No. 3044 (RP-353)

SUBJECTIVE HUMAN RESPONSE TO LOW-LEVEL AIR CURRENTS AND ASYMMETRIC RADIATION

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ABSTRACT

The responses of 50 subjects wearing winter clothing (0.86 clo) to two-hour-long exposures of various kinds of winter indoor conditions were studied. The conditions included air speeds between 0.05 and 0.5 m/s (10 and 100 fpm) and asymmetric radiation to a cold wall that produced radiant temperature asymmetries ranging from 0 to 20 K (0 to 36 F). The study was done at neutral or preferred temperatures and at conditions 3°C (5.4 F) lower. Some of the conclusions are: (1) The low mean radiant temperatures from the cold wall were compensated for by increased air temperature through the operative temperature concept. (2) The preferred operative temperature increased with air speed. (3) The level of occupant thermal acceptability at preferred temperatures was unaffected by air speeds of 0.25 m/s (50 fpm) or less or radiant asymmetries of 10 K (18 F) or less. (4) At air velocities greater than 0.25 m/s (50 fpm) the operative temperature determination procedure used seemed to overestimate radiation and underestimate convection. (5) Operative temperatures 3°C (5.4 F) less than the preferred temperature are probably too low for sedentary occupancy as acceptability levels were only about 60% in these tests and at air speeds greater than 0.15 m/s (30 fpm) the subjects did not reach equilibrium. That is, acceptability and comfort decreased with time.

INTRODUCTION

Thermal nonuniformities such as drafts, radiant asymmetry and vertical temperature differences in an otherwise thermally comfortable space may cause discomfort and detract from the environment. This study was undertaken to quantify the separate and additive effects of drafts and radiant asymmetry on sedentary people in neutral and cool environments. ANSI/ASHRAE Standard 55-81, "Thermal Environmental Conditions for Human Occupancy" (ASHRAE, 1981) recommends some limits on air movement and radiant asymmetry in order to limit local discomfort. The guidelines of the standard are based on separate draft and radiation studies conducted at thermally neutral conditions by Fanger (1977, 1978), McIntyre (1976), McNall and Biddison (1970), Rohles et al. (1974), Olesen et al. (1973), and Ostergaard et al. (1974). Previously studies have not been done on the combined effect of radiation and draft acting together in neutral environments, and there was little information on their separate effects in cool environments.

Drafts increase the local convective heat transfer on windward surfaces. Thus, skin temperature on the draft side may decrease and cause discomfort. Radiation to cold surfaces produces similar differences in skin temperature. The response of the two effects acting together could be greater than the sum of the separate effects. In a cool environment, peripheral blood vessels vasoconstrict to limit heat loss, and under this strain the responses to local cooling by radiation and draft could be more pronounced. It was therefore hypothesized that the human sensitivity to nonuniformities in cool environments is increased. That is, drafts and radiant asymmetries become more noticeable and detract more from the overall thermal acceptability of the space than in a neutral environment. The study was in response to ASHRAE work statement 353 and required two years to complete.

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FACILITIES

The testing was conducted in a climate chamber (Kjerulf-Jensen et al., 1975) where the air temperature (T_a), mean radiant temperature (T_r), and humidity are uniform and precisely controlled. A windbox with two 36-inch-diameter four bladed propellers driven by a quiet variable-speed electric motor is located along the center of one wall.

The chamber was modified for this study to produce controlled thermal nonuniformities. Two partition walls were extended from the windbox (Figure 1). One wall, capable of being cold, simulated the inside surface of a poorly insulated perimeter wall in winter and provided the required radiant temperature asymmetries (RTA). The other wall was a passive white cloth partition, whose temperature was close to the air temperature of the test zone. The cold wall was constructed from copper solar panels that were painted flat white and cooled with a refrigerated ethylene glycol water solution that flowed through the parallel tubes of the panels at a high rate. The desired surface temperature was achieved by automatically controlling the temperature of the entering water through mixing. Surface temperatures at nine uniformly dispersed locations were measured every minute with thermocouples, averaged, and displayed by an on-line microcomputer as well as the temperature of the entering and leaving glycol solution. The surface temperature of the pannel was very uniform. A gutter at the bottom of the cold wall collected and drained away any water that may have condensed on the cold surface.

Initial operation of the wall revealed that the cold vertical surface produced irritating drafts along the floor. To eliminate the cold drafts on the feet, the technique of Boje et al. (1948), who had done a similar experiment, was used. That is, a second floor of grates was constructed for the occupants 0.2 m (8 inches) above the true chamber floor. This configuration allowed the natural convective flow down the wall to occur when the wall surface was cooler than the ambient air, but the flow now continued through the grates without causing drafts on the feet of the occupants.

Occupant Location and Instrumentation

Up to four subjects were tested at one time. The test subjects sat in low- back chairs without arm rests at the locations shown in Figure 1. The chairs were arranged so subjects had radiation shape factors relative to the wall of 0.2 and 0.3, as calculated from the graphs of Fanger (1972). The orientation of the chairs was randomized.

A thermocouple tree at each end of the test corridor measured the air temperature at 0.1, 0.6, 1.1, and 1.7 m (4, 24, 43, and 67 inches) above the test floor. These temperatures were recorded every minute and averaged to determine the mean air temperature in the test space.

The mean radiant temperature (T_r) was calculated from (1) the average temperature of the cold wall and the subject's shape factor to it, (2) the shape factor to the surrounding test subjects and their estimated surface temperature and (3) the shape factor to the remaining surrounding surfaces, which were assumed to be at the average air temperature. In addition, and as a check, three black 0.15 m (6 inch) diameter globes were hung from the ceiling to have shape factors to the wall of 0.2 and 0.3 at a level 0.61 m (24") below the top of the cold wall. The mean radiant temperature experienced by the globes (T_{rg}) was determined from the globe temperatures, the temperature from radiation-shielded air temperature sensors next to the globes, and the air speed. This was continuously compared to the T_r calculated from surface temperatures. The differences were small, typically less than 1°C (1.8 F), with T_{rg} greater or equal to T_r.

Radiant temperature asymmetry was calculated for each subject location based on the measured surface temperature of cold wall and shape factors from ANSI/ASHRAE Standard 55-81. Periodically, the calculated radiant temperature asymmetry was compared to that determined from a net radiometer. The agreement was within 0.2 C (0.36 F).

Initial measurements were made with three matched omnidirectional anemometers to determine the average air speed in the unoccupied test space at different RPMs of the fan. The air movement for the test subjects was then controlled by regulating the RPM of the calibrated fan. In addition to the fan calibration, air movement measurements in the occupied space were made 0.3 m (12 in) upstream of subjects in the various seating locations at the 0.1, 0.6, and 1.1 m (4, 24, and 43 inch) level for each setting. Air motion fluctuations were also measured. The measured turbulence intensity values (standard deviation divided by mean velocity) of the test area are plotted in Figure 2.

The operative temperature (T_o) at each subject location was determined according to ANSI/ASHRAE Standard 55-81 from the nominal air speed and the local air and mean radiant temperatures.

CONDITIONS

Each subject experienced 32 different thermal environments. There were two operative temperatures: one at approximate thermal neutrality (N) that is, the persons cannot decide if the environment should be warmer or cooler, and the other at an operative temperature 3°C less then the neutral condition (N-3). The N-3 condition represents the probable lower limit of the acceptable zone for sedentary subjects. Four air speeds were employed at each of the two operative temperatures. The speeds were: V_1 = 0.05 m/s (10 fpm), which is essentially still air; V_2 = 0.15 m/s (30 fpm) which is the current upper limit of air speed for heating applications recommended by ASHRAE standard 55-81, V_3 = 0.25 m/s (50 fpm), the current upper limit for summer cooling recommended by standard 55-81; and V_4 = 0.5 m/s (100 fpm). Since air speed through convective heat transfer affects the temperature necessary for neutrality, the neutral temperature tended to increase with increasing air speed.

At each air speed and operative temperature, four different asymmetric radiant conditions were imposed on the subject. The asymmetry consisted of radiant heat loss to the cold wall on one side of the subject. This radiant effect was quantified with the radiant temperature asymmetry (RTA) concept defined in ASHRAE Standard 55-81. It is the maximum difference in mean radiant temperatures between the half spaces seen by a plane element looking in opposite directions. The plane element in this case was vertical, 0.6 m (24 inches) above the floor, with one side of the element for calculation or measurement purposes facing the cold wall and the other facing the opposite cloth wall. The radiant temperature asymmetries that the subjects experienced were: RTA = 0 K (0F), representing a radiantly uniform environment; RTA_2 = 5 K (9 F), which is the upper limit recommended by ASHRAE Standard 55-81 for radiant asymmetry in the vertical direction; RTA_3 = 10 K (18 F), the current maximum asymmetry recommended by Standard 55-81 in the horizontal direction; and RTA_4 = 17.6 K (31.7 F). For RTA_4, the refrigerated wall was operated at its coldest temperature (-3°C, 27 F). Since RTA depends on the temperature of the whole enclosure, RTA_4 was a little different for each air speed and temperature. It increased slightly with the higher air temperatures associated with the faster air speeds and ranged from 16.4 to 18.9 K (29.5-34 F).

The operative temperature is the average of the air and mean radiant temperatures experienced by the subject weighted by their respective heat transfer coefficients. The cold wall decreased the overall mean radiant temperature. This was compensated for by increasing the air temperature in order to maintain a constant operative temperature with increasing RTA.

The neutral operative temperature for the air speed and clothing level was initially chosen using ASHRAE 55-81. This starting value was changed if the mean thermal sensation vote or mean thermal preference vote after one hour indicated that it should be altered.

SUBJECTS

The test subjects were 25 men and 25 women from the New Haven area. Some of their physical characteristics are given in Table 1.

The subjects were paid $10 for each two-hour test; typically, they participated in two tests per day. The subjects wore their own clothing but were instructed to wear typical winter indoor clothing. Each day the insulation value of the clothing was estimated with the summation method of ASHRAE Standard 55-81. The average insulation of the test group was 0.86 clo with little difference between the men and women.

BALLOTS

Every half hour during the test, the subjective responses of the participants were gathered with the paper ballot of Figure 3. The ballot had six questions, which included the ASHRAE seven-point thermal sensation scale and four-point comfort scale. In addition, there were questions dealing with thermal preference, acceptability, draft, and local heating and cooling.

The comfort and thermal sensations were indicated by marking on the line. A continuous rather then discrete scale is helpful in decreasing response variance. The thermal preference question was included to complement the thermal sensation scale and to better identify neutrality.

The thermal acceptability question was included to quantify the overall effects of nonuniformity and the environment. The subjects judged whether the thermal environment would be acceptable or not as a real space. That is, if unacceptable, they would complain, leave, try to make a change, or suffer.

For the local heating/cooling question, the subjects indicated if some part of their anatomy felt warmer or cooler than the rest of the body and identified the part or parts. This question was included to identify specific subjective effects of the thermal nonuniformities of the space.

The draft question was not defined or limited to air movement. The occupants simply answered if they felt a draft or not.

At the end of each two-hour test, the subjects were asked to complete a second short questionnaire where they could indicate if they had experienced any local discomfort and, if so, where.

PROTOCOL

The subjects were arranged into groups of similar people, that is, young college men were grouped together, as were housewives, etc., and scheduled for testing. Groups typically consisted of four persons but occasionally were made up of only two. The schedule of tests was randomized as much as possible, though the first test was always some kind of a neutral condition. Each group usually participated in two consecutive two hour tests per day with a 15- to 20-minute break between tests. The subjects left the chamber during the break.

The subjects would arrive at least 15 minutes before the first test of the day and rest in a thermally neutral waiting area adjacent to the test chamber. Immediately upon entering the test space, the subjects completed the first ballot. The participants were instructed not to discuss how they voted or felt about the environment. The paper ballots were distributed and collected every half hour at each voting. The subjects varied their seating locations and orientations from test to test.

RESULTS

The purpose was to evaluate the relationships between the environmental and the subjective responses. The main factors were (1) operative temperature (N or N-3), (2) radiant asymmetry (RTA), and (3) air motion (v). Other factors were clothing insulation and time.

Operative temperature is an index temperature of the environment's potential for dry heat transfer. It depends on air temperature, mean radiant temperature, the convective heat transfer coefficient (and hence air velocity), and the radiant heat transfer coefficient. Therefore, the operative temperature factor in these experiments was not really independent of the two other main factors, air speed and RTA, which complicated the analysis.

The subjective responses evaluated are (1) thermal sensation (TS), (2) comfort (C), (3) temperature preference (TP), (4) thermal acceptability (TAC), (5) sensation of local coolness (LC), (6) sensation of local heating (LH), (7) perception of draft (D), and (8) local discomfort (LD).

Subjective responses were recorded from the five-vote periods of each two hour test. The records also contain the physical data corresponding to each voting period. For votes 2 through 5, the data stored are the values averaged over the 30 minutes preceding the vote. For the first vote, the physical data corresponds to the first 15 minutes of the test. These data are summarized in Tables 4 to 18 of the technical report (Berglund and Fobelets, 1985).

The air motion in the calculations and figures is specified as (1) the nominal air velocity (measured in the absence of subjects), and (2) the effective air velocity (measured 0.30 m, 12 inches, upstream of the subjects). In each analysis and figure, the air velocities utilized are specified.

An overview of the data can be seen in Figures 4 and 5, where the means of the test results gathered at nominal air speeds of 0.05 and 0.15 m/s (10 and 30 fpm) are plotted in Figure 4 and those for air speeds of 0.25 and 0.5 m/s (50 and 100 fpm) are displayed in Figure 5. It is seen that the results at neutral conditions (N), identified with solid lines, are fairly stable throughout the exposure period and are particularly so during the last hour. The subjective responses were less stable in the cool environments (N-3), particularly the thermal acceptability values of Figure 5, which tended to decrease steadily with time.

Subjective Responses versus Time

The human responses of thermal sensation, and thermal acceptability at votes 3, 4 and 5 are plotted against nominal air speed in Figures 6 and 7 to demonstrate the effect of time, or experiment duration, on response. There was little change in the thermal sensation and thermal acceptability vote values at neutral conditions (N) between votes 3, 4, and 5, but at the neutral minus 3°C (N-3) operative temperature conditions the votes changed progressively with time. Apparently, while thermal stability was achieved quickly at neutral conditions, the subjects at the N-3 conditions were continuing to lose body temperature after two hours. At the N-3 conditions, vote 4 typically was closer to vote 5 than vote 3, suggesting that they were approaching quasi-stability. Because of these temporal patterns of response, it was decided to confine the analysis of relationships between physical factors and responses to vote 5.

Subjective Responses versus Physical Factors

The results of vote 5 for all conditions are contained in Table 2 and plotted in Figures 8-19. Thermal sensation results are displayed in Figures 8 and 9. The thermal sensations for the neutral conditions reflect the success achieved in adjusting the air temperature in the test space to produce an average TS of 0. This success is mirrored in the thermal preference votes at neutral conditions in Figure 10. The responses to the N-3 conditions are similarly grouped but offset to cooler sensations and warmer preferences.

The comfort responses of vote 5 displayed in Figure 11 appear to be little affected by air velocity or radiant asymmetry. However, the thermal acceptability levels of Figures 12 and 13 were affected. At neutral conditions, increasing radiant asymmetry caused more of the subjects to judge the environment to be thermally unacceptable. Velocity had a somewhat similar but subdued effect. At the N-3 conditions, the 0.5 m/s (100 fpm) velocity was consistently the least acceptable (Figure 12) while the acceptability levels of the other air speeds were grouped together. Interestingly, at N-3 conditions the tests with maximum radiant asymmetry (RTA=16.5 K, 30 F) were the most acceptable (Figure 13). This response may be related to the increased air temperature required to maintain the operative temperature.

The percentage of persons experiencing local cooling is plotted in Figure 14. It is seen that increasing air speed did not typically increase the perception of local cooling. The percentage of persons feeling local cooling at the colder N-3 conditions were higher and the percentage increased linearly with increasing radiant asymmetry. The fraction of subjects experiencing local warming is plotted in Figure 15 for neutral conditions only, as local warming was rarely mentioned at the N-3 conditions. The warming response appears to increase linearly with RTA and to be independent of air motion. The local warming is likely related to the increased air temperature necessary to compensate for the lower mean radiant temperature caused by the RTA.

The frequency of experiencing a draft is displayed in Figures 16 and 17. The percentage of subjects reporting a draft sensation is seen to be linear with air speed for both the N and N-3 condition responses and having the same slope (Figure 16). The draft sensation was, however, independent of radiant asymmetry (Figure 17).

Local discomfort information was only gathered at vote 5 with a separate ballot. These results are given in Figures 18 and 19. The fraction reporting local discomfort was quite high, about 25% at N and 50% at N-3. The separate balloting may have encouraged the subjects to indicate discomfort. There was an increase in discomfort at RTAs above 10 K (18 F) and there was a slight increase with increasing air speed. The anatomical distribution of the discomfort and local cooling perceptions were similar. At neutral conditions, the few perceptions indicated were uniformly distributed, but at the N-3 conditions, the perceptions were typically associated with the hands, feet, legs, and trunk.

The effects of air motion on thermal sensation, acceptability, draft, and operative temperature can be seen in Figure 20 with the radiant asymmetry data pooled together at each velocity. The thermal sensation and acceptability levels remained relatively constant while operative temperature and the perception of draft increase with velocity. It appears that at 0.5 m/s (100 fpm) the operative temperature should have been higher as the thermal sensations are less than those at lower air speeds.

Figure 21 shows the effect of increasing RTA with all of the velocity data pooled at each RTA. Thermal sensation, acceptability, perception of draft and operative temperature are all approximately constant and independent of RTA.

Statistical Analysis and Regressions

A two-way analysis of variance was performed on the responses of the fifth vote at both the N and N-3 conditions to determine if there were velocity, RTA, and interaction effects. The analysis was done on the men only, the women only, and on the responses of the men and women combined. The model for the analysis of variance (ANOVA) is

$$Ysyz = M + Rs + A2y + A3z + (A2A3)yz + Esyz \qquad (1)$$

where Ysyz = subjective response corresponding to subject, s, air velocity, y, and RTA, z.
- M = average for all tests (50 subjects x 4 velocities x 4 RTAs)
- R = part of the response that is due to individual subjects
- A2 = part of the response due to the velocity effect
- A3 = part of the response due to the RTA effect
- A2A3 = part of the response due to interaction between velocity and RTA effects
- Esyz = random component (unexplained variance)

For the test of significance, the F-ratio (ratio of mean sum of squares of source to the error mean sum of squares) was compared to the 5% probability of the F distribution. The degrees of freedom for the ANOVA are shown below:

	Degrees of freedom	
Subjects	S-1	S=50 for all or 25 for men or women alone
Velocity	3	
RTA	3	
Interaction	9	
Error	15(S-1)	
Total	16S-1	

Results of all the tests for significance are summarized in Table 3.

The ANOVA shows that the interaction of velocity and RTA is not statistically significant for 29 of the 30 cases tested, which means that the subjective responses from velocity and RTA factors are simply additive. Table 3 also confirms that the sensations of draft are independent of radiant asymmetry. Student-Newman-Keuls (S-N-K) tests were run on those M+F items of the ANOVA table that were significant to learn where the differences were, and these results are summarized in Table 4.

The statistical model used to quantify the regressions is as follows:

$$Y = a(0) + a(1)*v + a(2)*RTA + a(3)*v*RTA \qquad (2)$$

where Y = psychophysical response
v = air velocity (effective velocity) (m/s)
RTA = radiant temperature asymmetry (K)

The fourth term of the sum represents the interaction between the velocity and RTA factors. The objective of the comparison as stated is to compare the relationship above at the two levels of operative temperature. Operative temperature is not included as such in the model because it is itself dependent on the air velocity. The regressions were made on the last or 5th vote. The regression equations and a(i) coefficients determined for the various subjective responses and conditions are listed in Table 5.

One can see with these regression equations that there were response differences between the men and women. The regression results for thermal acceptability have perhaps the most practical value of those listed in Table 5, as the effects of air motion and radiant asymmetry on acceptability are nicely quantified at N and N-3 conditions.

In multiple regression through all subjects, the coefficients of multiple correlation are quite low (TS:R=0.26), even though the factors were shown to be statistically significant. The major reason for this result is that the effects of air velocity and radiant temperature were compensated for by an increase in air temperature. Therefore, the range of subjective responses investigated was very narrow.

Relationships between the Subjective Responses

In the previous sections, the relationship between the environmental factors of the experiment and the resulting subjective responses were analyzed. This section looks at how some of the subjective responses are interrelated. For example, Figure 22 shows that the relationship between the thermal sensations and thermal preferences of the subjects was linear. The linearity is unaffected by air speed or radiant asymmetry. This figure further reveals the irony and difficulty in adjusting an environment to subjective neutral conditions, for according to the regression equation, when thermal sensation was 0, a net 10.5% of the particpants would have preferred the temperature warmer. Conversely, when the thermal preference was zero, meaning they wished no change, the mean thermal sensation was +0.21. The popular definition of "neutral" as a condition where one can not decide if it should be warmer or cooler did not quite work for these subjects.

Similar to Figure 22, air speed and RTA had no noticable effect on the relationships between comfort and thermal sensation and between comfort and thermal preference, as seen in Figures 23 and 24. Thus, the subjects were very consistent in their feelings and judgements.

The fraction of participants judging the environment to be thermally acceptable was linearly related to the group's mean comfort sensation. From the regression, "comfortable" corresponds to 100% acceptability while "slightly uncomfortable" corresponds to only 57% acceptability. Again, the relationship was independent of air motion and radiant asymmetry.

DISCUSSION

Operative Temperature

The neutral conditions of this test series were achieved by adjusting the air temperature during each two hour test until the thermal sensation and thermal preference were approximately zero. Figure 22 revealed that for the 50 subjects of this study, a zero thermal sensation did not coincide exactly with zero thermal preference. A contributing difficulty, as Rohles and Nevins (1968) and others have demonstrated, is that subject responses change with time, particularly during the early stages of a constant condition test. In addition, Griffiths and McIntyre (1974) and Berglund and Gonzales (1978) have shown that people are rather insensitive to small thermal changes. Therefore, it is not too surprising that thermal sensation and thermal preference results at vote 5 frequently did not equal zero. In future experiments of this nature, it would be advisable to keep both T_a and T_r constant with time; then all of the variability would be in the subjective response to the fixed condition.

The operative temperature (T_o) of the test environment was calculated from the mean radiant and air temperatures using the operative temperature equation of ASHRAE Standard 55-81. The resulting operative temperatures for the different levels of radiant temperature asymmetry at a given air speed were approximately equal, as seen in Figures 9 and 10 for example. This is particularly true for RTA equal or less than 10 K (18 F) and velocities of 0.25 m/s (50 fpm) or less. Figures 16 and 22 show that thermal acceptability declines sharply for RTA above 10 K (18 F), and in Figure 18 local discomfort at neutral conditions increases strongly at maximum RTA. The discomfort and unacceptability likely complicates the subject's determination of neutrality. At air speeds of 0.5 m/s (100 fpm), T_o decreases as RTA increases (Table 8 and Figures 39-41 of technical report (Berglund and Fobelets, 1985)) making the operative temperature equation suspect at this speed. Therefore, in order to determine the probable true neutral operative temperatures of these tests, the T_os from tests where RTAs were maximum were eliminated from consideration. Further, only the T_os of tests where either the absolute values of thermal preference and thermal sensation were equal or less than 0.1 and 0.15, respectively, were used. The T_os from votes 3, 4, and 5 that meet these requirements are averaged in Table 6 for each air speed. For comparison, the optimal operative temperature for winter according to ASHRAE Standard 55-81 is 21.7°C (71 F) for sedentary persons wearing 0.9 clo (the clothing of this study averaged 0.86 clo) at an air speed of 0.15 m/s (30 fpm) or less.

The results indicate that the calculation of operative temperature from air and mean radiant temperatures at the higher air speeds was not completely correct. Radiant asymmetry actually improved the comfort and acceptability of the 0.5 m/s (100 fpm) environment, particularly at N-3 conditions.

Using the subjective thermal sensation data from this experiment, one can determine the contribution to TS made by T_a and T_r and in that way deduce the effective T_o equation for each velocity. By definition operative temperature is:

$$T_o = (hc/(hc+hr))*T_a + (hr/(hc+hr))*T_r \tag{3}$$

or

$$T_o = A*T_a + (1-A)*T_r \tag{4}$$

where hc and hr are the convective and linearized radiant heat transfer coefficients for the human body. Thermal sensation (TS) in cool and neutral environments is linearly related to operative temperature:

$$TS_a = a(0) + a(1)*T_o \tag{5}$$

substituting the definition of T_o into the expression for TS above:

$$TS_b = b(0) + b(1)*T_a + b(2)*T_r \tag{6}$$

The coefficients of equation 5 were evaluated at each velocity by linear regression of the N and N-3 data for RTA = 0 or $T_a = T_r = T_o$. The results are given in Table 7. The same can be done for equation 6 using all of the test conditions. The coefficients for equation 6 are also given in Table 7. The a(0) and b(0) values are about the same as are the R values. When $T_a = T_r = T_o$, TS equation 6 becomes:

$$TS = b(0) + (b(1) + b(2))*T_o \tag{7}$$

Then equating equations 6 and 7 and solving for T_o:

$$T_o = (b(1)/(b(1) + b(2)))*T_a + (b(2)/(b(1) + b(2)))*T_r \qquad (8)$$

where b(1)/(b(1)+b(2)) = A and b(2)/(b(1)+b(2)) = 1-A. These values of A designated A-TS are tabulated in Table 7 along with those from ASHRAE Standard 55-81, which are designated A-ASHRAE. Because the R values of the regressions were not high, the validity of the A-TS values found in this study is limited. The thermal sensation data at any velocity was collected at only two conditions (N and N-3) and this limited range may have contributed to the low R. Also by definition, operative temperature is defined in terms of dry heat transfer, not thermal sensation. It is interesting that the A of 0.68, based on TS, found by McNall and Biddison (1970) in a similar study with velocity in the 0.10 - 0.15 m/s (20-30 fpm) range agrees well with that determined through this TS analysis. The hc values that are implied from the A term (calculated with hr = 3.8 W/°Cm^2) are also compared to those of the ASHRAE standard in Table 7. In addition, Table 7 lists the neutral operative temperatures found experimentally (Table 6) by regression through only the RTA=0 data (TS_a), by regression through all data TS_b, and from ASHRAE Standard 55-81.

Generalizations and Comparisons

Figure 25 shows the generalized relationships for the percentage of occupants judging the environment to be thermally acceptable. Since the differences in the responses, at N for a given air speed, to RTAs of 10 or less are small and random, these are averaged together in the figure. However, the maximum RTA caused thermal acceptability to decrease about 7% and is shown separately. These findings support ASHRAE Standard 55-81, which recommends that RTAs in the horizontal direction not exceed 10 K (18 F). Studies by Fanger et al (1986) lead to a similar recommendation. At N-3 conditions, the space is so thermally unacceptable that RTA effects are not distinct. The acceptability at 0.5 m/s (100 fpm) was lower in both N and N-3 conditions and for all RTA. The acceptability responses at the slower air speeds of 0.05, 0.15, and 0.25 m/s (10, 30, and 50 fpm) were nearly the same.

The percentage of the occupants who felt local cooling (LC_N and LC_{N-3}) was independent of air speed and is a linear function of RTA (Figure 14).

In contrast to the local cooling perceptions, the percentage of persons experiencing a draft was independent of RTA and strongly related to air speed (R = 0.95), as shown in Figure 26. The N and N-3 draft response lines are almost parallel with the responses at the cooler N-3 conditions being slightly more sensitive to air motion. Also plotted on the figure are data from a recent draft study by Fanger and Christensen (1986). This was a study of drafts to the head and neck, as were others by McIntyre (1979) and Houghton (1938). The agreement between the percent dissatisfied values of Fanger at neutral conditions and this study is reassuring, even though the questionnaires and procedures were different in the two studies. The turbulence intensity levels were also different, with turbulence being much less in the present study. The subjects of the Fanger study were very adept at detecting air motion, though typically only about one-third of those found the air motion unacceptable. These results imply that the perceptions of local cooling and draft are distinct and separable.

Even at still air conditions (air speeds of 0.05 m/s (10 fpm)) some subjects indicated that they experienced a draft. If these still air draft responses are subtracted from those at higher air speeds, the result would represent the percentage experiencing a draft (PED) due to air movement only. Such results and the multiple linear regression through them are plotted in Figure 27.

$$PED = 113\ (v-0.05) - 2.15\ T_a + 46 \qquad r^2=0.84 \qquad (9)$$

Also drawn on Figure 27 are Fanger and Christensen's (1986) loci of the percentage dissatisfied (PD) due to a draught from air movement which are curvi-linear and more sensitive to temperature.

$$PD = 13800\ [((v-0.04)/(Ta-13.7) + 0.0293)^2 - 0.000857] \qquad (10)$$

Notice that two PED data points at 19°C agree well with the PD formulation.

CONCLUSIONS

The following conclusions can be drawn from this study:

The operative temperature concept for combining air and mean radiant temperatures into a single temperature scale is an effective means of characterizing and controlling complex environments, although the coefficient A in the operative temperature equation of ASHRAE Standard 55-81 may be too low at high air speeds.

The neutral operative temperature, calculated according to ASHRAE Standard 55-81 from the experimentally determined neutral conditions, for velocities of 0.25 m/s (50 fpm) or less were unaffected by radiant temperature asymmetries of 10 K (18 F) or less.

Thermal acceptability at neutral conditions was unaffected by air speeds of 0.25 m/s (50 fpm) or less and RTAs of 10 K (18 F) or less.

Thermal acceptability decreased when radiant temperature asymmetry increased beyond 10 K (18 F).

Thermal acceptability decreased when air speed increased from above 0.25 m/s (50 fpm) even at neutral conditions.

An operative temperature 3°C less than neutral is probably too low for human sedentary occupancy as thermal acceptance of such conditions was only 63% in this study.

There were differences in the subjective responses between the men and women of this study.

The perception of draft was a linear function of air speed and temperature and independent of radiant temperature asymmetry.

The sensation of local cooling was related to RTA and independent of air speed.

There was no interaction between velocity and RTA on the subjective responses of this study. That is, effects from velocity and radiant asymmetry are independent and additive.

Relationships were found relating thermal sensation with thermal preference, comfort, and thermal acceptability.

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TABLE 1

Test Subject Characteristics

	Age yrs	Weight kg	Height m	Clo Clo	Skin Area m^2	Kg/m^2 skin kg/m^2
Males (25)						
Average	25.92	74.12	1.76	0.85	1.89	38.93
St. err.	1.40	2.36	0.01	0.01	0.03	0.62
Minimum	18.	54.	1.62	0.69	1.56	34.10
Maximum	38.	104.	1.87	1.03	2.27	47.28
Females (25)						
Average	32.52	60.76	1.62	0.86	1.63	36.90
St. err.	1.44	1.95	0.01	0.01	0.03	0.70
Minimum	19.	43.	1.52	0.74	1.40	30.61
Maximum	41.	81.	1.76	0.94	1.84	44.06
Males and Females (50)						
Average	29.22	67.44	1.69	0.86	1.76	37.96
St. err.	1.10	1.79	0.01	0.01	0.03	0.48
Minimum	18.	43.	1.52	0.69	1.40	30.61
Maximum	41.	104.	1.87	1.03	2.27	47.28

TABLE 2

The Means and Standard Deviations of the Means of Environmental Parameters and Subjective Responses of All 50 Subjects at Vote 5

Vote # 5

Test	Air temp. Mean/s.e.	Mean rad. Mean/s.e.	Oper. temp Mean/s.e.	Rad. asymm. Mean/s.e.	Dew pt. Mean/s.e.	Air veloc. Mean/s.e.	Th. sens. Mean/s.e.	Comfort Mean/s.e.	Th. pref. Mean/s.e.	Th. accept Mean/s.e.	L.cool	L.warm Mean/s.e.	Draft (%)	L.disc
AAA	21.22/0.06	21.59/0.05	21.43/0.05	-0.31/0.02	6.73/0.63	0.06/0.01	-0.19/0.10	+0.26/0.06	+0.26/0.07	+0.92/0.04	42/ 7	2/ 2	20/ 6	30/ 7
AAB	22.40/0.08	20.75/0.06	21.44/0.07	5.22/0.04	6.14/0.31	0.05/0.01	+0.26/0.11	+0.22/0.05	-0.02/0.07	+0.94/0.03	16/ 5	2/ 2	10/ 4	18/ 5
AAC	23.85/0.08	20.22/0.07	21.92/0.07	10.44/0.06	5.68/0.34	0.05/0.01	+0.46/0.12	+0.17/0.05	-0.12/0.06	+0.94/0.03	30/ 7	8/ 4	6/ 3	22/ 6
AAD	25.76/0.10	19.04/0.07	22.89/0.09	18.64/0.09	4.93/0.25	0.02/0.00	+0.23/0.10	+0.36/0.07	-0.12/0.07	+0.84/0.05	50/ 7	24/ 6	28/ 6	46/ 7
ABA	21.71/0.06	22.01/0.07	21.88/0.07	-0.31/0.02	5.24/0.30	0.12/0.00	-0.32/0.11	+0.29/0.07	+0.24/0.08	+0.92/0.04	28/ 6	4/ 3	30/ 7	26/ 6
ABB	22.69/0.07	21.00/0.07	21.71/0.07	5.25/0.05	5.34/0.26	0.12/0.00	+0.26/0.12	+0.16/0.05	+0.02/0.07	+0.96/0.03	24/ 6	6/ 3	14/ 5	28/ 6
ABC	23.54/0.07	20.27/0.07	21.79/0.07	9.95/0.06	5.05/0.19	0.12/0.00	+0.11/0.12	+0.22/0.07	+0.06/0.07	+0.96/0.03	26/ 6	0/ 0	24/ 6	22/ 6
ABD	25.23/0.09	18.73/0.06	22.46/0.07	18.36/0.10	4.41/0.09	0.12/0.00	+0.32/0.11	+0.14/0.04	-0.04/0.06	+0.92/0.04	46/ 7	8/ 4	22/ 6	38/ 7
ACA	22.29/0.08	22.49/0.08	22.41/0.08	-0.21/0.02	4.94/0.19	0.19/0.00	-0.13/0.11	+0.32/0.07	+0.14/0.08	+0.92/0.04	26/ 6	0/ 0	36/ 7	34/ 7
ACB	23.04/0.08	21.30/0.07	22.03/0.07	5.20/0.05	5.83/0.28	0.20/0.00	+0.12/0.13	+0.14/0.05	+0.02/0.06	+0.94/0.03	12/ 5	0/ 0	34/ 7	26/ 6
ACC	23.86/0.07	20.42/0.07	22.02/0.07	10.10/0.06	5.12/0.13	0.19/0.00	+0.15/0.13	+0.26/0.07	+0.06/0.08	+0.88/0.05	22/ 6	6/ 3	26/ 6	26/ 6
ACD	25.59/0.09	18.96/0.06	22.76/0.08	18.48/0.12	4.82/0.13	0.22/0.01	+0.34/0.14	+0.37/0.07	-0.08/0.08	+0.84/0.05	50/ 7	14/ 5	30/ 7	48/ 7
ADA	22.95/0.07	23.07/0.06	23.02/0.07	-0.14/0.01	6.35/0.31	0.40/0.01	-0.49/0.12	+0.45/0.10	+0.28/0.08	+0.88/0.05	30/ 7	0/ 0	70/ 7	38/ 7
ADB	23.53/0.08	21.70/0.07	22.46/0.07	5.40/0.05	4.97/0.16	0.41/0.01	-0.08/0.12	+0.31/0.07	+0.20/0.07	+0.90/0.04	40/ 7	2/ 2	62/ 7	40/ 7
ADC	24.15/0.06	20.69/0.07	22.31/0.06	10.07/0.06	5.19/0.18	0.41/0.01	-0.02/0.12	+0.25/0.08	+0.14/0.07	+0.86/0.05	28/ 6	2/ 2	58/ 7	38/ 7
ADD	25.16/0.09	18.72/0.06	22.42/0.07	18.10/0.09	6.08/0.70	0.43/0.01	+0.17/0.15	+0.43/0.09	+0.04/0.09	+0.80/0.06	56/ 7	10/ 4	62/ 7	42/ 7
BAA	18.09/0.05	18.74/0.05	18.46/0.05	-0.39/0.02	5.05/0.14	0.07/0.01	-1.37/0.15	+1.13/0.15	+0.72/0.06	+0.56/0.07	44/ 7	0/ 0	22/ 6	50/ 7
BAB	19.50/0.05	18.14/0.05	18.71/0.05	5.17/0.04	5.35/0.20	0.07/0.01	-1.07/0.12	+0.90/0.11	+0.72/0.06	+0.66/0.07	56/ 7	0/ 0	28/ 6	58/ 7
BAC	20.75/0.08	17.53/0.07	19.05/0.07	10.15/0.06	5.94/0.65	0.06/0.01	-0.88/0.14	+0.80/0.12	+0.62/0.07	+0.68/0.07	54/ 7	0/ 0	36/ 7	46/ 7
BAD	22.26/0.10	16.47/0.06	19.80/0.08	16.65/0.15	4.98/0.15	0.02/0.00	-0.78/0.13	+0.60/0.09	+0.48/0.08	+0.66/0.07	68/ 7	4/ 3	36/ 7	52/ 7
BBA	18.57/0.09	19.12/0.07	18.88/0.08	-0.30/0.05	5.29/0.23	0.12/0.00	-1.25/0.14	+0.95/0.13	+0.68/0.07	+0.56/0.07	52/ 7	0/ 0	44/ 7	50/ 7
BBB	19.56/0.07	18.23/0.06	18.79/0.06	4.98/0.05	4.80/0.11	0.12/0.00	-0.91/0.15	+0.72/0.12	+0.56/0.07	+0.68/0.07	58/ 7	0/ 0	44/ 7	44/ 7
BBC	20.46/0.08	17.46/0.06	18.86/0.07	9.90/0.07	5.04/0.09	0.12/0.00	-1.09/0.14	+0.89/0.13	+0.62/0.07	+0.68/0.07	64/ 7	0/ 0	40/ 7	44/ 7
BBD	21.69/0.08	16.17/0.06	19.35/0.07	16.28/0.11	4.79/0.10	0.12/0.00	-0.74/0.14	+0.71/0.11	+0.50/0.07	+0.66/0.07	72/ 6	4/ 3	38/ 7	56/ 7
BCA	19.26/0.08	19.67/0.08	19.49/0.08	-0.17/0.05	5.17/0.20	0.19/0.00	-1.19/0.13	+0.90/0.11	+0.74/0.06	+0.52/0.07	64/ 7	0/ 0	72/ 6	46/ 7
BCB	20.04/0.07	18.54/0.07	19.17/0.07	5.19/0.03	5.13/0.19	0.19/0.00	-1.06/0.14	+0.86/0.13	+0.60/0.07	+0.68/0.07	48/ 7	0/ 0	58/ 7	40/ 7
BCC	20.77/0.09	17.60/0.08	19.09/0.08	10.00/0.06	4.91/0.15	0.19/0.00	-1.17/0.16	+1.01/0.13	+0.64/0.08	+0.48/0.07	70/ 7	0/ 0	52/ 7	50/ 7
BCD	22.13/0.10	16.47/0.06	19.74/0.08	16.44/0.15	4.74/0.13	0.22/0.01	-0.57/0.14	+0.55/0.11	+0.42/0.07	+0.76/0.06	66/ 7	10/ 4	48/ 7	48/ 7
BDA	19.70/0.08	20.09/0.07	19.92/0.07	-0.19/0.01	5.09/0.19	0.40/0.01	-1.43/0.15	+1.29/0.14	+0.78/0.06	+0.50/0.07	52/ 7	0/ 0	94/ 3	54/ 7
BDB	20.45/0.07	18.90/0.07	19.55/0.07	5.27/0.06	4.83/0.15	0.41/0.01	-1.27/0.15	+1.09/0.15	+0.68/0.07	+0.54/0.07	56/ 7	2/ 2	82/ 5	52/ 7
BDC	21.11/0.08	17.96/0.06	19.43/0.07	9.90/0.07	4.94/0.12	0.41/0.01	-1.52/0.14	+1.28/0.13	+0.84/0.05	+0.46/0.07	64/ 7	0/ 0	88/ 5	60/ 7
BDD	21.95/0.09	16.37/0.06	19.59/0.07	16.31/0.12	4.41/0.15	0.43/0.01	-1.35/0.14	+1.14/0.14	+0.72/0.06	+0.50/0.07	76/ 6	0/ 0	78/ 6	60/ 7

TABLE 3

Significance of the F-Ratio from the ANOVA on Subjective Responses of Vote 5

Response	To	Group	Velocity	RTA	Interaction
TS	N	M+F	*	*	-
		M	-	*	-
		F	*	*	-
	N-3	M+F	*	*	*
		M	*	*	-
		F	*	*	-
Comfort	N	M+F	*	*	-
		M	*	*	-
		F	*	*	-
	N-3	M+F	*	*	-
		M	*	*	-
		F	*	*	-
Thermal pref	N	M+F	*	*	-
		M	-	*	-
		F	*	*	-
	N-3	M+F	*	*	-
		M	*	*	-
		F	*	*	-
Accept-ability	N	M+F	*	*	-
		M	-	*	-
		F	*	-	-
	N-3	M+F	*	*	-
		M	-	-	-
		F	*	*	-
Draft	N	M+F	*	*	-
		M	*	-	-
		F	*	-	-
	N-3	M+F	*	-	-
		M	*	-	-
		F	*	-	-

* Indicates significant difference at 5% level

TABLE 4

Results of S-N-K Tests on the Significant M+F Items in the ANOVA Summary of Table 3

Neutral Conditions

Response	Velocity	RTA
TS	0.50 0.15 0.25 0.05	0 5 10 20
Comfort	0.15 0.05 0.25 0.50	5 10 20 0
Thermal pref	0.05 0.25 0.15 0.50	20 10 5 0
Acceptability	0.50 0.25 0.05 0.15	20 0 10 5
Draft	0.05 0.15 0.25 0.50	10 5 20 0

N-3 Conditions

Response	Velocity	RTA
TS	0.50 0.05 0.15 0.25	0 10 5 20
Comfort	0.15 0.25 0.05 0.50	20 5 10 0
Thermal pref	0.15 0.25 0.05 0.50	20 5 10 0
Acceptability	0.50 0.25 0.05 0.15	0 10 5 20
Draft	0.05 0.15 0.25 0.50	20 5 10 0

Underlined values are statistically equal. Lowest treatment (velocity or RTA) mean on left.

TABLE 5

Multiple Regression Results

$$Y = a(0) + a(1)*v + a(2)*RTA + a(3)*v*RTA$$

Response	To	Group	a(0)	a(1)	a(2)	a(3)	R
TS	N	M+F	-0.026	-0.635	0.027	--	0.26
		M	-0.097	--	0.017	--	0.20
		F	0.033	-1.196	0.036	--	0.32
	N-3	M+F	-1.190	-0.487	0.034	-0.051	0.28
		M	-0.822	-0.591	0.017	--	0.22
		F	-1.394	-1.240	0.031	--	0.31
Comfort	N	M+F	0.200	0.338	0.001	--	0.11
		M	0.128	0.144	0.007	--	0.14
		F	0.274	0.516	-0.005	--	0.17
	N-3	M+F	0.880	0.877	-0.016	--	0.25
		M	0.633	0.494	-0.009	--	0.17
		F	1.131	1.251	-0.023	--	0.32
Therm. pref	N	M+F	0.110	0.382	-0.014	--	0.24
		M	0.107	--	-0.009	--	0.15
		F	0.157	0.532	-0.019	--	0.31
	N-3	M+F	0.660	0.349	-0.011	--	0.20
		M	0.592	0.293	-0.011	--	0.18
		F	0.729	0.404	-0.010	--	0.24
Accept	N	M+F	0.958	-0.136	-0.004	--	0.12
		M	0.965	--	-0.006	--	0.16
		F	0.934	-0.236	--	--	0.12
	N-3	M+F	0.631	-0.357	0.005	--	0.15
		M	0.663	--	--	--	N.A.
		F	0.564	-0.480	0.009	--	0.22

TABLE 6

True Neutral Operative Temperatures

m/s	abs(TP) ≤ 0.1 vote 3	4	5	ave	abs(TS) ≤ 0.15 vote 3	4	5	ave	Grand Average
0.05	21.5	21.7	21.4	21.6	21.5	21.5	--	21.5	21.5
0.15	21.8	21.8	21.6	21.8	--	21.8	21.8	21.8	21.8
0.25	22.2	22.1	22.0	22.1	22.4	22.2	22.2	22.3	22.2
0.50	22.4	22.4	--	22.4	22.5	22.5	22.4	22.5	22.4

TABLE 7

Linear Regressions of Thermal Sensation

$$TS_a = a(0) + a(1)*T_o$$

Velocity	a(0)	a(1)	R	T_o @ TS = 0
0.05	-7.292	0.3328	0.503	21.9
0.15	-7.242	0.3273	0.504	22.1
0.25	-6.676	0.2937	0.463	22.7
0.50	-6.944	0.2845	0.447	24.4

$$TS_b = b(0) + b(1)*T_a + b(2)*T_r$$

Velocity	b(0)	b(1)	b(2)	R	T_o @ TS = 0	A-TS
0.05	-8.264	0.2068	0.1756	0.57	21.6	0.54
0.15	-6.870	0.2214	0.0844	0.50	22.5	0.72
0.25	-7.214	0.2365	0.0790	0.48	22.9	0.75
0.50	-9.508	0.3085	0.0940	0.57	23.6	0.77

Comparisons

Velocity	A-TS	A-ASHRAE	hc	hc-ASHRAE
0.05	0.54	0.42	4.5	2.9
0.15	0.72	0.42	9.8	2.9
0.25	0.75	0.49	11.4	4.1
0.50	0.77	0.58	12.7	5.9

To Comparisons at TS = 0

Velocity	T_o Table 6	T_o TS_a	T_o TS_b	T_o ASHRAE 55-81
0.05	21.5	21.9	21.6	21.7
0.15	21.8	22.1	22.5	21.7
0.25	22.2	22.7	22.9	
0.50	22.4	24.4	23.6	

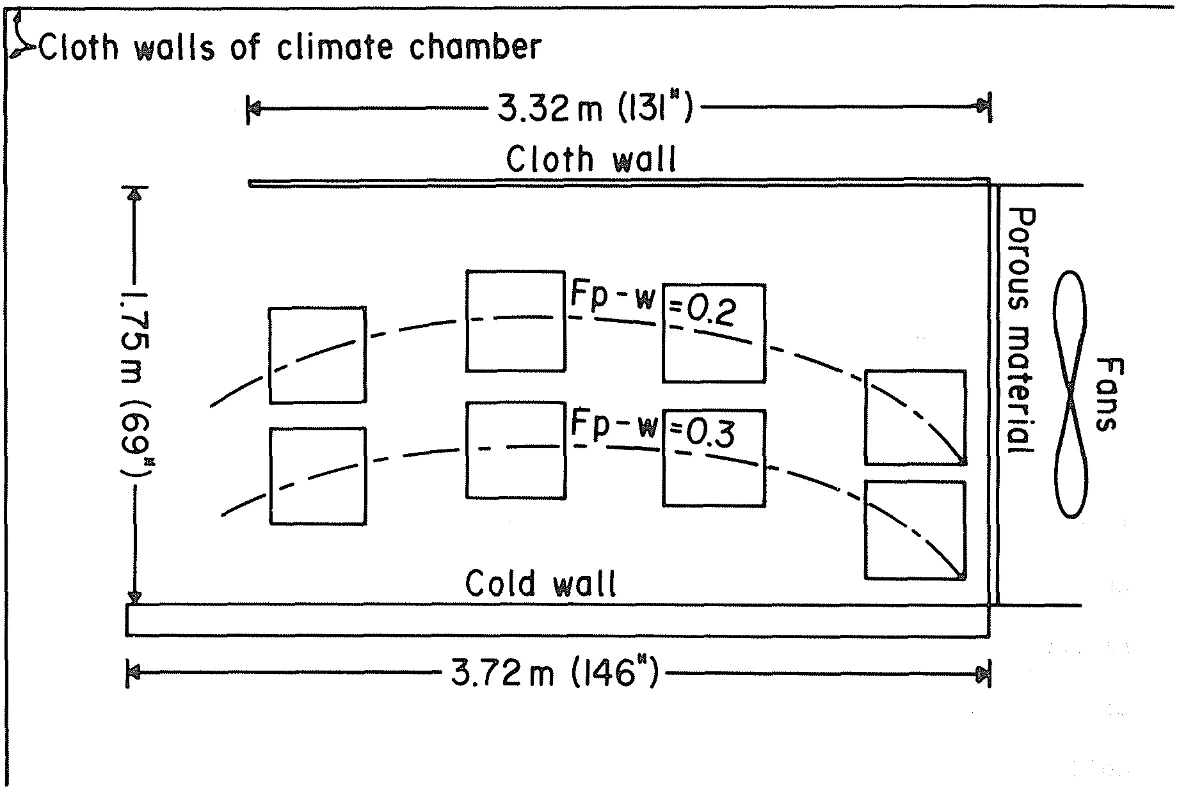


Figure 1. Plan view of test space with seating locations for shape factors of 0.2 and 0.3

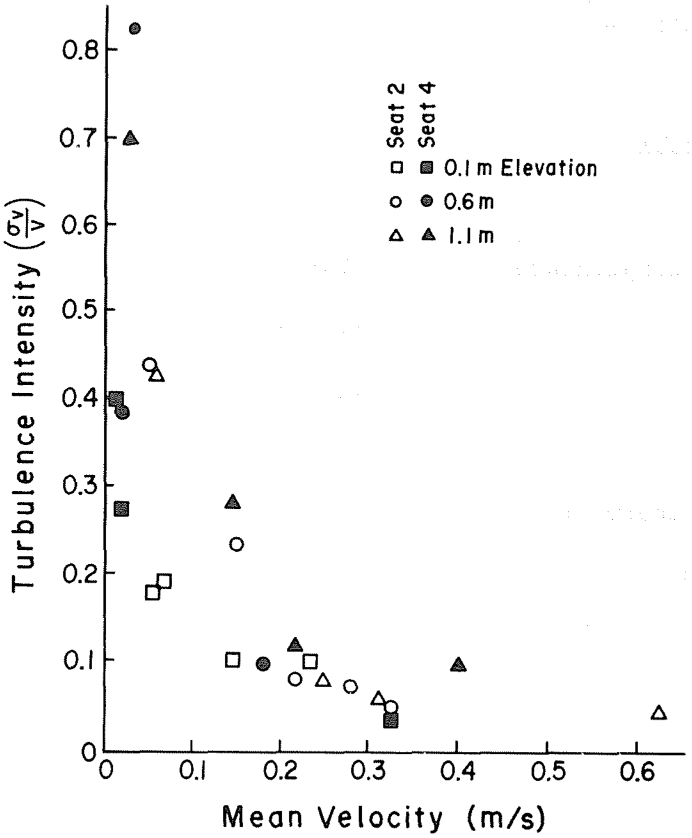


Figure 2. Turbulence intensity measurements at the second and fourth chair positions from the fan along the 0.2 shape factor locus

Name: ____________________

Date: ____________________

Elapsed Time: ____________

Mark on the line how you feel at this moment?

hot
warm
sl warm
neutral
sl cool
cool
cold

comfortable
sl uncomfortable
uncomfortable
very uncomfortable

Would you like the temperature — Warmer / No change / Cooler

Is the environment thermally acceptable? Yes No

Is some part of you

Cooler? Yes No What?

Warmer? Yes No

Do you feel a draft? Yes No

Figure 3. Subjective response ballot administered every half hour

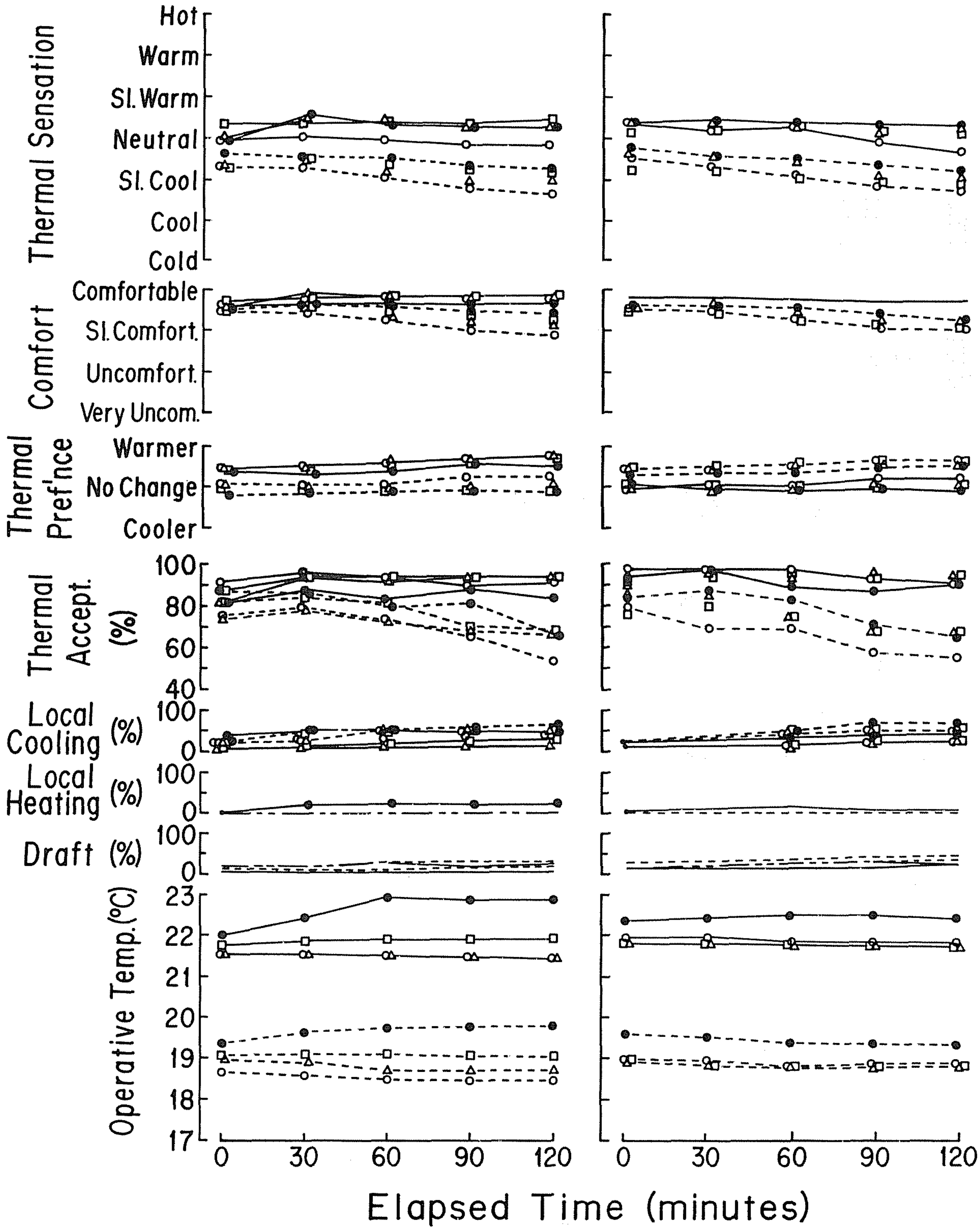


Figure 4. Mean values of human responses to nominal air speeds of 0.05 (10 fpm) (left) and 0.15 m/s (30 fpm) (right). Solid lines for neutral (N) conditions, dashed lines for N-3°C conditions. O RTA = 0 K, Δ RTA = 5 K (9 F), □ RTA = 10 K (19 F), and ● RTA = 18 K (32 F)

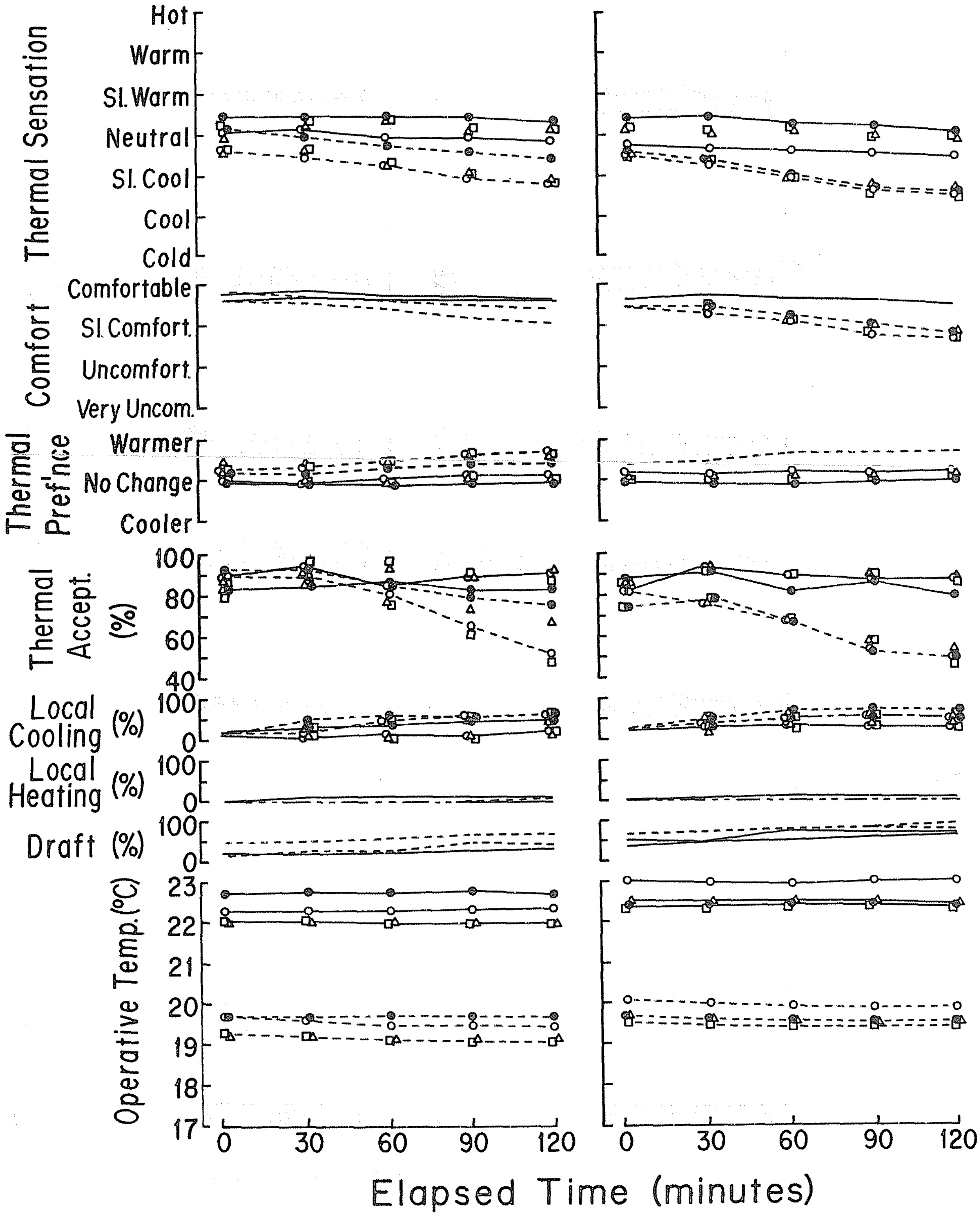


Figure 5. Mean values of human responses to nominal air speeds of 0.25 m/s (50 fpm) (left) and 0.5 m/s (100 fpm) (right). Same key as Figure 4

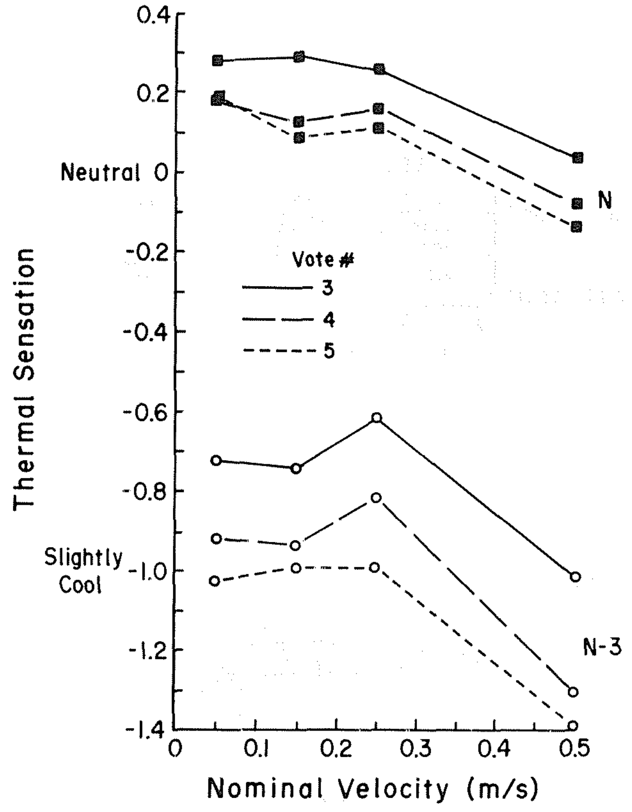


Figure 6. Thermal sensations at votes 3, 4, and 5 with RTA pooled. Each point is the mean of 50

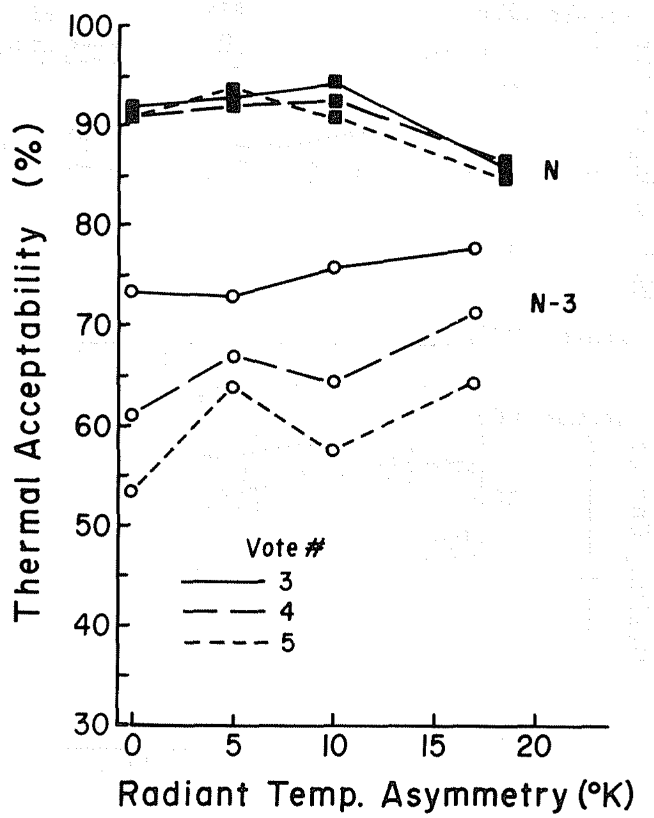


Figure 7. Thermal acceptability of votes 3, 4, and 5 with velocities pooled. Each point is the mean of 50

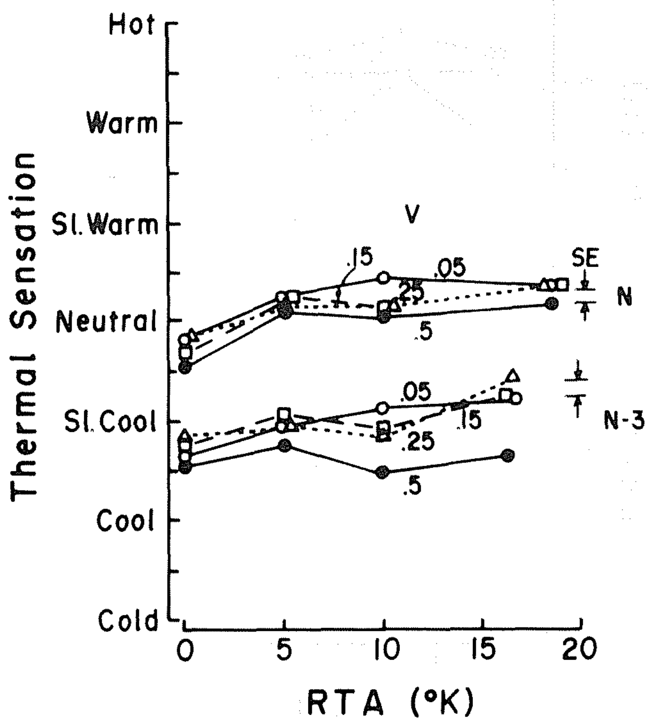


Figure 8. Effect of radiant temperature asymmetry (RTA) on thermal sensation at vote 5

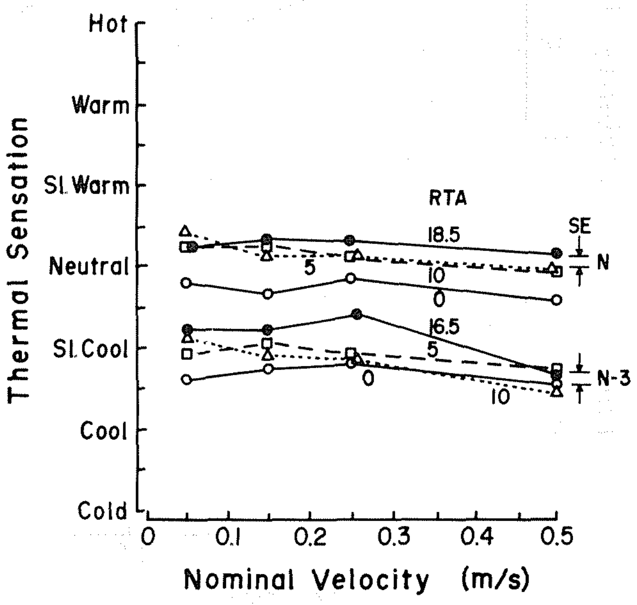
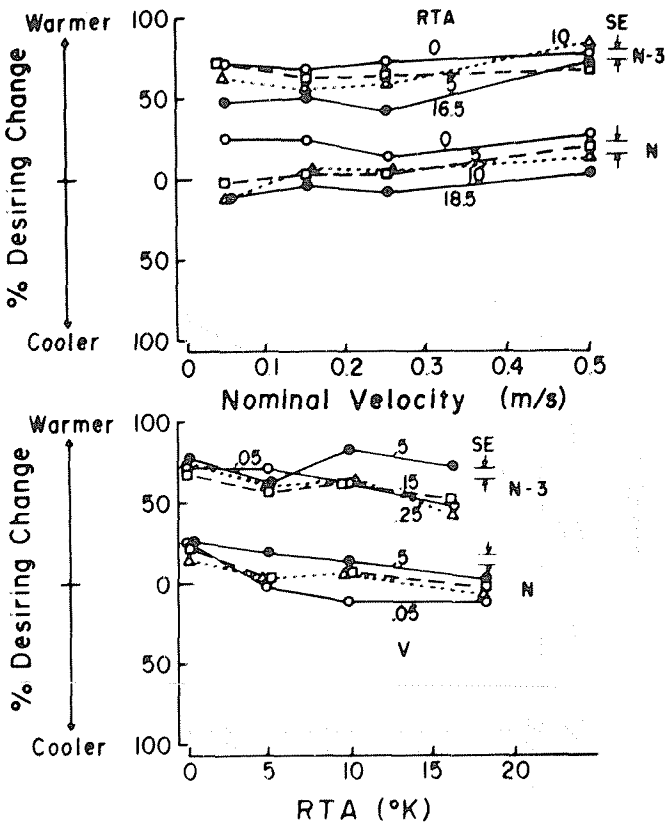


Figure 9. Effect of air speed on thermal sensation at vote 5



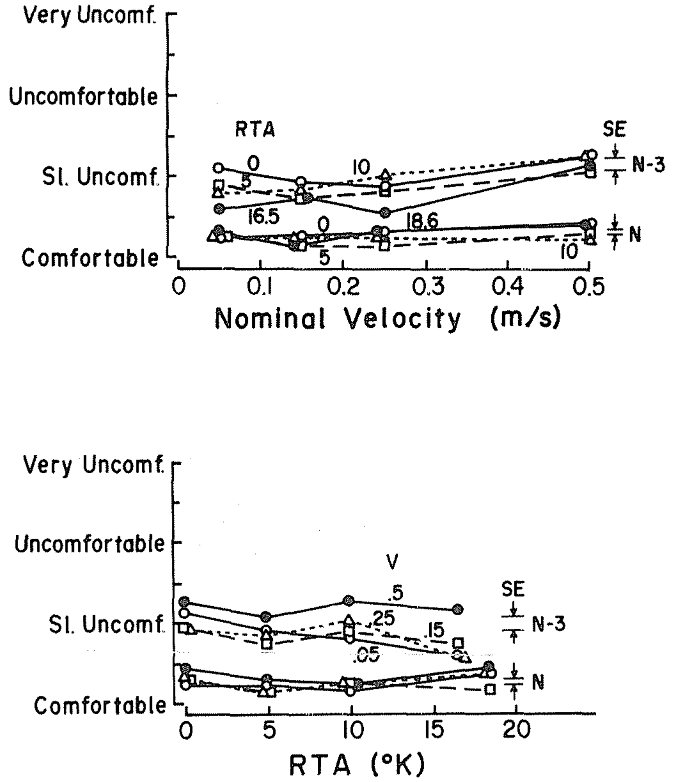
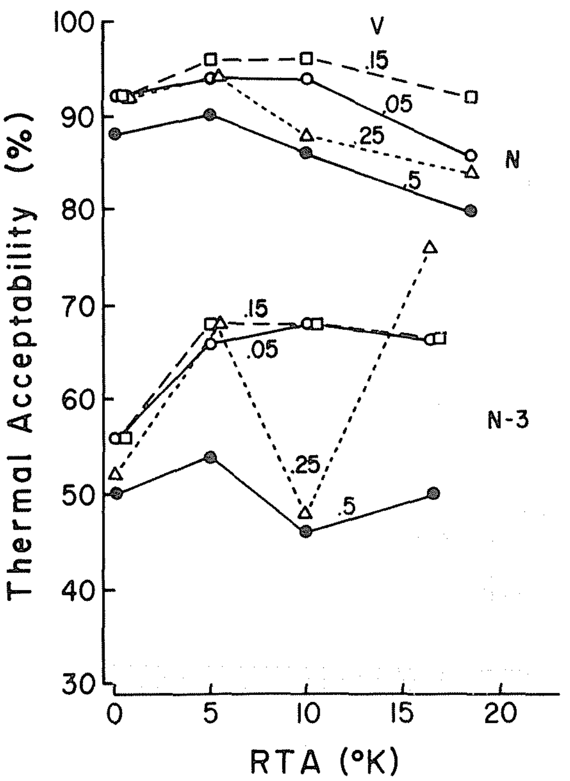


Figure 10. Thermal preferences at vote 5

Figure 11. Comfort responses at vote 5



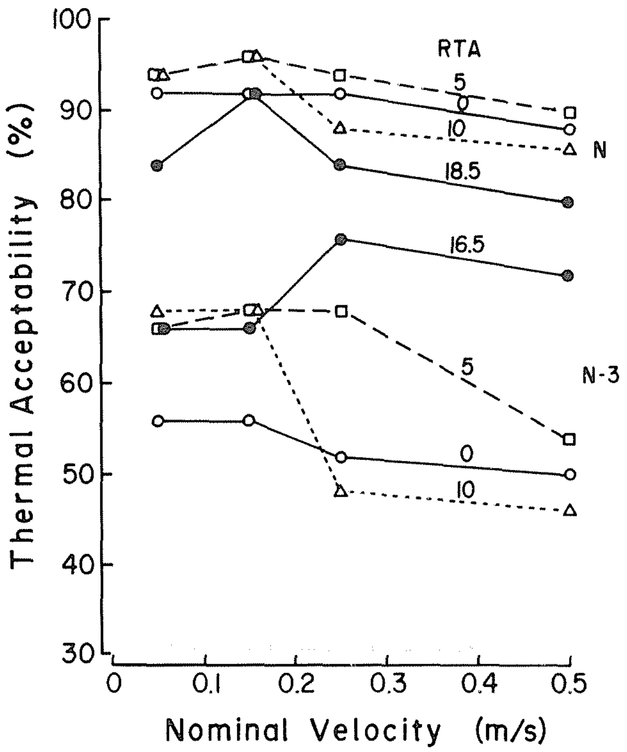


Figure 12. Thermal acceptability and radiant asymmetry at vote 5

Figure 13. Thermal acceptability at various air speeds (vote 5)

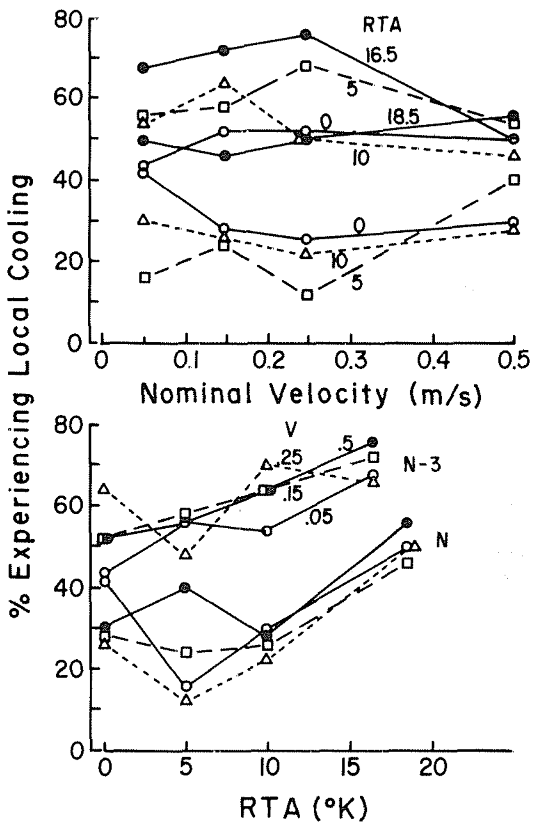


Figure 14. Percentage feeling local cooling at vote 5

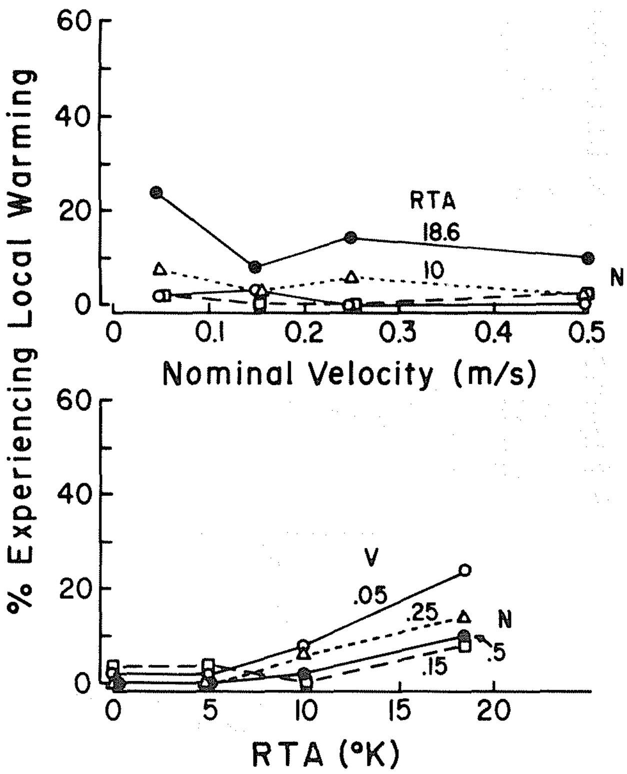


Figure 15. Percentage feeling local warming at vote 5

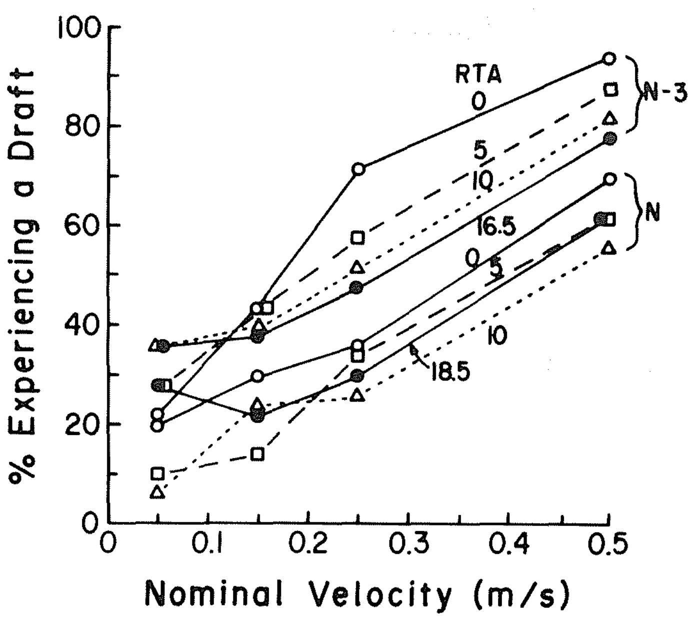


Figure 16. Effect of nominal air speed on feeling a draft at vote 5

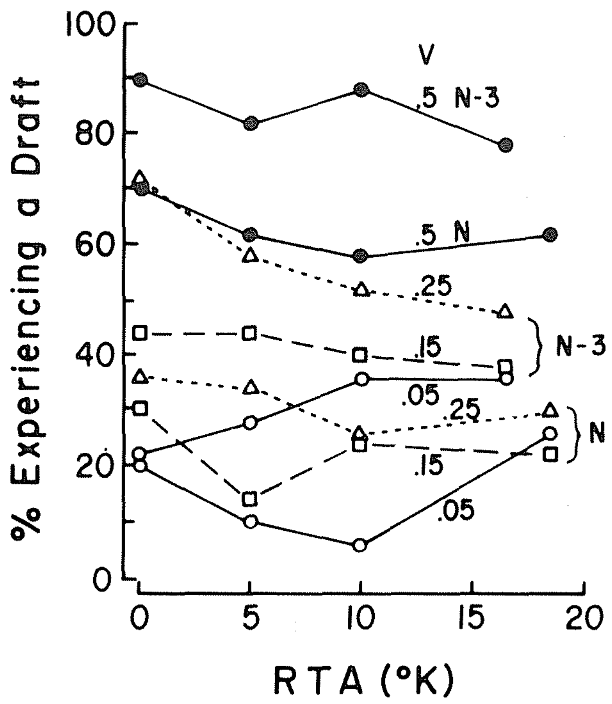


Figure 17. Effect of radiant asymmetry on perception of a draft

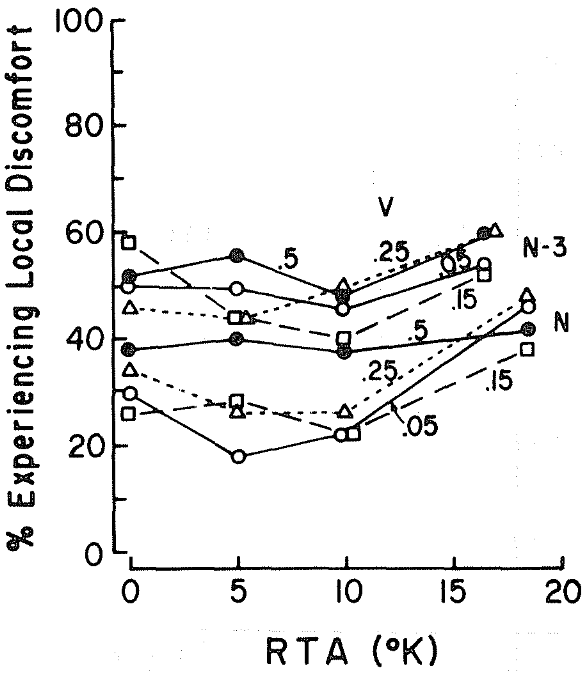


Figure 18. Local discomfort and air speed at vote 5

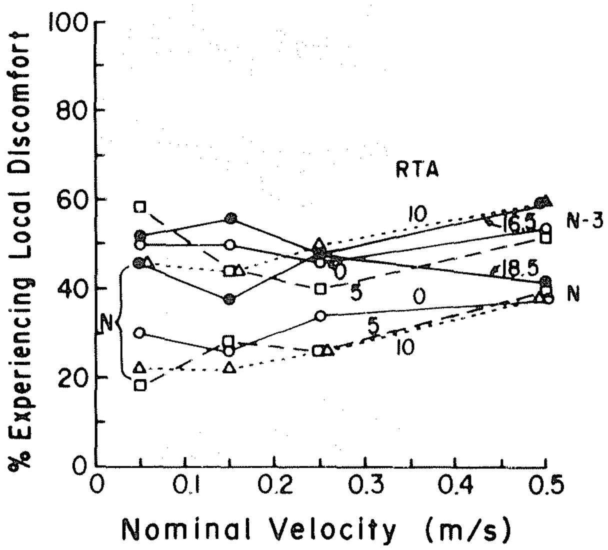


Figure 19. Local discomfort and air speed at vote 5

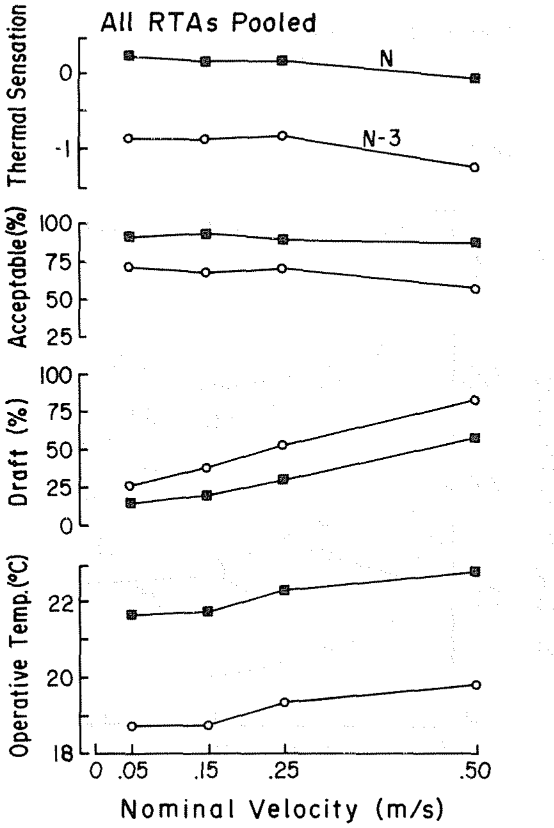


Figure 20. Responses to air speed with RTA pooled

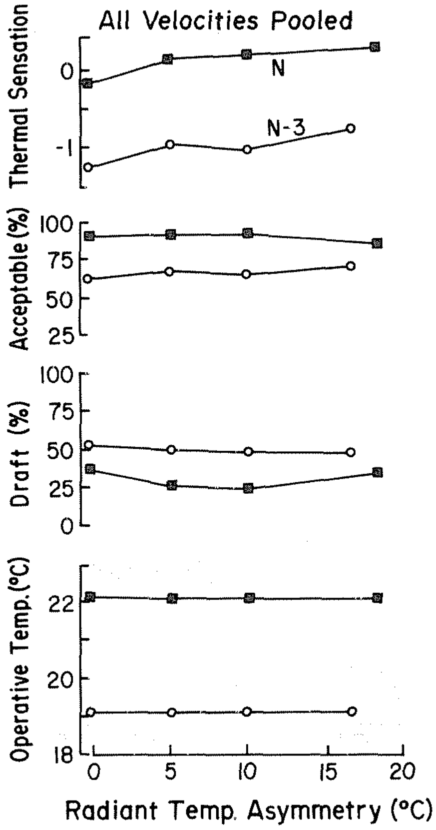


Figure 21. Responses to radiant asymmetry with all air speeds pooled

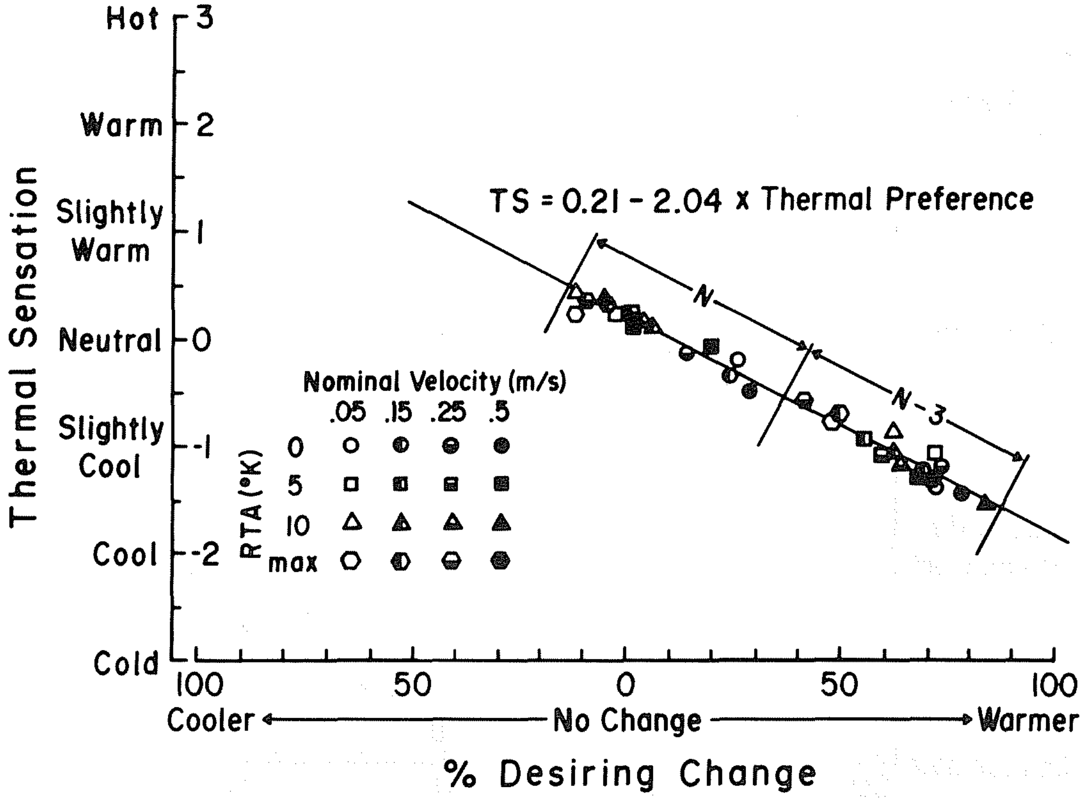


Figure 22. Simultaneous thermal sensation and thermal preference vote means at vote 5

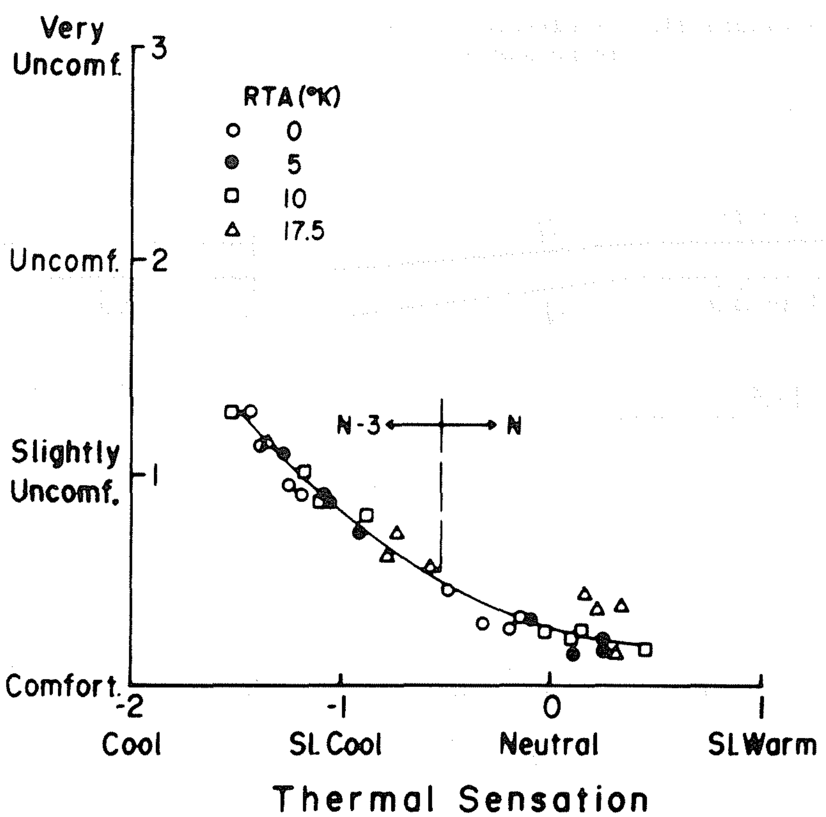


Figure 23. Simultaneous comfort and thermal sensation responses at vote 5

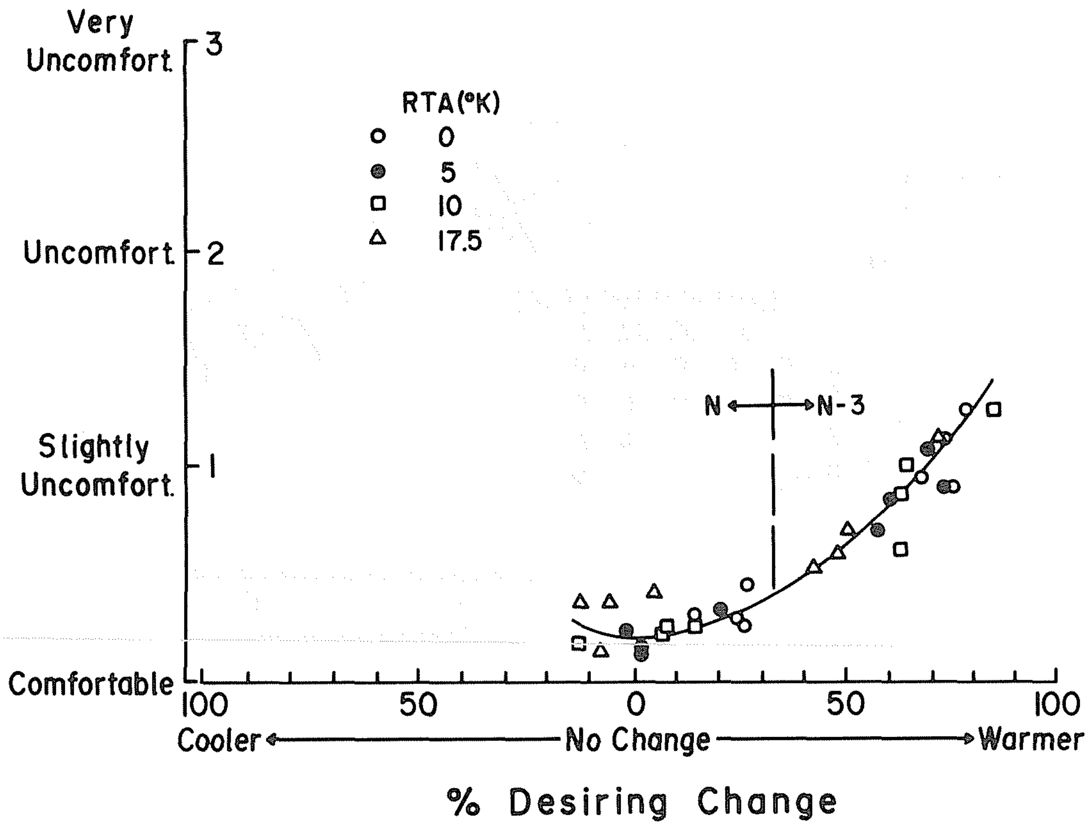


Figure 24. Simultaneous comfort and thermal preference responses at vote 5

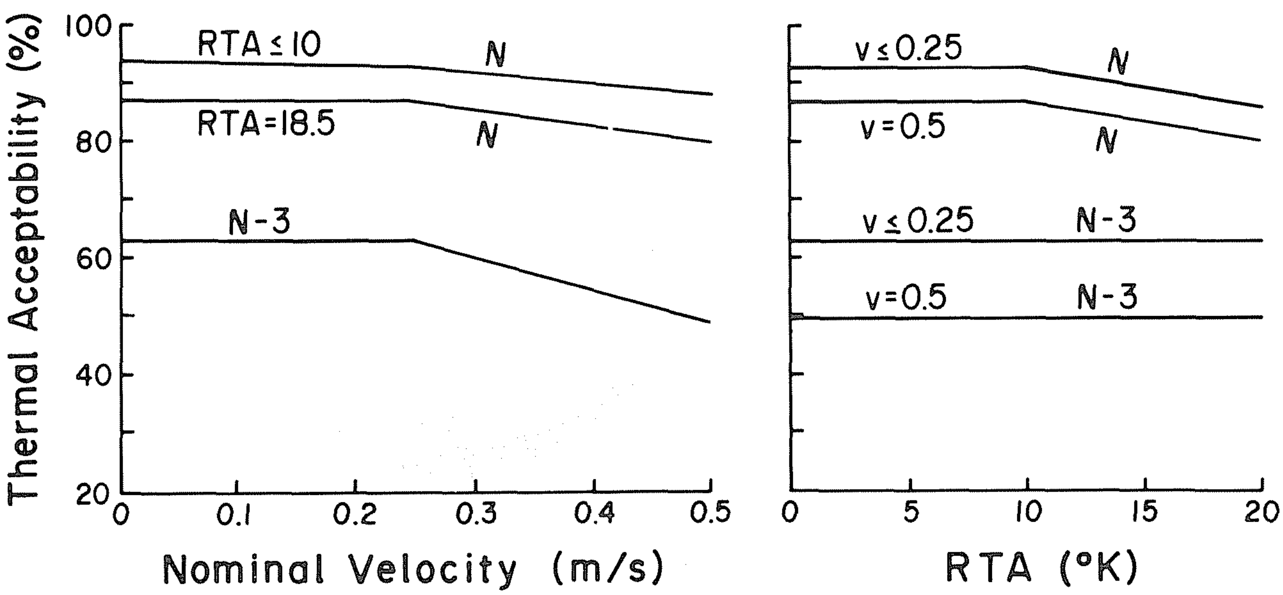


Figure 25. Generalized relationships of thermal acceptability to air speed and radiant asymmetry

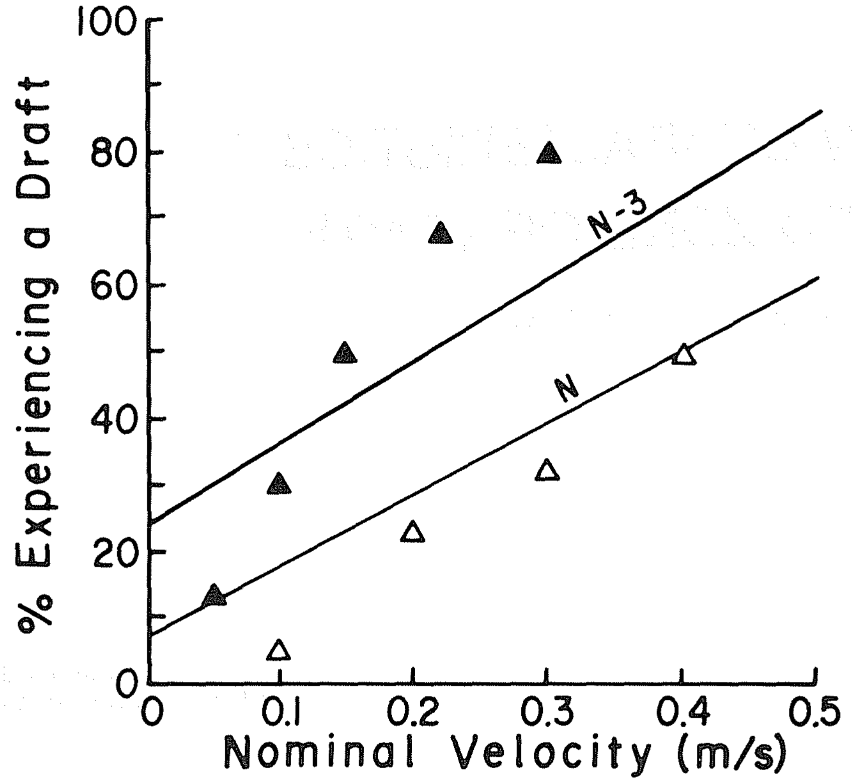


Figure 26. Regression lines of total percentage of subjects experiencing a draft at the N and N-3 operative temperature conditions. ▲ is percent sensing air movement at neutral conditions in study by Fanger et al. (1986). Δ is percentage dissatisfied with air movement in same study by Fanger et al.

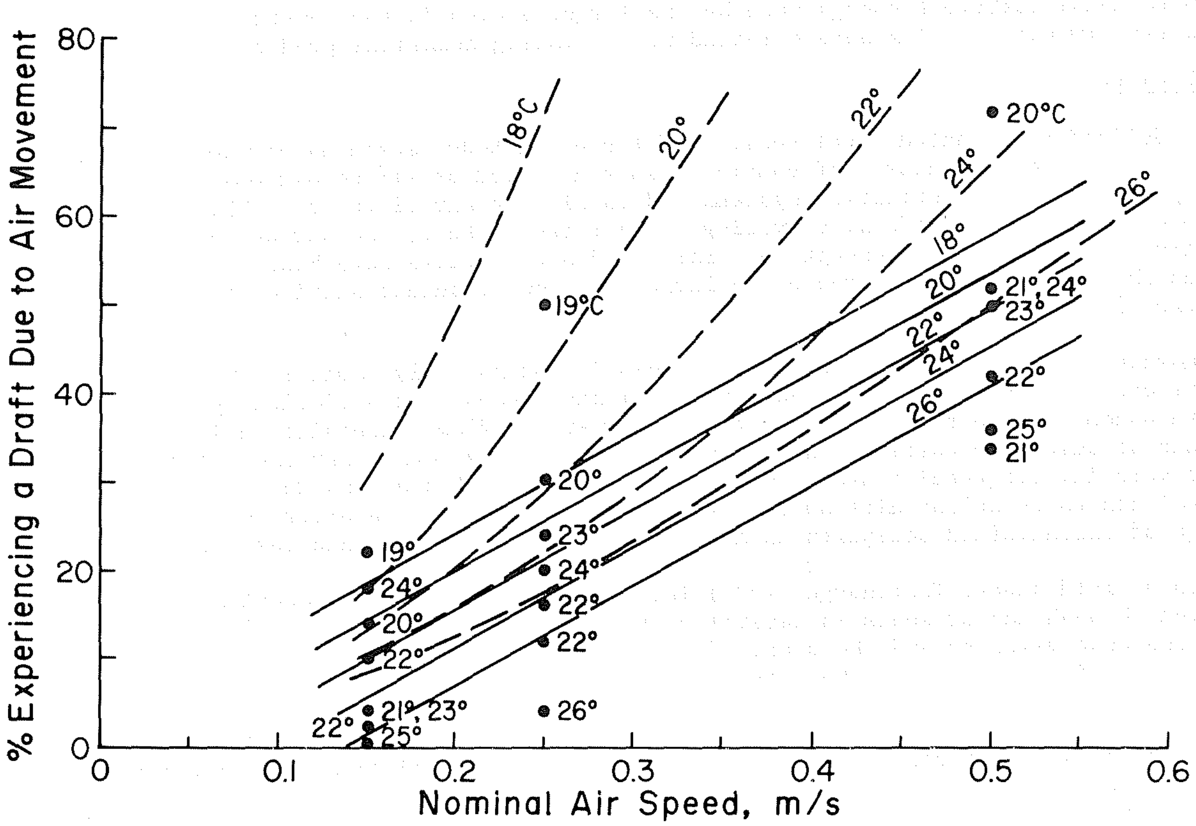


Figure 27. Percentage of subjects experiencing a draft due to air movement. Each point is mean response of 50 at air temperature indicated. The equation for the solid multiple linear regression lines is PED = 113 (V - 0.05) - 2.15 Ta + 46 (r^2 = .84). The dashed lines are from a study by Fanger et al. (1986)