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MEASURING THE COMFORT-PRODUCING EFFECTIVENESS OF SPACE HEATERS DURING TRANSIENT WARMING

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ABSTRACT

Twelve subjects, six men and six women evaluated the effectiveness of three space heaters in producing a comfortable thermal environment during a transient warming period. The subjects voted every three minutes during a one hour exposure period in which the temperature of the occupied space was allowed to drift from 10°C to 22°C. The results showed that Heater Nos. 2 and 3 provided comfort for the subjects faster than Heater No. 1, even though all heaters had the maximum wattage of 2600 W. The results showed that the male and female subjects had similar responses and that head, hands, trunk, and back comfort were the same regardless of heater. The study represents a new methodology for evaluating the human response to the transient warming conditions developed by space heaters.

INTRODUCTION

For years, small space heaters have been used to provide additional heat quickly to indoor space, and the current emphasis on energy conservation has brought a new and increased use and popularity to the space heater. As a result, the potential buyer has many heaters to choose from and no criterion upon which to base his decision. Obviously, such factors as physical size, price, and operating costs are critical to this decision, but when these factors are similar, the buyer is at a loss to arrive at any valid criterion for purchase.

One question that is always paramount to the buyer is "will the heater make me comfortable?" Beyond this, the question posed is "will Heater A provide comfort quicker than Heater B?" These questions, together with the criteria noted above, were the basis for this study; the questions, it should be added, can be answered most validly by using people to evaluate the comfort-producing qualities of the heaters. Thus, the purpose of the research reported in this paper was to determine the comfort of the human occupant during a transient warming period resulting from the use of space heaters.

METHODS OF PROCEDURE

Experimental Design

Three heaters were selected for study. Six men and six women served as test subjects. The order in which each subject was exposed to each heater was balanced and different for each subject of a given gender. Three consecutive days were allotted for the testing of each subject, with each subject being exposed to a different heater each day. The schedule of testing by subject is presented in Table 1. The exposure lasted 60 minutes and votes on five subjective ballots were recorded every three minutes.

Subjects

The subjects were six Japanese men and six Japanese women whose ages ranged from 19 to 22 years. All were recruited from local universities in Osaka, Japan and all volunteered. Each subject was paid $90 for participating.

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Apparatus and Equipment

All tests took place in a climate-controlled room. This room measures 2.7 m by 3.6 m; it has a 2.4 m ceiling. The floor is covered with carpet.

Three heaters were used and were designated Heater No. 1, Heater No. 2, and Heater No. 3; these are described in Table 2.

During the test, the heater was centered on the south wall and placed 0.1 m from the wall. The area in the chamber adjacent to the room was used for the pre-exposure conditioning space.

Each subject, male and female alike, was provided with a two-piece cotton-polyester jacket, a long-sleeved undershirt, long underpants, a crew-neck sweater, trousers, shoes, and socks. When worn over underwear, the clo of the ensemble was 0.87. (This value was determined in tests with an electrically heated copper manikin.) A medium-weight jacket, gloves, heavy rain shoes and cap were provided for the subject while in the pre-conditioning area.

Five subjective measures were used. The first was used for measuring the thermal sensation and thermal comfort; it is shown in Figure 1. The remaining four were used to measure the comfort of the subject's head, hands, chest, and back, and these are presented in Figure 2. For these tests, the ballots were printed in Japanese.

Procedure

The subjects were recruited from several local universities. When the subject reported for the test, his/her oral temperature was taken. If the temperature was 37.0°C $\pm$ 0.5°C the subject was instructed to change into the indoor clothes provided. He/she was then read an orientation statement describing the purpose of the tests, the balloting procedures, and the general experimental protocol.

Thirty minutes after the reading of this statement, the subject put on the cap, gloves, and sweater and entered the pre-conditioning area of the environmental chamber. The temperature in this area was 5°C.

After 30 minutes in this area, the subject entered the climate-controlled room, took off his cap, gloves, and sweater and sat 1.5 m in front of the heater. At this time the temperature of the location where he was sitting was 10°C. He immediately voted on all five ballots. Three minutes later, upon instruction of the experimenter, the subject voted again. This procedure was repeated every three minutes until the last voting at the end of 60 minutes. Upon completing the last ballot, the subject was removed from the environmental room, changed his clothes, and was dismissed. This procedure was repeated for the next two days using a different heater each day. The temperature in the area of the subject was allowed to drift upward to approximately 22°C. The temperature profiles for this condition for the three heaters are presented in Figure 3.

RESULTS

The responses to the four ballots for measuring the comfort of the head, hands, chest, and back were scored according to the key in Figure 4. Following this, the responses to these and the thermal sensation (TS/TC) ballot were treated separately. The analysis and interpretation of the results will be discussed separately as follows:

The Thermal Sensation/Thermal Comfort (TS/TC) Ballot

Twenty-one separate analyses of variance, one of each voting period, were conducted. The main sources of variance were "Heater" with 2 degrees of freedom, "Gender" with one degree of freedom, and the Heater-by-Gender ("HxG") interaction with two degrees of freedom. The statistical significance of the F-ratios resulting from these analyses is presented in Table 3. As demonstrated in this table, at the beginning of the exposure, time--0 and 3 minutes--there was no difference in the comfort experienced from the three heaters. However, after six minutes and on all of the votes until 30 minutes, the heaters were responsible for different comfort votes. In order to determine which of the heaters produced the greatest feeling of comfort, Tukey tests were made for each of the voting periods that had an F-ratio statistically significant at $p < .05$. These tests are summarized in Table 4. They show that for all of the votes, Heater 2 provided the greatest amount of comfort. In addition, these tests show that Heater 1 was consistently the poorest of the three heaters in its comfort-producing qualities.

Referring back to the analyses of variance in Table 3, we observe that none of the F-ratios associated with gender was statistically significant at $p < .05$. This shows that the men and women responded the same to the tests. There were only two F-ratios for the heater-by-gender interaction that were statistically significant at $p < .05$, and while they are difficult to explain, they represent no meaningful pattern and certainly are not in sufficient number to say that men respond differently to different heaters than women do. The mean votes for each voting period are plotted for the three heaters on Figure 5. This demonstrates even more dramatically the superiority of Heater No. 1 in producing comfort.

Another index that was determined was the mean time that the first vote of 2, 3, 4, and 5 was recorded. This time-to-comfort measure presents a different and, indeed, a unique approach for assessing the comfort-producing qualities during transient temperature conditions. It was first used to assess the comfort-producing effectiveness of automobile air-conditioning systems during transient cooldown. It was employed in the present study to measure the comfort-producing effectiveness of the heaters during transient warming.

For graphing Figure 6, the time that the first 2 (cold/cool) vote was recorded was identified for each subject. Then the mean time for all 12 subjects was computed. The temperature at this time was also determined for each subject and similarly, the mean temperature for the 12 subjects was determined. This procedure was repeated for the 3 (cool) vote, 4 (cool-comfort) vote, and 5 (comfort) vote for each heater. Next, t-ratios were computed to determine the reliability of the differences between the times. As shown in Table 5, the mean time of the first 4 vote (cool/comfort) for Heater 2 was 8.8 minutes. This was significantly faster than the 24.5 minutes of Heater 1, but it was not statistically significantly faster than Heater 3.

Table 6 shows comparable data for the recording of the 5 vote, comfort. Here we see the superiority of Heater No. 2 again with a mean time-to-comfort (5) of 21.3 minutes. This time was significantly faster, $p < .01$, than the 46.8 minutes of Heater No. 1. Another point should be made for showing the superiority of Heater No. 2. Of the twelve subjects, six never recorded a vote of 5 (comfort) during the 60 minutes' exposure to Heater No. 1, whereas only two subjects exhibited this behavior for Heater No. 2 and three subjects for Heater No. 3.

When examining Figure 6, it is easy to follow the course of the exposures. At the outset, all of the subjects experienced the sensation of cold/cool at between 13.4°C and 14.4°C at about the same time. But there the similarity of the responses ends. Heater No. 2 warmed the subjects quickly and when the room temperature was 19.2°C the subjects reported feeling comfortable; this occurred in 21.3 minutes. In contrast, it took 46.8 minutes for Heater No. 1 to produce comfort. This difference is particularly interesting in light of the temperature profiles presented in Figure 3. This figure shows that all three heaters follow the same temperature gradient and we should expect similar responses from the human subjects. Since we did not, there is something inherent in the heaters themselves that contributes to the difference. This observation also provides evidence for using human subjects in tests such as these.

Comfort of the Body Parts

Twenty-one separate analyses of variance were conducted on the responses to each of the body parts. Of these, only the responses for the comfort of the hands yielded a meaningful number of F-ratios. To be specific, in the analysis of the head comfort responses, only four of the F-ratios associated with the heater as a source of variance were significant at $p < .05$; these were at 12, 15, 48, and 54 minutes. For the chest-comfort votes, 6 of the 21 analyses had F-ratios that were significant at $p < .05$; these occurred at votes 4, 5, 6, 7, and 8 after 9, 12, 15, 18, and 21 minutes, respectively. For the back comfort votes, only three of the analyses of variance yielded F-ratios that were statistically significant at $p < .05$. However, 13 of the 21 analyses of variance of the responses to the hand comfort ballot were statistically significant at $p < .05$. These are presented in Table 7. With reference to the F-ratios for heaters, a pattern similar to that of the TS/TC is observed; namely, the heaters did not produce any difference in hand comfort until the third vote after six minutes. Significant F-ratios were then observed for the next six votes, remained nonsignificant for votes 10, 11, and 12, and then emerged significant again for the next six votes from 13 through 18. In fact, when we compare the hand-comfort votes to those of the TS/TC ballot, we find 13 significant F-ratios for the hand votes and 12 for the TS/TC votes--an indication of the contribution that hand comfort makes to overall comfort.

As was the case in the previous analysis, the means of those votes whose F-ratios were significant were subjected to Tukey tests to determine the significance of the differences.

These are presented in Table 8. The pattern for almost all of the tests is similar. Heater No. 2 provides the greatest amount of hand comfort and Heater No. 1 produces the least.

Referring back to Table 7, none of the F-ratios for gender or the heater-by-gender interaction was statistically significant at $p < .05$.

A plot of the hand vote means are presented in Figure 7. This graphs shows the similarity of Heater No. 2 and Heater No. 3 in producing hand comfort in the early stages of the tests, however, after 30 minutes, Heater No. 2 is much superior to both Heater No. 1 and Heater No. 3 in ththe air velocities of the three heaters. And whereas the air velocities of Heaters No. 1 and No. 2 were similar, the air velocity of Heater No. 3 was almost twice the mean value.

T-tests were conducted to determine the significance of the differences between these means; the results of these tests are presented in Table 9. These findings demonstrate that the mean air velocity of Heater No. 1 was significantly below that of Heater No. 2 ($p < .02$), as well as being significantly less than the velocity of Heater No. 3 ($p < .01$), and, of course, the air velocity associated with Heater No. 2 was significantly less ($p < .01$) than that of Heater No. 3.

DISCUSSION

The human response to the thermal environment depends upon seven factors: (1) dry-bulb or air temperature, (2) the water vapor pressure or relative humidity, (3) the mean radiant temperature, (4) the air velocity, (5) the physical activity of the human occupant, (6) the clothing the occupant is wearing, and (7) the temporal nature of the exposure.

While most of these variables have been the subject of extensive research, the temporal dimension has received only limited attention. At the outset, three types of temporal aspects of the exposure dimension have been identified (Rohles 1981). The first of these is related to cyclical fluctuations. These are associated with thermostat tolerances and the size and efficiency of the building (storm windows, insulation, infiltration). Research in the cyclical factor has been reported by Rohles et al. (1980).

The second type of temporal exposure involves discrete changes in the thermal environment, such as those experienced when going from the residence to the automobile and then to the supermarket and returning (Rohles and Wells 1977). Exposures of this type are more representative of everyday living.

The third exposure dimension is related to ramps or drifts and is usually exemplified by the night setback of thermostats. The effects of temperature drifts on comfort have been studied by Berglund and Stolwijk (1978) and more recently by Rohles et al. (1985). Moreover, it is this aspect of the temporal dimension that Rohles (1979) described in his research on automobile air-conditioning. Whereas the automobile study involved a transient cooling temperature condition, the current study involved a warming temperature transient.

In addition, the procedures used in the present study were patterned after those in the automobile research, which were designed to identify the duct size, location, air velocity, and air temperature combination that produced a condition of comfort in the shortest period of time.

The goal of the present study was to identify the spot heater that produced thermal comfort in the shortest period of time, and the results of the present study definitely point to the superiority of Heater No. 2.

Other features of the study are also worthy of note. The Thermal Sensation/Thermal Comfort Ballot is a hybrid scale in that it combines the choices on the traditional thermal sensation ballot with responses on feelings of comfort. This hybrid ballot has been suggested by Rohles (1985) as being easily translated from English into other languages. This study represents the first non-English use of the ballot and the results were clear and produced meaningful and discriminative results.

The ballots for measuring the comfort of the head, hands, trunk, and back was also suggested by Rohles (1985). These, however, with the exception of the vote for the comfort of the hands did not discriminate between the heaters as well as the TS/TC ballot. Nevertheless, this study represents the first time it has been used for this purpose.

Another finding should be addressed. This is the similarity of the responses by the male and female subjects. In many of the comfort studies differences in the responses of the two sexes have been observed. Interestingly this difference was not observed in the present study.

As was true in the automobile air conditioning study, the use of time-to comfort as a dependent variable also permitted a different approach to assessing comfort. With this criterion, Heater No. 2 proved to be the heater that produced comfort quickest. It should also be pointed out that Heater No. 2 was the only heater that had a visible flame. Whether this contributed to the quicker comfort response is only conjuture, yet the psychology of "seeing" the heat could have influenced the responses of the subjects favor Heater No. 2 over the others.

In summary, then, this study can provide the heater manufacturer with empirical evidence to aid in marketing the heater. The evidence tells the prospective buyer which heater will make him/her comfortable in the shortest period of time. The results of this study do not address the price of the heaters nor their energy use. These must be considered in the marketing but so far as comfort and time are concerned, the results of the study are precise and definitive.

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TABLE 1
Order of Exposure to the Three Heaters by Subject

Subjects	Day 1	Day 2	Day 3	Subjects	Day 1	Day 2	Day 3
Male				Female			
1	1	3	2	1	1	3	2
2	1	2	3	2	1	2	3
3	3	1	2	3	2	3	1
4	2	1	3	4	2	1	3
5	2	3	1	5	3	1	2
6	3	2	1	6	3	2	1

TABLE 2
Specifications of the Heaters

		Heater No. 1	Heater No. 2	Heater No. 3
A.	Type of Heater			
	Radiation	yes	yes	no
	Convection	yes	yes	yes
	Air velocity (m/s)*	(0.31)	(0.38)	(0.68)
B.	Control System:	Off + 4 steps	2 steps	Off + 4 steps
	gas quantity in watts	1. 2600	1. 2600	1. 2600
		2. 1760	2. 1060	2. 1960
		3. 1280		3. 1570
		4. 930		4. 1220
C.	Size			
	height (mm)	575	460	500
	width (mm)	420	470	590
	length (mm)	190	170	207
	weight (kg)	15	11.5	16
D.	Flame Visible	no	yes	no

*based on mean value during tests

TABLE 3
Analyses of Variance of the Thermal Sensation/Thermal Comfort Votes: Significance of the F-Ratios

		Source of Variance		
Vote	Time (min)	Heater (H)	Gender (G)	H x G
1	0	ns	ns	ns
2	3	ns	ns	ns
3	6	02	ns	ns
4	9	01	ns	ns
5	12	01	ns	ns
6	15	01	ns	ns
7	18	01	ns	ns
8	21	01	ns	ns
9	24	01	ns	ns
10	27	01	ns	ns
11	30	02	ns	04
12	33	ns	ns	ns
13	36	04*	ns	ns
14	39	ns	ns	ns
15	42	ns	ns	05
16	45	ns	ns	ns
17	48	02	ns	ns
18	51	02	ns	ns
19	54	ns	ns	ns
20	57	ns	ns	ns
21	60	ns	ns	ns

ns - F-ratio not statistically significant at $p < .05$; see separate tables for Tukey tests of significance between the means whose associated F-ratios are significant at $p < .05$.

* - Tukey test not significant.

TABLE 4
Tukey Test Results on the Reliability of the Differences between the Mean Thermal Sensation/Thermal Comfort Votes Whose F-Ratios were Significant at p < .05

TS/TC Vote	Time	Heater	Means	Group*
3	6	2 3 1	3.1 2.6 1.8	A A B B
4	9	2 3 1	4.0 3.3 2.4	A A B
5	12	2 3 1	4.3 3.7 2.8	A A B
6	15	2 3 1	5.0 4.0 3.0	A A B B
7	18	2 3 1	5.4 4.3 3.4	A A B B
8	21	2 3 1	5.8 4.8 3.5	A B C
9	24	2 3 1	5.8 4.9 3.8	A A B
10	27	2 3 1	5.3 5.0 3.8	A A B
11	30	2 3 1	5.2 4.7 3.8	A A B B
17	48	2 3 1	4.6 4.1 3.8	A A B B
18	51	2 3 1	4.7 3.9 3.8	A A B B

*Means in groups with same letters do not differ from one another at p < .05.

TABLE 5
Mean Voting Time That the First 4 Vote (Cool/Comfort) Occurred

Heater No.	N	Mean	SD	t-ratio between means 2	3
1	12	24.5	15.6	3.28**	2.33*
2	12	8.8	5.6	--	1.61
3	12	13.0	7.1	--	--

** $p < .01$
* $p < .05$

TABLE 6
Mean Voting Times That the First 5 Votes (Comfort) was Recorded

Heater No.	N	Mean	SD	t-ratio between means 2	3
1	12	46.8	18.5	3.33**	2.18*
2	12	21.3	19.0	--	1.04
3	12	29.6	20.1	--	--

**$p < .01$
*$p < .05$

TABLE 7
Analyses of Variance of the Hand-Comfort Votes:
Significant of the F-Ratios

Vote	Time (min)	Source of Variance: Heater (H)	Gender (G)	H x G
1	0	ns	ns	ns
2	3	ns	ns	ns
3	6	01	ns	ns
4	9	02	ns	ns
5	12	01	ns	ns
6	15	01	ns	ns
7	18	01	ns	ns
8	21	01	ns	ns
9	24	02	ns	ns
10	27	ns	ns	ns
11	30	ns	ns	ns
12	33	ns	ns	ns
13	36	01	ns	ns
14	39	01	ns	ns
15	42	02	ns	ns
16	45	02	ns	ns
17	48	02	ns	ns
18	51	03*	ns	ns
19	54	ns	ns	ns
20	57	ns	ns	ns
21	60	ns	ns	ns

ns - F-ratio not statistically significant at $p < .05$; see separate tables for Tukey tests of significance between the means whose associated F-rations are significant at $p < .05$.

* - Tukey test not significant

TABLE 8

Tukey Test Results on the Reliability of the Difference between the Mean Hand-Comfort Votes Whose F-ratios were Significant at $p < .05$

Hands

Vote	Time	Heater	Means	Group*
3	6	2	7.3	A
		3	5.3	A B
		1	4.2	B
4	9	2	8.5	A
		3	6.3	A B
		1	4.7	B
5	12	2	9.8	A
		3	7.3	A B
		1	5.4	B
6	15	2	10.7	A
		3	8.0	A B
		1	5.4	B
7	18	2	10.6	A
		3	8.8	A
		1	5.4	B
8	21	2	9.9	A
		3	9.6	A
		1	6.7	B
9	24	2	10.2	A
		3	10.0	A
		1	7.6	B
13	36	2	10.9	A
		3	9.6	A B
		1	8.1	B
14	39	2	11.2	A
		3	8.9	B
		1	8.4	B
15	42	2	10.8	A
		3	8.4	B
		1	8.3	B
16	45	2	10.6	A
		3	9.1	A B
		1	8.4	B
17	48	2	11.0	A
		3	9.3	A B
		1	8.7	B

*Means in groups with same letters do not differ from one another at $p < .05$

TABLE 9
Mean Air Velocities (m/s) for the Three Heaters Over the Entire Test Period and Accompanying t-Tests between the Means

Heater No.	Velocity (m/s) N	Mean	SD	t-ratios between means Heater No. 2	Heater No. 3
1	21	0.31	0.10	2.69*	9.25**
2	21	0.38	0.06	--	8.33**
3	21	0.68	0.15	--	--

*$p < .02$.
**$p < .01$.

RATING	SUBJECTIVE RATING
1	COLD
2	COLD/COOL
3	COOL
4	COMFORT/COOL
5	COMFORT
6	WARM/COMFORT
7	WARM
8	HOT/WARM
9	HOT

Figure 1. *Thermal sensation/thermal comfort ballot*

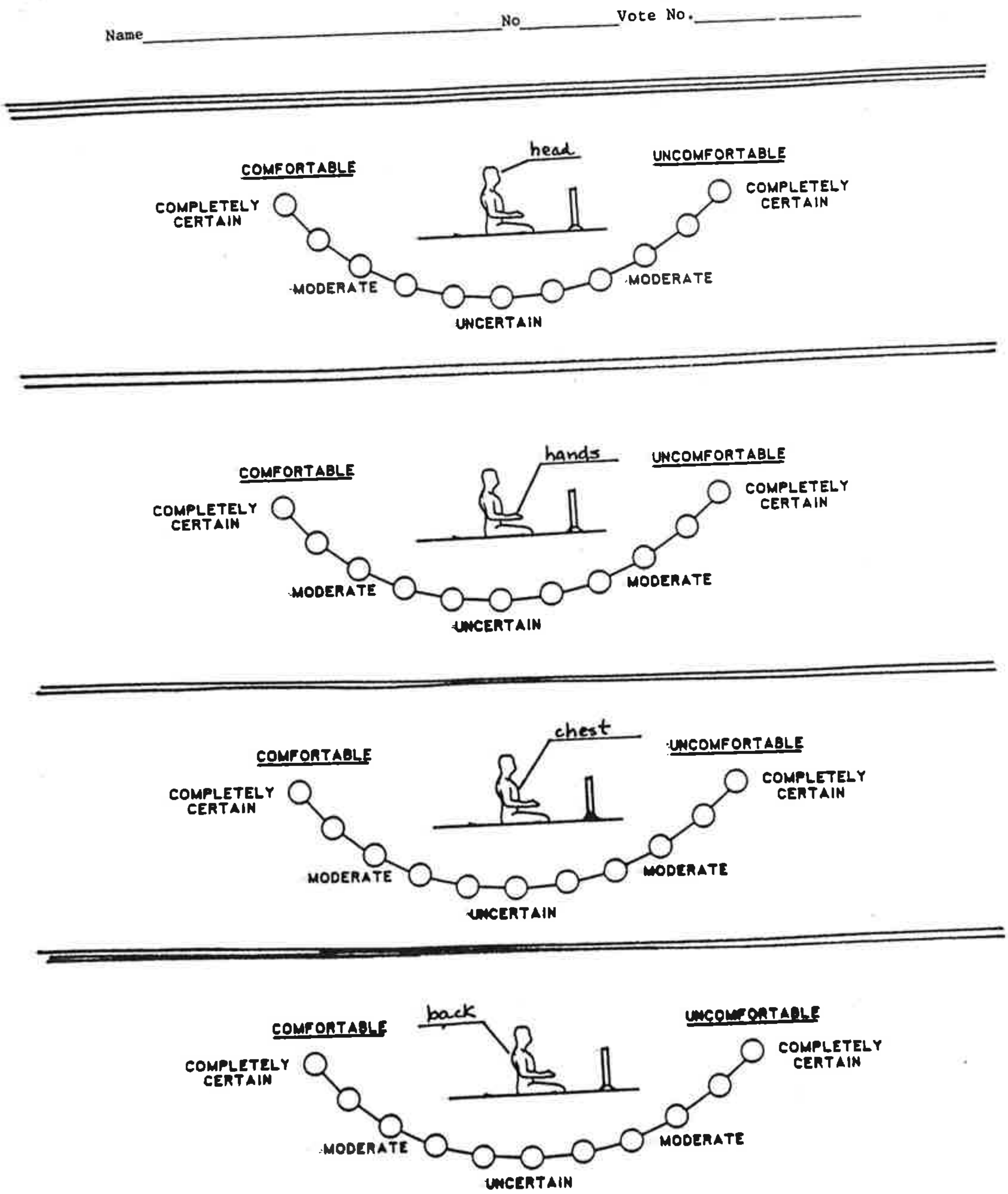

Figure 2. *Ballots for measuring the comfort of the head, hands, trunk, and back*

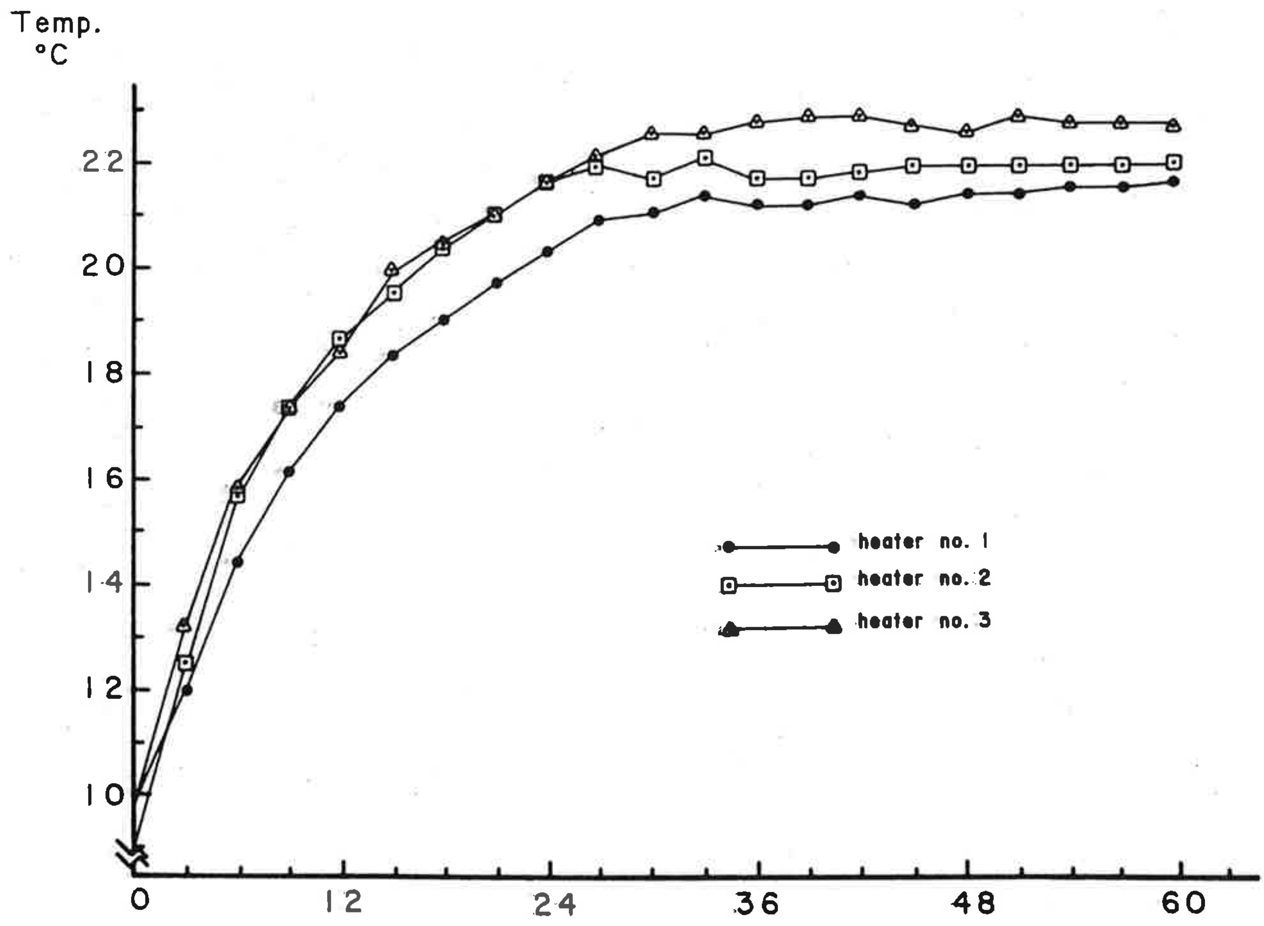

Figure 3. Ambient temperature conditions during tests

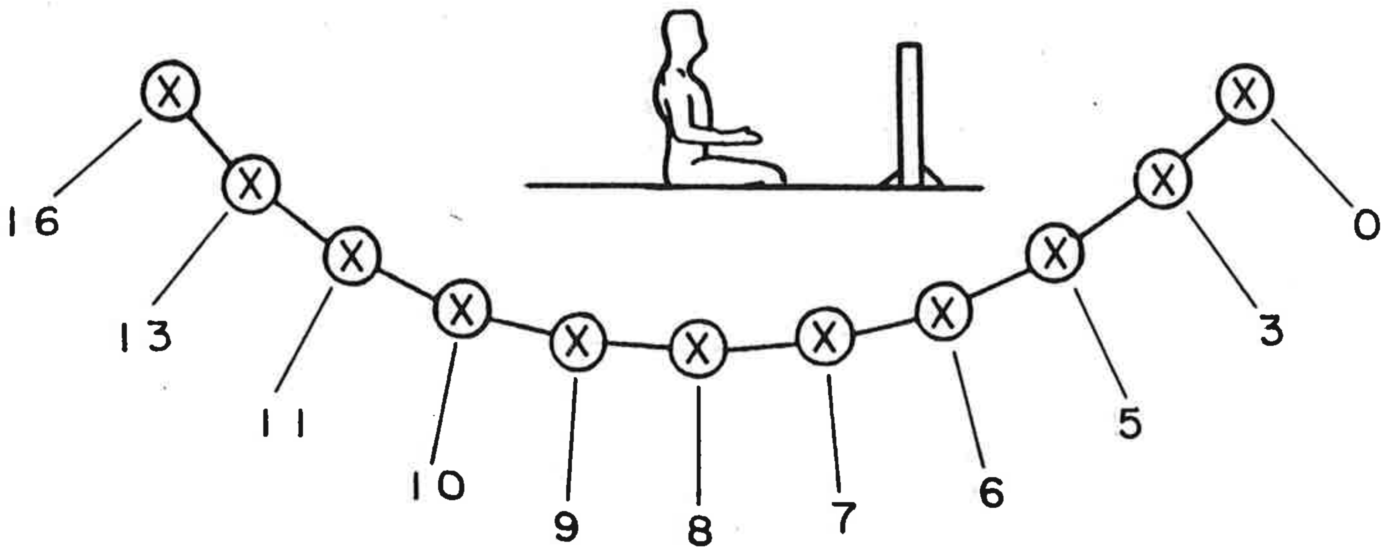

Figure 4. Scoring values for the head, hands, trunk, and back comfort ballots

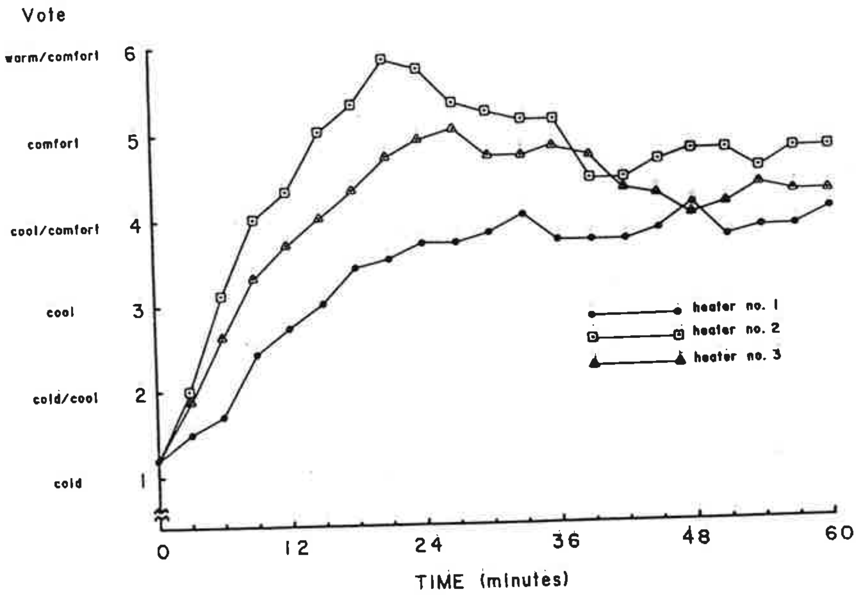

Figure 5. Mean thermal sensation/thermal comfort votes for the three heaters over time

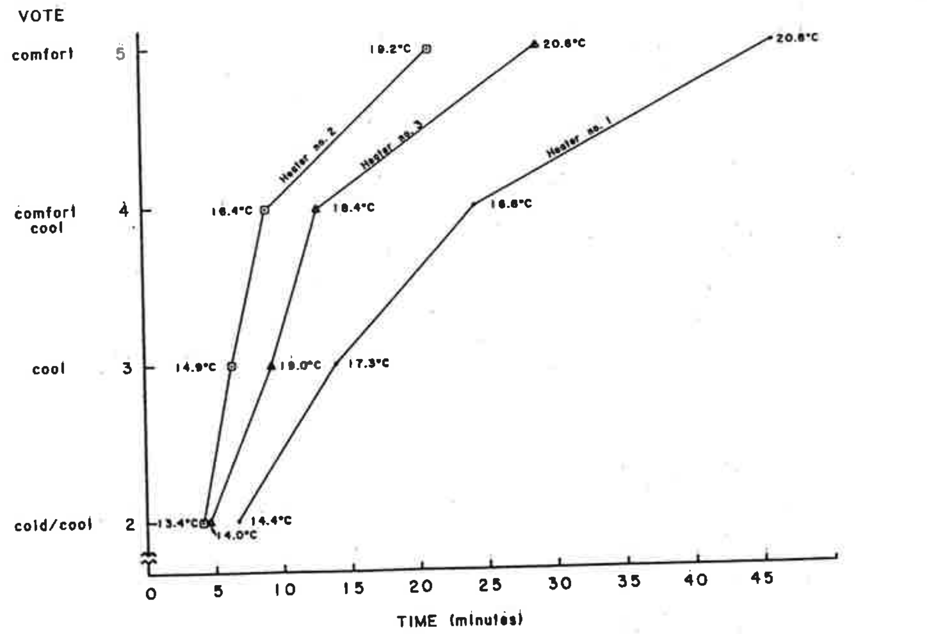

Figure 6. Mean times that the first cold/cool, cool, comfort/cool, and comfort votes were registered for the three heaters and the corresponding temperatures at those times

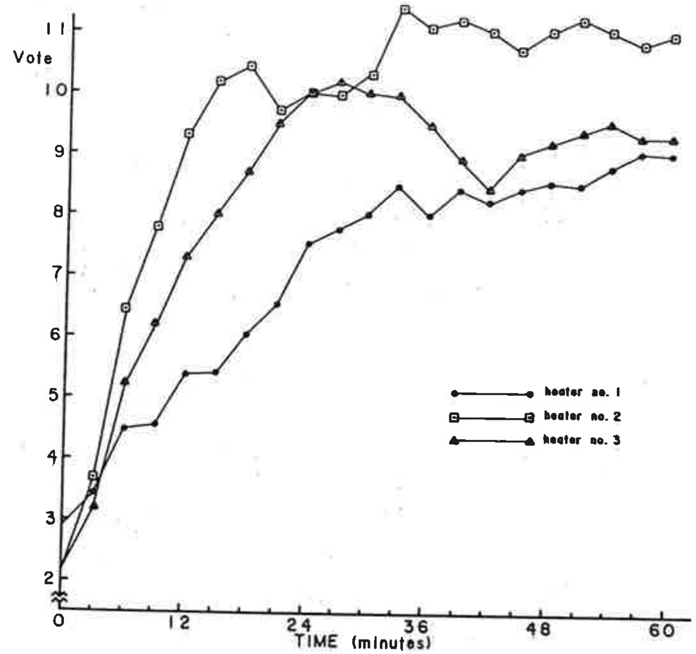

Figure 7. Mean hand comfort votes over time by heater

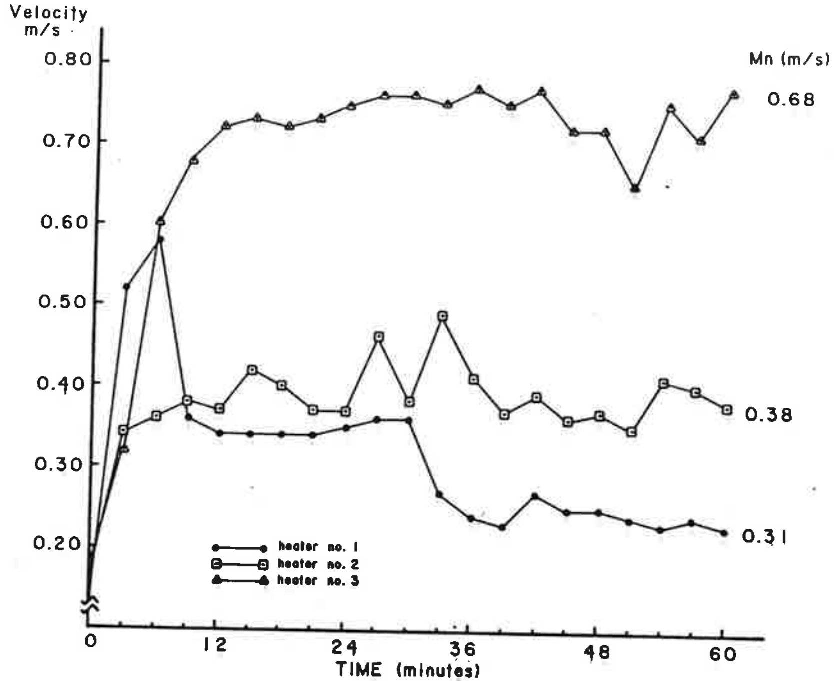

Figure 8. Mean air velocities by heater over time