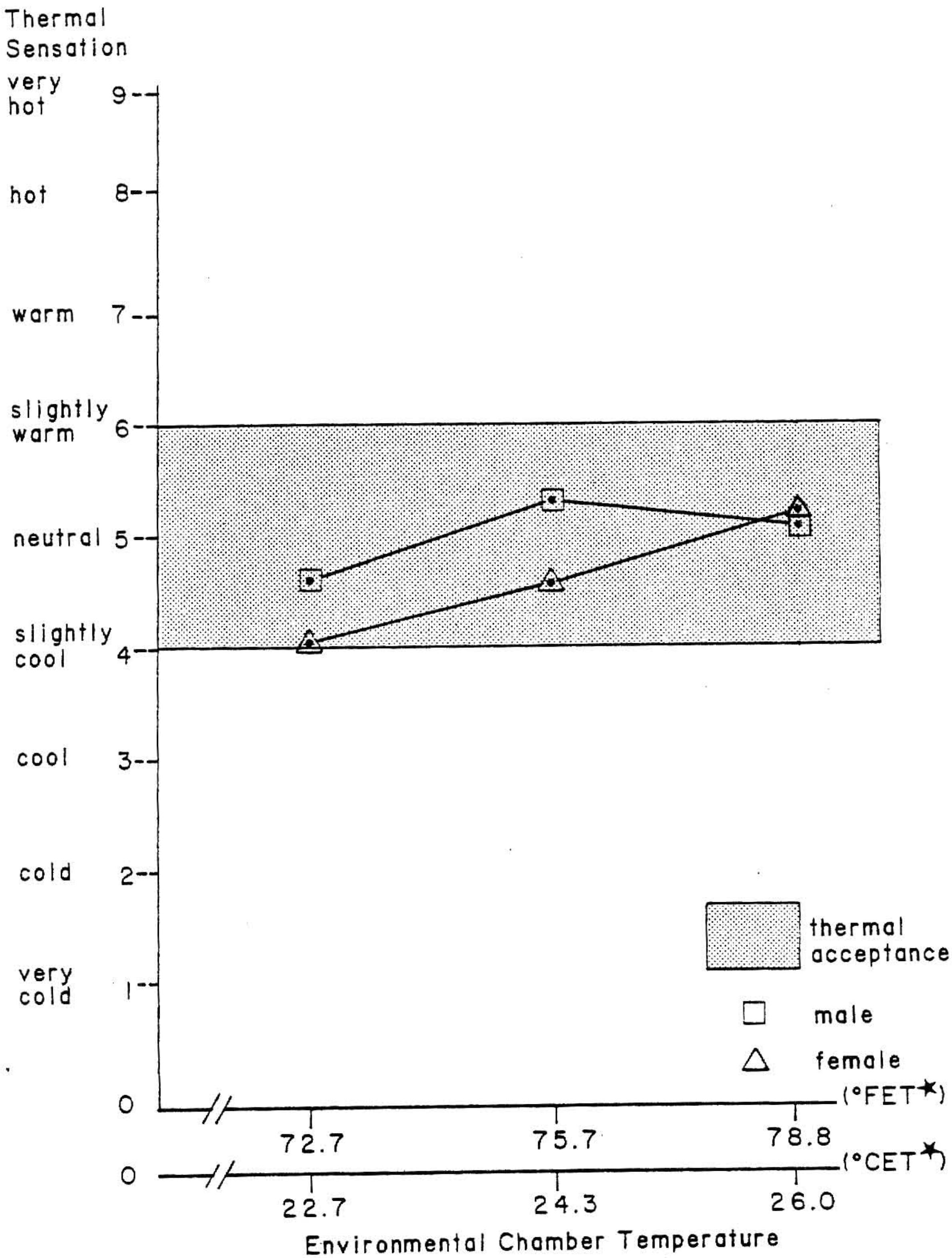

Figure 13 Mean thermal sensations of body at three environmental temperatures for males and females.

THE EFFECTS OF CLOTHING INSULATION AND TEMPERATURE ON THERMAL COMFORT

BY

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B. S., Kansas State University, 1975

AN ABSTRACT OF A MASTER'S THESIS

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ABSTRACT

The effect of clothing insulation and temperature on the thermal responses of male and female college students was investigated. A 3 x 2 x 2 factorial design was used. The independent variables were 1) three effective temperatures of 22.8°CET* (72.7 FET*), 24.3°CET* (75.7 FET*), and 26.0°CET* (78.8 FET*); 2) two levels of clothing insulation of 0.54 clo units (light weight ensemble) and 0.95 clo units (medium weight ensemble); and 3) sex (male and female). Temperatures were based on the thermal comfort summer envelope boundaries established by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE). The dependent variables of thermal response were measured using the 1) thermal sensation ballot for the body as a whole and for the hands, face, and feet; 2) thermal comfort ballot; and 3) weighted mean skin temperature. Subjects were tested for 90 minutes under controlled conditions in an environmental chamber and were provided clothing ensembles. Six test replications for each temperature were performed which yielded data for 216 test subjects.

Results based on Duncan's Multiple Range and ANOVA statistical tests indicated 1) subjects could perceive the difference in thermal insulation values of the light weight and medium weight clothing ensembles; 2) subjects could perceive the difference in temperatures of 22.8°CET* (72.7 FET*) and 24.3°CET* (75.7 FET*) or 26.0°CET* (78.8 FET*); and 3) males and females responded differently.

Results based on further statistical analysis of variable interactions using Fisher's LSD Test indicated the light weight

ensemble was acceptable in the summer envelope with the exception of females' weighted mean skin temperature and males' thermal sensation of body responses which were unacceptably cool at 22.8°CET* (72.7 FET*), but to a minimal extent. At 24.3°CET* (75.7 FET*) females were cooler than males in thermal sensation of hands, face, and body. Thermal comfort scores indicated the light weight ensemble was more desirable than the medium weight ensemble at 26.0°CET* (78.8 FET*). Subjects' feet in the medium weight ensemble were unacceptably warm at 24.3°CET* (75.7 FET*) and 26.0°CET* (78.8 FET*) due to the socks and shoes worn as opposed to sandals for the light weight ensemble.

Slightly less than 80% of the subjects wearing the light weight ensemble found 22.8°CET* (72.7 FET*) acceptable. This is below the minimum specified by the ASHRAE Standard, <u>Thermal Environmental Conditions for Human Occupancy</u>, but only minimally. The medium weight ensemble was slightly unacceptable to 80 percent or more of the subjects at any of the three temperatures. Subjects in the light weight ensemble found 26.0°CET* (78.8 FET*) sightly more acceptable compared to 24.3oCET* (75.7 FET*) specified in the ASHRAE Standard.[5]