

PHYSIOLOGICAL REACTIONS OF SURGEONS AND  
OPERATING THEATRE STAFF TO THEIR WORKING ENVIRONMENT

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### ABSTRACT

A review of the literature, including quantitative re-evaluation of published results, indicated that an examination of the working environment provided by operating theatres should rely primarily upon subjective responses, and that such responses should be obtained from a large number of different subjects under actual working conditions in order to increase the validity of the findings. For practical purposes, measurements of physiological reactions and of performance were reduced to a secondary, confirmatory role.

Accordingly, visits were made to over thirty operating suites in the British Isles, representing a wide range of designs and conditions. Each suite was visited three times at approximately four month intervals, and observations were made during an average of five half-day working sessions on each occasion. Using special instrumentation, measurements of air temperature, humidity, air velocity and thermal radiation were made, and many details of the suite, of the work being performed and of the subjects themselves were recorded. At convenient intervals, surgeons and operating theatre staff were interviewed briefly. The standard form of interview included Bedford's seven-point thermal scale, and visible perspiration was also noted. Over 2,500 such interviews were carried out. On a reduced sample, quantitative measurements of skin temperature and of local sweat-rate were obtained.

Using sequential multiple regression analysis, the effect of the measured variables on comfort and on bodily responses was determined. Air temperature was by far the most important variable; the effects

of all other measured variables were small. Consistent differences between the temperatures preferred by surgeons and anaesthetists were found. The variation of response between occasions for the same person was found to be almost as great as the variation between people. Response distributions for standard conditions were prepared. The perception of individual parameters of the working environment was investigated. A pilot study of manual performance was carried out.

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SECTION 1.INTRODUCTION.

# 1. Historical background of environmental measurements.

Man can live and work in extremes of climate, from the polar regions to the Equator, but has always been conscious of the advantages of an equable thermal environment. In primitive communities, it is the external climate that must be endured for the greater part of the time, and the long-term effects may be considerable. Hippocrates said that climate has great effects on the physique, intelligence and temper of peoples. The inhabitants of hot, stifling regions, he said, are small and not noted for their qualities of bravery or endurance, while a temperate climate produces men of better physique, the variable nature of their environment bringing out also their higher mental qualities. This belief, being difficult to disprove, has survived. A modern climatologist, Lee (1958), puts it down to a psychological bias in its proponents, most of whom have always lived in a variable, temperate climate. Whatever the effects of external climate may have been in antiquity, and may still be in the study of anthropology, they now play a decreasing part in man's experience, since the greater part of the work on which a civilized society depends, is done indoors. The thermal environment can thus to a large extent be under man's control, and an understanding of its effects is essential for the efficient provision of adequate working conditions. Writing more than a century ago, D.B. Reid (1844) held that defective ventilation was responsible for a greater amount of evil than any other single cause, save only 'mental anxiety' and 'deficient nutriment'. The advanced civilizations of today have succeeded only in providing more adequate

nutriment for their citizens, who must still suffer under the remaining two evils, probably to a greater extent than before. Increased industrialisation means that a far greater proportion of people now work in a thermal environment that is not under their individual control - in many cases it is not under anyone's control, and when it is, little understanding exists of the combined effects of the several thermal parameters, or of their optimum levels.

In 1714, with Fahrenheit's definition of a satisfactory thermometric scale, the first measurements of thermal environment became possible. Two centuries were to pass before it became common for measurements to be made for practical purposes as opposed to intellectual curiosity. Ellis (1758) made measurements of temperature in many parts of the world, and was struck by the fact that a given temperature was much more disagreeable in moist climates than in dry. He was probably one of the first to realise that factors other than temperature can play a large part in causing thermal strain. Blagden (1775) performed hot-room experiments which confirmed the different physiological effects of moist and dry air, but the science of hygrometry was only placed on a firm basis by the middle of the next century. The present form of instrument in common use is the whirling hygrometer, which provides a reliable measure of wet and dry bulb temperature from which the relative humidity can be obtained by means of tables. Leslie (1804) described experiments on the cooling effect of wind, and devised a large-bulbed thermometer whose cooling time was very dependent on the wind velocity, for use as an anemometer. A similar instrument, the kata thermometer, has reverted



to this use after being proposed as a measure of warmth by Sir Leonard Hill (1914), and is in fact the standard method used today by engineers for measurements of undirected air velocity in open spaces. The influence of radiant heat on the thermal equilibrium of the body is a matter of common observation. The sun's heat is readily perceptible, and most domestic heating in Britain relies on radiant heating of various kinds. Not until 1878, with the enunciation of Stefan's law, was any quantitative understanding of radiation exchange achieved, and the measurement of radiant heat is still troublesome. Bedford and Warner (1954) used a Moll thermopile for direct measurement, but it is tedious to use and involves many observations, rendering it unsuitable for non-uniform environments. Vernon (1930; 1932) had introduced the globe thermometer as a means of assessing the influence of radiation on comfort, and Bedford and Warner related its readings to the mean radiant temperature, which may be defined as the equilibrium temperature attained by a perfectly black body exchanging heat with its surroundings by radiation alone.

## 2. Historical background of environmental stress indices.

Thus by the latter part of the nineteenth century the means were available for the exact quantitative evaluation of the four main parameters of the thermal environment. No attempt was made to estimate their relative importance, still less to combine them into some unified index of thermal stress (see footnote). The reason for this seems to have been partly the

Footnote. Throughout this thesis a distinction will be made between measures of stress, such as temperature, humidity, radiation, work load and rate of working, and measures of strain, such as body temperature,

Footnote (Continued) skin temperature, sweat rate and subjective reports of discomfort. Composite indices of thermal stress are now usually derived by considering measures of thermal strain.

This was not always the case.

great gulf between academic investigation and the more mundane applications of its results, a gulf which is still, to the detriment of both sides, very much in evidence; and partly the belief, very prevalent throughout the nineteenth century, that the deleterious effects of an unpleasant indoor environment were due to some other property of the air. Lavoisier is reported by Leblanc (1842) to have examined the composition of the air in crowded rooms, and to have pronounced towards the end of the previous century that an excess of carbon dioxide was responsible for the unpleasant effects. That this was a classic case of association and not cause, was first demonstrated in 1914, although a rival theory of an exhaled toxic organic substance - anthroptoxin - enjoyed extended popularity from 1862, when it was proposed by Pottenkofer, to 1914, when it was finally disproved by the work of Sir Leonard Hill, who was also responsible for the demise of the carbon dioxide theory.

A further reason for the failure of nineteenth century scientists to devise any comprehensive indices of thermal stress may have been their pre-occupation with determinism and consequent disinterest in any such variable phenomenon as man's response to heat, still less in something so esoteric as a feeling of comfort or well-being. Rubner (1897) remarked that the feeling of comfort is in many people obtuse, undeveloped

and variable, and advised against placing any reliance upon it. It is unfortunate that the psycho-physicist Gustav Fechner was working in other fields, for he developed highly sophisticated methods of dealing with subjective response as early as 1860, and it is in fact from some of his work that the method of probit analysis has been developed (Finney, 1947). The most promising advances in dealing with subjective response to heat have made use of this statistical technique and use is made of the method in the next section of this thesis.

All early attempts to produce an index of thermal stress circumvented the unpredictability of human reactions by ignoring them and seeking for what would now be termed an 'analog' device. As early as 1826 Hoberden took the wind-sensitive thermometer of Leslie as an index of 'sensible cold', realising that it combined the cooling effects of temperature and air movement in a single figure. Haldane (1905) recommended the wet-bulb temperature as an index of physiological stress in the hot, humid Cornish mines with which he was concerned, because it combined the effects of temperature and humidity. Sir Leonard Hill's Katathermometer, introduced about 1914, had the refinement that it measured the 'cooling power' of the air over a range approximating to body temperature ( $100-95^{\circ}\text{F.}$ ), while Dufton's cupatheoscope introduced in 1932 and refined in 1936, was an internally heated black cylinder on legs, whose surface temperature approximated to that of the clothed human body. In spite of these evolutionary developments, which made each succeeding device more complicated to use and thus defeated progressively one of the original purposes of a single-figure index, they all combined the effects of the

environmental parameters in their own idiosyncratic way. Painstaking research made it possible to predict the reading of each device from a knowledge of the relevant thermal parameters, and they were all self-consistent, but it was gradually realised that they were only artefacts, and bore little resemblance to human reaction. Further, they could measure only the integrated effect of the thermal parameters on heat balance, and it was still necessary to measure separately each factor in order to set limits upon its permissible variations. At a given reading on one of these 'heat stress analogs', wide variations of comfort and even of heat balance were possible. Human reactions may be perverse and divergent, but they are individually meaningful. Each experimental subject is an unchallengeable authority on what is for him comfortable or tolerable, and can perceive individually as well as integrate the effects of the separate parameters of his environment.

In view of this it is perhaps remarkable that one of the first attempts to use human subjects as indices of warmth has been so successful, for they were used strictly as instruments for the comparison of pairs of environments. Houghton and Yagloglou (1923, 1924) and Yagloglou and Miller (1925) worked with trained subjects, inviting them to state whether a given environment gave rise to a sensation of warmth greater than or less than that evoked by another they had left just previously. This technique of 'paired comparisons' was and is much used by experimental psychologists to derive a ranking order in subject matter where no scaled measurement is possible and where no absolute reference point is available, as for example in experimental aesthetics. In the field

of thermal comfort subjects have their own body temperature as a reference point, which is very fortunately standardised between people, and can make a scaled estimate of the magnitude of their own bodily reactions. It was therefore unduly pessimistic to treat thermal comfort as if it were so esoteric a sensation as colour preference, and more recent work has not taken this view. From this and subsequent work the Effective Temperature Scale was derived, specifying any given combination of temperature, humidity and air velocity by the temperature of still, saturated air that would evoke the same sensation of warmth. The Basic Scale was derived for subjects stripped to the waist and the Normal Scale for lightly clothed subjects. In its final form this Index has been widely used, gaining immensely in value by its universality, though it may be criticised on several points. For instance, Yaglou (1949) realised that it seriously overestimates the effect of humidity at low temperatures; this error was due, he says, to the neglect of the thermal effect of moisture absorbed by clothing. Dunham et al. (1946) found that the effects of air velocity at very high temperatures were more complex than depicted by the Index. It makes no allowance for a mean radiant temperature different from ambient temperature, though this can have a large effect on thermal balance and sensations of comfort.

This last objection was overcome by Vernon and Warner (1932), who substituted the globe thermometer reading for the dry-bulb temperature and applied a simultaneous correction to the wet-bulb temperature. Recent work by Ferres et al. (1954) suggests that the simpler correction proposed by Bedford (1964), which omits the wet-bulb correction, gives an adequate description over a very large range of radiant temperature and it is to

be preferred for its simplicity. It should be emphasised, however, that radiant excess temperature was not included in the original work and is an empirical addition at a later date. It lacks elegance in that the effect of air velocity on the Corrected Effective Temperature is now two-fold. The globe thermometer reading is affected by air velocity, in a way not related to variations in sensation, but to its own construction and dimensions. Already difficulties are encountered due to the fact that globe thermometers of two different sizes are in current use. In addition, three different methods are in use of obtaining the wet-bulb temperature, which can also lead to confusion. It is to be hoped that the trend away from integrating devices will continue and that thermal environments will in the future be specified in terms of precise scientific parameters, un-related to the particular methods used for their determination. These need not be parameters obscure in their meaning; the temperature, vapour pressure, air velocity and mean radiant temperature are familiar quantities, precise in their definition, readily understood and independent of each other. Of the nineteen indices described in a recent review article (MacPherson 1962) not one makes use of these four.

The Effective Temperature scale is a means of specifying conditions of equal thermal effect, based on subjective estimates of the physiological effects of heat. It must have been extremely difficult for the experimental subjects to judge, for instance, that an environment in which 80% of their heat loss was due to evaporation did in fact lead to the same total heat loss as another in which only 20% of their heat loss was due to evaporation. They were not asked to estimate their degree of

comfort, for, as the authors pointed out in the original paper, 'at high temperature and humidity there is no comfort'. That they were successful in their aim has been shown by the later work of Houghton, Tongue, Miller and Yant (1951), who showed that the total heat loss was indeed constant at a given Effective Temperature, in spite of the fact that the proportion of heat lost by means of radiation, convection and evaporation differed greatly for different combinations of temperature and humidity. This work involved the careful measurement of heat production by gaseous exchange, of the useful work performed and of the loss in weight by evaporation. It did not rely on the subjective estimates of the subjects. An interesting point is that this confirmatory experiment was concerned with continued occupation, while in the original experiment the subjects made their judgements immediately on entering the second environment. This is a common criticism of the Effective Temperature scale, which is shown by this work to be groundless. The effect of an increased level of working was found to be simply an increased heat load, causing the same pattern of physiological response to occur at a lower Effective Temperature. Thus the subjects, who were men clothed in 'light summer suits', were able when resting to adjust their heat-loss mechanisms in such a way as to maintain their total heat-loss almost exactly constant at 400 Btu/hour over the Effective Temperature range 65-85°F. Continued exposure to an environment above or below this range caused heat storage or loss to occur and their body temperatures could not be maintained by the normal thermo-regulatory means. When working by raising and lowering a weight of 16.8 kg. a distance of 1.494 metres

every 8 sec., their heat loss was constant at about 810 Btu/hour in the range 45-70°F. On consideration of heat balance alone, then, it would appear that an environment that is to be suitable for continued occupation by men who may be sitting still or working at a moderate rate must not lie outside the range 65-70°F. However, mere maintenance of body temperature does not imply comfort. For instance, it may be more comfortable to lose the greater part of the necessary heat-loss by radiation and convection than by evaporation, or the contrary. Which situation will occur at a given Effective Temperature is determined by the particular combination of temperature, humidity, etc. leading to the integrated value. Or again, the most comfortable conditions may lie at any point within the range that is physically tolerable. No measurement of physiological variables can decide these questions, since comfort is a subjective judgement and can be influenced by factors other than those affecting heat balance. One person may simply prefer conditions under which his skin is warm and his neighbour conditions under which his skin remains cool, and though both may be identical in their physical reactions and in the rate of heat loss they require, they will differ in their judgement of a given environment. Bedford (1936) has shown that skin temperature, though associated with feelings of comfort, cannot be used to predict them. At a given value of skin temperature it was possible for an individual to report that he was too hot or too cool, with equal statistical probability. Air temperature was a better index of comfort.



### 3. Historical background of studies of thermal sensation.

A very real advance was made by Bedford in his survey of British factories in winter. For the first time subjects were used who were actually at work in a familiar place instead of taking part in a laboratory experiment. Nearly two thousand workers were questioned in a well-designed interview, making possible the extraction of some order from chaos. They were not asked to compare the environment with some other, but merely, in an informal though strictly standard way, whether they were comfortable. If they replied that they were too warm, they were asked quite simply if they were slightly too warm, or much too warm. If they were cold, a similar form of question. If comfortable, whether they were ideally comfortable or whether they would prefer a temperature slightly warmer or cooler within the comfort range. This resulted in their being placed on a seven-point scale, each category reached in the above way, but labelled perfunctorily much too warm, too warm, etc. and assigned an arbitrary weight. At each level of thermal stress, the numbers of votes obtained in each category, weighted appropriately, were added together and divided by the unweighted total number of votes at that level, to give a figure termed the 'mean thermal vote'. It should be noted that a written form of this questionnaire, in which the subject has all seven categories in front of him, is not the same; ambiguities of language can result and a precise instrument, by mis-use, become less valuable. Many investigators since 1936 have used questionnaires that have a similar form, some with five categories of choice and some with nine, some written and some verbal. Their results are critically compared

in Section II of this thesis. The method used in the present investigation was exactly that of Bedford, and care was taken to avoid 'subject-fatigue' by including many people, questioned infrequently. Many American surveys have tended to use relatively small numbers of subjects, questioned over and over again, apparently in the belief that their subjects can be calibrated and used as integrating instruments. In fact, it appears that so great a part is played by a person's previous thermal experience that no two people can be considered equivalent, even under identical conditions, except insofar as they are each entitled to their own opinion. There is no substitute for a large experimental population if one wishes to generalise the findings of a survey to predict the behaviour of a large population.

The results of Bedford's survey showed that in the range of conditions he studied, the Effective Temperature did not correlate more closely with the mean thermal vote than did the dry-bulb temperature. The 'Equivalent Temperature', a factorial approximation to the reading of Dutton's eupatheoscope, gave a slightly better correlation. A multiple regression equation, incorporating the four thermal parameters of temperature, vapour pressure, air velocity and mean radiant temperature, gave no better correlation with sensation than the Equivalent Temperature. A corresponding survey carried out by Hickish (1955) in summer, supported the view that the dry-bulb temperature was a very satisfactory index of comfort and that little was to be gained by the use of more complex indices under the conditions experienced by light industrial workers in Britain. Even in tropical conditions, the work of Ho (1952) and

Webb (1959) showed that the Effective Temperature gave no improved correlation with thermal sensation over that found using dry-bulb temperature. However, Webb was able to derive a multiple regression equation incorporating temperature, vapour pressure and air velocity into what he called the Singapore Index, quoted like Effective Temperature, in terms of the temperature of still, saturated air that would give rise to the same mean thermal vote. This index, also known as the Equatorial Comfort Index, showed a significantly better correlation with sensation than any other index. It was also simple in form and suitable for digital computation. It was derived by considering the effect of the three thermal factors on the numerical value of the mean thermal vote. The mean radiant temperature did not differ significantly from air temperature, and was ignored.

#### 4. Measures of strain.

The concept of the mean thermal vote as introduced by Bedford can be considered as an accurate but arbitrary measure of physiological strain within the comfort range. No measure of physiological strain has been devised that is not arbitrary. Even one of the most successful, the P4SR (McArdle et al. (1947)), designed for use above the comfort range, though it predicts with a high degree of accuracy the rate of sweating of fit, acclimatised young men, does merely that, and no more. The authors themselves conclude that no formal proof can be offered to show that the rate of sweating is the best index of physiological strain. In itself, though it is expressed in litres per hour, the P4SR is an arbitrary number. No effects other than the sweat rate are implied

by its value per se. In the same way, the value of the mean thermal vote is meaningful only when related by experience to other consequences of thermal stress. It is true that an environment evoking a mean thermal vote of zero from a sufficiently large group of subjects is in a sense the optimum, but even this is not so if the optimum required is the condition under which the maximum number are comfortable and the distribution of votes about the optimum is skew. Further experiments are necessary for indices of this type in order to predict from their value any useful consequences. This has been done in the case of the P4SR by Adam, et al (1955). They have shown that the mean rectal temperature and pulse rate correlate well with the index and can be predicted with some accuracy from its value. These consequences of thermal stress have a greater clinical meaning and limits can be placed on their variation if the subject in question is not to collapse. By this means they predicted that above a P4SR of 3.5 an increasing number of men would be unable to complete a particular work schedule in a four-hour exposure. This is in agreement with the value predicted by McArdle et al (1947) and was supported by experimental evidence. More recent work by Löfstedt (1966) has derived limits for subjects other than fit, acclimatized young men, which are considerably lower. The conclusion of this author was that body temperature was the best index of thermal strain, and that the P4SR was the best available means of predicting changes in body temperature due to thermal stress.

In an exactly analogous way, it should be possible to predict from the value of the mean thermal vote what proportion of a population

will judge the environment to be uncomfortable. This is a meaningful quantity, essential for the design of working environments. A decision must be reached as to what proportion may be permitted to be uncomfortable, but this cannot be decided by scientific analysis and is usually a matter for negotiation. A realistic figure is that more than 80% should be comfortable within the comfort range, although this implies that out of a group of five at least one is likely to be uncomfortable whatever the conditions. Some investigators have found that in their surveys even at the optimum condition, fewer than 80% were comfortable. No general expression has been derived for the distribution of comfort votes about the optimum, even under the commonly encountered conditions of continued occupation by normally clothed people doing light work. In Section II of this thesis a number of surveys covering conditions of this type are reviewed and from their results an expression is derived that relates the width of the comfort range to the optimum temperature and predicts in detail the distribution of votes about the optimum. In addition, the mean thermal vote is shown to be related in a definite way to this distribution.

##### 5. The effect of individual factors of the environment.

It has already been remarked that the effects of the separate parameters of thermal stress may be perceived individually as well as integrated. Thus the effect of increasing air velocity is at first merely to reduce the sensation of warmth, but above a certain point the subject becomes conscious of a draught. The threshold of this sensation has been shown by Baetjer (1924) to be strongly dependent upon the air temperature.

It is clearly desirable to limit the air velocity to a range in which it is perceived neither as too still nor too draughty. This requires a parallel investigation, for it cannot be derived from a knowledge of the integrated effect of all four parameters acting together. Again, there is a central range of humidity which affects only the sensation of warmth, but outside this range a subject will report that quite apart from the resultant thermal sensation, the environment is too dry or too damp. Little work has been done on this, but it is of interest particularly in an operating theatre where the humidity is usually rather high. Miura (1931) states that at 70°F. a relative humidity of 70% is perceived as unpleasantly damp, but one would expect such a sensation to be strongly dependent on other factors, notably temperature and air velocity.

A related problem is that of the 'stiffness' of a room. This common pejorative is frequently used in connection with operating theatres and it might be thought that a reason for this would be apparent. However, Langdon and Keighley (1964) in a review of user research in office design, remark that the definition of stiffness in terms of thermal conditions has not been made. Better understanding exists of the levels of radiant heat that are permissible, due to the common use of this type of heating in industrial situations. The work of Chrenko (1953 a, b.) is particularly relevant since it concerns radiant heating from above and the results are directly applicable to surgeons working beneath a hot lamp. These and other particular effects of the thermal environment are considered in subsequent sections of this thesis.

Three other factors enter into any investigation of heat response,

namely the clothing, rate of working and previous thermal experience of the subjects. All three are usually dictated by the situation and apply more or less equally to all subjects. The number of different investigations made necessary by different combinations of these factors is an indication of the state of understanding of their operation. No generalisation has been made that would enable one to predict satisfactorily the results of their variation. All three affect heat balance, but in a given situation do not vary sufficiently between subjects to explain the wide differences in subjective response obtained, often from people for whom all seven measurable variables take the same value. The reason must be partly due to the bodily differences of the subjects, in terms of build and metabolism. The sex, age, race, build and height of the subjects in the present investigation were recorded and their influence is investigated. Other workers have found differences due to sex, but Yaglou and Messer (1941) showed that these were probably due to differences in clothing. No differences between races have been proved, even under the tropical conditions studied by Webb (1959) and Ellis (1953). British operating theatres provide an opportunity for a controlled comparison of quite large numbers of different races. Hellon and Lind (1956) and Hellon, Lind and Weiner (1956) have shown a marked influence of age on certain physiological reactions to thermal stress, but some associated work reported by Hellon (1957) on the influence of physique was inconclusive. In either case, the differences they found were small in spite of the high levels of thermal stress they investigated. One must certainly look elsewhere in the range of conditions encountered in operating theatres.

## 6. The influence of emotion.

Common figures of speech testify to the influence emotion can have upon thermal sensations; to keep a cool head, and to avoid getting hot under the collar, running a cold sweat or getting cold feet is clearly essential in an operating theatre. It is well known that some bodily reactions to thermal stress, notably sweating, vasodilation and pulse rate, may also be influenced by emotional stimuli. It is reasonable to assume that sensations of comfort or discomfort are also influenced by the subject's state of mind, since although thermal discomfort implies a departure from the body's thermal equilibrium, what is actually perceived is probably only the concomitant effects, the means by which the body attempts to regain a state of heat balance, and some of these may be activated not only by thermal stress but also by emotional stimuli. Most investigations of thermal strain have been directed towards a strictly practical end, and such factors have always been ignored since they are not under the control of architect or heating engineer. Their effects, if present, have been ascribed to 'residual variation'. Even the best indices of thermal stress have therefore shown poor correlation with subjective reaction, and a better understanding of the reasons for residual variation between persons is urgently required if attainable standards of comfort are to be improved. There are obvious difficulties in data collection of this kind, and still greater difficulties of analysis. Previous workers have been unable to cope with more than four simultaneously varying factors. By the use of a multiple regression programme on a modern



electronic computer, these difficulties of analysis may be largely overcome. By this method, it has been possible in the present investigation to include a large number of factors, such as the nature and difficulty of the work in hand, the number of interruptions and the noise level, the speed of working and the tension in the theatre, that might be expected to influence the state of mind, or level of attention of the subject, and hence his perception of the thermal environment. Conversely, thermal stress could be expected to influence the perception of noise, if both are distractions from the task in hand. Bursill (1958) has shown that thermal stress can affect peripheral awareness while performing a central task. The effect disappeared when the central task was easy, and was increased by prolonged exposure to heat. There are two possible mechanisms by which heat could have produced this effect, but so little is known about the interaction of other stresses with heat that it is impossible to decide between them. Broadbent (1957), in a paper on noise, suggested that the perceptual system has a limited channel capacity for information, and that even totally different stimuli can interact by competing for the attention with the task in hand. On this view, one could regard the action of heat as producing distractive bodily stimuli, which then affect the attention by loading the perceptual system. This is a possible explanation for the effects observed by Bursill and this mechanism would predict an interaction between the perception of heat stress and other distractive stimuli in the present investigation. On the other hand, previous work on the interaction of heat with other stresses, which used direct measurements of efficiency, levels of heat

stress well above the comfort range and loud noise or serious sleep deprivation as the other stresses have shown no interaction. (Peplor (1959), Viteles and Smith (1946).) This result is in accordance with the current theory of the action of these stresses. Broadbent (1963) suggests that heat impairs performance by a mechanism of its own, while noise and lack of sleep act on some common mechanism in opposite directions. Bursill suggested that heat was 'altering central levels of attention', a somewhat ambiguous phrase which could lend support to either view. Broadbent pointed out that other levels of heat stress might show some interaction, though by this he meant higher levels which could prevent sleep. All these experiments which have shown performance decrements due to heat have used levels of heat stress very much in excess of those found in operating theatres, and tasks very much simpler and less demanding than surgery. It is usually possible to investigate these effects only in the laboratory, where the task can be designed to give a good measure of efficiency or skill. Perhaps the nearest approach to realism was achieved by Mackworth (1950) who transferred a wireless telegraphy task to the laboratory, and showed a marked effect of heat. An interesting result of his investigation, which was again of very high levels of thermal stress, was that the most skilled operators were the least affected by heat - by an increased effort they were able to maintain their efficiency at a high level. Thus one would expect heat to have its most severe effect when the task in hand is already taxing the ability to the utmost and no reserves of skill are available. This lends support to the possibility that a more complex task could show a performance decrement at lower levels of heat stress.

It is clearly impossible to measure the efficiency with which a surgeon is working, but if the distractive stimuli that compete for his attention with those necessary for the performance of the surgical task, are competing also with the stimuli of his responses to heat stress, then his subjective perception of the thermal environment may be an index of the combined effect of all such stimuli. For instance, a surgeon who is performing a difficult operation on which he must concentrate, may have his concentration taxed to the limit by the noise and movement of staff around him. If he is also aware of the effects of heat, such as an uncomfortable feeling of warmth and a tendency to sweat, these will constitute a much more serious distraction than if he were mentally and physically relaxed, perhaps performing some routine procedure well within his ability and not demanding much concentration. An environment is judged uncomfortable only if its effects are perceived. The above combination of circumstances could have the effect of lowering the threshold of perception, and could result in a judgement of the thermal environment as uncomfortable even though the effects on heat balance were in fact very small. This may be one reason why the thermal environment in operating theatres appears so often to be a scapegoat for feelings of frustration and displeasure whose true causes lie elsewhere. The ways in which the perception of thermal environment is influenced by other factors of the working environment are investigated and discussed in this thesis.

#### 7. Measurement of performance.

Any direct measurement of efficiency or skill should be made simultaneously with the application of the stress under investigation.

This being impossible in the surgical situation, an attempt was made to measure the efficiency which a surgeon could bring to bear on an operation immediately following the exposure to stress. This is in a sense a measure of the fatigue produced by the stress of the preceding session. The method adopted was to measure manual tracking skill on a modified pursuit motor, since this task has been shown by Pepler (1959, 1960) not to discriminate between different types of stress and gives a good measure of performance with quite short test sessions. Using a pursuit task of the rotor type, Teichner and Wehrkamp (1954) were able to show performance decrements due to heat with test sessions of only  $5 \times 20$  sec. duration. This length of test can be fitted into a surgeon's working routine with a minimum of disturbance. However, in an observational survey of the present kind, involving brief visits to a large number of theatres, it was not possible to obtain repeated test scores from each subject, and the results are indicative only.

#### 8. Measurement of physiological variables.

Emotional sweating can take place at all temperatures and is believed to be suppressed by high temperatures (Hellon and Lind 1956). It is most profuse on the palm of the hand and on the forehead. Bodily sweat glands can be influenced by emotional stimuli, but are mainly activated by thermal stress (Kuno 1934). A comparison of the sweat rates on the forehead and the arm could thus yield valuable objective information on the roles played by the two causes of sweating in the theatre situation. This type of investigation cannot be carried out in a laboratory mock-up, because the vital effect of emotional stress would be absent. There were

difficulties in measuring the sweat rate of working surgeons because of the minimal interference with working routine that was permissible. For instance, the usual technique of weighing a subject naked before and after exposure to heat, to determine the total evaporated fluid loss, was ruled out because surgeons are busy men and the apparatus is not easily portable. For the same reasons, measurements of pulse rate and body temperature were not attempted. Continuous recording, involving unacceptable interference with the working routine, would have been necessary if the small variations expected on the results of other work were to be detected. Robinson, Turrell and Gorking (1945) made careful measurements on clothed men working at different temperatures and humidities. They found that at 82°F. neither pulse rate nor rectal temperature were increased significantly above their values at 73°F, regardless of the relative humidity, whereas both sweat rate and skin temperature showed a curvilinear relationship with relative humidity at the higher temperature. Temperatures above 82°F. were recorded very seldom in the present investigation and were usually associated with below-average humidities. Hollon and Lind (1956) found very small changes in pulse rate and rectal temperature even at a temperature of 96°F. It was therefore decided to attempt only measurements of sweat rate and skin temperature. Following a suggestion by Prof. J.S. Weiner, a method of measuring local sweat rate was developed that proved very satisfactory. At the same time, a measure of skin temperature on the back of the neck was obtained. This is the only area of dry skin exposed by surgical garb. The results of this part of the investigation cover necessarily a small

part of the population, as it was not always possible to make the measurements.

#### 9. The present survey.

The present investigation of operating theatres was undertaken because there was very little knowledge of the physical conditions under which surgeons were working and still less of their effects. All measurements taken by engineers had been made necessarily in empty theatres or at the periphery of a theatre in use and had concerned only the four main thermal parameters. The existing methods of measuring the thermal environment, reviewed in this introduction, were impossible to use within or even near the sterile zone at the centre of the theatre and there was reason to believe that the local conditions might be very different within the group about the operating table. Special instruments had to be developed, small, compact, portable and quick-acting. They are described in Section III of this thesis. In addition, the conditions found comfortable by people doing other jobs, less demanding and less tense, did not seem to be satisfactory for surgeons. Over the past thirty years, as Angus (1959) points out, the temperatures required by surgeons have fallen from over 80°F. to somewhere between 60 and 70°F, with no discernible agreement on the optimum. Due to unavoidable, or rather ever-present heat gains, temperatures in British operating theatres fall commonly above this level, especially in summer time, and there has been considerable demand for the installation of cooling plant. The very large volumes of air supplied without recirculation to theatres make this a very costly undertaking, particularly within the framework of a national hospital scheme. An ad hoc investigation

of the nature and extent of the heat problem in theatres was required, and in the course of it the additional data incorporated in this thesis were obtained.

The aims of the work were thus firstly to derive multiple regression equations combining the main parameters of the environment into expressions which predict the subjective reactions of surgeons and operating theatre staff; secondly to investigate their perception of the separate variables, and to set limits on the permissible variation; thirdly to investigate the interaction of the other factors with the perception of the thermal environment and fourthly to support the validity of the subjective work with a number of objective measurements.

SECTION 2.

RECALCULATION OF PUBLISHED DATA.



## 2. 1. Introduction.

A number of surveys carried out in the last forty years have studied in great detail the thermal environment preferred by large groups of people, under conditions that have some relevance to those found in operating theatres. In Table 2.1. are set out eleven such surveys that obtained responses from their subjects by using questionnaire techniques similar to the one used in the present investigation. They cover a range of thermal stress from well below to well above the values found in British operating theatres and they are all concerned with the prediction of zones of comfort, as opposed to zones of physical tolerance. Unfortunately, their results are set out in a wide variety of ways, making detailed numerical comparison virtually impossible. Results are often quoted as a comfort zone for a given arbitrary proportion comfortable. In some cases it would be difficult to derive the comfort zone for a different proportion comfortable.

All the subjects in these surveys were engaged in sedentary or light work, involving little physical effort other than that required to maintain posture. Houghton, Teague, Miller and Yant (1951) have shown that the metabolic rate increases by only ten percent from sitting to standing; this would probably not be sufficient to introduce any meaningful bias to the results of the different surveys. Further, all subjects wore the clothing they considered comfortable, in the main rather light clothing, and were not subjected to mean radiant temperatures measurably different from air temperature.

In spite of these similarities, it was still considered necessary

to carry out large-scale surveys in each case. The different results demonstrate the large part played by the different thermal experience of the groups of subjects. It would be remarkable if no general conclusions could be drawn from such a large research effort, representing conditions under which the vast majority live and work, but no attempt has been made in the literature to do so. The reason is probably that they cover such a large range of temperature and show at first sight such very different results. It is reasonable that special investigations should be made in cases where there are unusual circumstances, such as the need to wear heavy protective clothing, or where high levels of energy expenditure or of radiant heat are encountered, but there should be no need under normal circumstances to do more than discover the optimum temperature to which the group are acclimatised.

In this section data from some of the surveys in Table 2.1. will be re-calculated, making possible their accurate numerical comparison. An expression will be derived from them which relates the width of the comfort zone to the optimum temperature and predicts quite accurately the results of a number of other surveys. The expression makes it possible to extrapolate to other situations and has certain implications for the design of working environments.

## 2. 2. Method.

The aim of any survey of thermal comfort is to obtain a usable measure of sensation. It has long been realised that human judgement is unsuited for scalar estimation of any kind, but recent work has gone further than this. The application of information theory to psychophysics

has produced some remarkably consistent results in the perception of a wide variety of sensory stimuli (Miller 1956). The name 'prothetic' has been given to continua whose perception is believed to be mediated by an additive process at the physiological level, and temperature sensation is one of this class. Miller (op. cit.) shows that there is reason to believe that the limit of human discrimination in the perception of an unidimensional prothetic continuum corresponds to the ability to distinguish reliably between only seven categories of sensation. Thus a powerful theoretical and experimental justification can be made for using the seven-point scale of thermal sensation proposed by Bedford (1936). It could be argued that whole-body sensation is multi-dimensional, particularly as thermal discomfort is really the quantity under investigation. However, thermal questionnaires are usually phrased so as to direct the subject's attention to the task of evaluating temperature rather than the magnitude of his sensation of discomfort, which is thus relegated to a secondary, evaluative role.

The results of a questionnaire can be seen from the foregoing to be not scalar, but semi-quantal at best. No satisfactory statistical treatment of semi-quantal data has been produced. Many comfort studies have recognised this, and sacrificed information by presenting their results merely as a distribution of the percentage comfortable against a thermal index. Bedford's sequence of questioning has the advantage that this presentation represents the result of an actual question requiring the quantal response 'comfortable or not comfortable', whereas this division has to be made artificially by means of the wording of the

category labels of written questionnaires that present all categories at once. The mean thermal vote utilises all categories, but in an arbitrary way, justified by its practical success in producing on most data a linear relationship with temperature. Information is again lost, however, in that there is no implied relationship between the mean thermal vote, and the proportion too cold, comfortable, and too hot. Chronko (1955) showed that the data of Ellis (1952) gave a sigmoidal relationship between the proportion uncomfortable due to heat and the mean thermal vote. The probit transformation (Finney 1947) provides a method of dealing with this, and was used by Webb (1959) for thermal comfort data. In Section 2. 3. a variety of different questionnaires are critically compared by this means. Probit analysis has been developed specifically for the purpose of handling quantal data, to which the results of most comfort surveys can be reduced. In the following section the validity of such reduction will be examined; several different questionnaires will be reduced to quantal form by consideration of their wording, and the results compared with each other. Subsequent sub-sections again use the probit transformation to recalculate published data, following the method set out by Finney (op. cit.), an iterative approximation to the maximum likelihood solution.

### 2. 3. Examination of three forms of questionnaire.

In Table 2. 2. are set out three forms of questionnaire used by different authors. That used by Hickish (1955) is Bodford's original form, also used by Ellis (1952, 1953) and in the present survey. The numerical values assigned to its reply categories are also those used

by Bedford; an added constant brings the optimum vote to zero. In order to obtain values of the mean thermal vote comparable with each other and with Bedford's results, numerical values had to be assigned to the differently worded response categories used by the several authors. In order to test these weightings, the mean thermal vote has been calculated for the published data. The proportions reporting discomfort due to heat and due to cold have been derived by taking together those categories with weights (+2, +3) and (-2, -3) respectively. The probits of these proportions are plotted, in Graphs 2.1, 2.2 and 2.3, against the mean thermal vote. In every case, the result is a good straight line, which indicates a normal distribution of response to the questionnaire. Also, the optimum as defined by a mean thermal vote of zero is in each case the point of intersection of the probit lines, which is the point at which the proportion 'too hot' is equal to the proportion 'too cold'. This indicates that the mean thermal vote gives a true estimate of the optimum, without bias due to the wording. The slope of the 'hot discomfort' regression on the mean thermal vote takes a closely similar value in all three cases, namely 1.15-1.21. Data for the 'cold discomfort' line is very scanty in these investigations, except in the case of Houghten and Cook (1939), where the slope of this line agrees closely with that of the hot discomfort line. There is some indication that the slope of the cold discomfort line is greater in the data of Hickish(1955) and less in the case of Webb(1959). This would indicate that the mean thermal vote is more sensitive to the proportion 'too cold' when the temperature is high than it is when the temperature is low. The indicated optimum was at 67°F. D.B. for Hickish subjects, at 73°F.D.B. for those of

Houghton and Cook, and at 82°F. D.B. for those of Webb. Clearly, more clothing could be worn by the British factory workers than by the residents of Singapore, and this could lead to the effects observed. The more heavily clothed subjects, though considering a particular temperature on balance 'too cold', would perhaps less readily choose the extreme category for recording their sensation, and the mean thermal vote would therefore appear less sensitive to the proportion too cold.

Thus far, the mean thermal vote would seem to be related to the probit values in a uniform way, enabling a prediction of the proportions too cold and too hot to be made from a knowledge of the mean thermal vote. Unfortunately there is a large systematic variation in the probit values corresponding to a given mean thermal vote for the different populations. At a mean thermal vote of zero, the corresponding probit values are 3.10, 3.72 and 3.89 respectively for the data of Hickish, Houghton and Cook, and Webb, i.e. a steadily increasing proportion uncomfortable, due to heat and cold equally, with an increase in the temperature to which the group is acclimatised. These figures correspond to 94.4% comfortable at 67°F, 80% comfortable at 75°F, and 73.3% comfortable at 82°F, these uncomfortable being divided equally between those too hot and too cold at these optimum temperatures. No great reliance can be placed on the exact figures, since they were obtained from the point of intersection of two probit lines, occurring at low values of response in each case. The probit method affords a very reliable estimate of the 'median' value, at which 50% response is obtained, and an attempt to evaluate the relationship between the comfort zone and the optimum temperature will in the following sub-section be based on this fact.

Summary The following conclusions may be drawn from this examination of questionnaire technique and weightings:-

1. The replies leading to a given value of the mean thermal vote are normally distributed and therefore suitable for probit analysis.
2. The weighting suggested in Table 2. 2. leads to comparable values of the mean thermal vote and may also be used to reduce the results to comparable quantal form.
3. The mean thermal vote gives an un-biased estimate of the optimum.
4. The probit,  $P$ , of the proportion reporting discomfort due to heat is related to the mean thermal vote,  $M$ , by an equation of the form  $P = aT + b$ , where  $a = 1.18 \pm 0.03$ , and  $b$  takes a value specific to the experimental population, tending to increase with increasing optimum temperature and lying in the range 3 - 4.
5. A similar relationship holds for the proportion reporting discomfort due to cold, with the same value for ' $b$ ', but some indication that ' $a$ ' may vary with optimum temperature.
6. The mean thermal vote is thus an extremely useful index of the comfort response of a group, particularly for use as the dependent variable in a computer analysis, since it is readily generated without reference to tables, unlike probit values. It may not, however, be transformed to any measure of the proportion too hot, comfortable or too cold, without further investigation of the relationship that holds for a particular body of data.

## 2. 4. Comparison of the form of published response distributions.

This section examines the data published in the first five surveys appearing in Table 2.1. The mathematical calculations have been carried out by means of probit regression analysis; the results are given in Tables 2.3.-2.8. The text consists of a discussion of these results in some detail.

### 1. Three tropical surveys

Conditions in operating theatres may involve heat, high humidity and low air velocity. These conditions are encountered to a much greater degree in the tropics. The results of tropical surveys might therefore have some relevance to the present survey, bearing in mind the additional factor of long-term acclimatisation.

Table 2.3. sets out the numerical results of five probit regression analyses of data from the surveys of Ellis (1952, 1953) and Webb (1959), and one graphical estimate where the numbers of observations on which the published figures were based were not given. This made it impossible to assign the correct weights in the calculation. The published results were reduced to quantal form by deriving in the first instance the proportion reporting discomfort due to warmth, as the reply categories weighted (+2, +3) in Table 2.2. The surveys of Ellis used Bedford's form of questionnaire, though in written form. In reading the necessary data from Fig.2, p.392, of Ellis (1953), an assumption was involved, namely that none of the men was too cold above the point where 100% were 'reasonably comfortable'. This was not stated specifically, as the data was presented in the form of a plot of the percentage 'reasonably comfortable' against



Normal Effective Temperature. Significant heterogeneity was found in these results, and has been allowed for in the estimation of standard deviations. The 'warmth discomfort' results for Webb's data are his own, except that the '10% level', above which more than 10% of the population experienced discomfort, has also been calculated. The calculation of the standard deviation for this result involved the assumption that the mean value of the thermal index lay close to the median value. With these exceptions, the results shown in Table 2.3. are numerically accurate representations of the published data. The detailed probit calculations, though very lengthy, have the advantage that they permit accurate statistical comparison of the results. The graphical representations of these data that have been published are of comparatively little use for this purpose.

On the basis of these calculations, it can be shown that the observed differences between the slopes of the probit regression do not approach significance, and that the observed differences between the median values, though significant at the 0.05 level, are within 1.F.<sup>0</sup> of their mean, and therefore of little practical significance. The '10% levels' of the indices, at which 10% of the subjects reported discomfort due to warmth, are not significantly different. Thus regardless of the chosen index, more than 10% of the subjects reported discomfort above 78°F, and more than 50% above 82°F. This close agreement between three different indices, all expressed as the temperature of an equivalent environment whose relative humidity is 100% and whose air velocity is zero, is a very good indication of their validity.

In Section B of Table 2.3. are set out the corresponding calculations on the same data for the proportion reporting any sensation of warmth, i.e. those whose reply would be weighted +1, +2 or +3. The data for these calculations were all given explicitly, and it was thought they might serve as a check on the previously mentioned results. It may be seen that the heterogeneity in the data of Ellis (1953) has disappeared; it could therefore have been due to the assumption made in reading the data. On the other hand, the data of Ellis (1952) here shows very significant heterogeneity. There is no reason to suppose that this would not also have appeared had the figures been available for calculation in Section A. The subjects in this survey were sailors on board a warship, and there was very considerable variation in the clothing they wore. A proportion were stripped to the waist; Ellis shows that this proportion varied directly with temperature. It is not surprising that with this additional factor the probit regression on an index that does not take account of variations in clothing should give an inadequate description of the results. The method is highly satisfactory for the other surveys, where no great variation in clothing took place, but it will be shown below that in a survey of British factory workers whose clothing also varied according to choice, it again provides an inadequate description.

The slope of the 'warmth' regression lines in Section B of Table 2.3. are all lower than their 'warmth discomfort' counterparts in Section A, but the differences are not statistically significant. The median values of the indices in Section B, at which 50% of subjects reported some

sensation of warmth, differ from each other significantly at the 0.001 level, and so do the 10% values. Reference will be made to these differences in Section 2.4. where it will be shown that they vary systematically with the acclimatisation of the subjects. All six values differ from their 'warmth discomfort' counterparts in Section A of Table 2.3. significantly at the 0.05 level or better.

Webb (1959) found that his Singapore Index, also called the Equatorial Comfort Index, showed better correlation with mean thermal vote than did Effective Temperature, but it should be noted that the weights he assigned to his response categories in the calculation of the mean thermal vote were not those of Table 2.2, and thus not directly comparable with the work of Bedford.

## 2. American surgeons and operating theatre staff at work.

The survey of Houghton and Cook (1939) was carried out in one operating theatre during a summer period of three months. It involved questioning a small group of people many times. Relative humidity was held constant at 50%, air velocity was not varied and presumably all other factors remained more or less constant while the air temperature was varied within fairly narrow limits. The numbers of responses obtained are too small to allow any separation of different staff categories. The results of two probit regression analyses carried out on this data are set out in Table 2.4. The index of thermal stress was the Effective Temperature. The results may be compared with each other and with the results of the three tropical surveys dealt with above.

The difference in shape between the 'warmth discomfort' and 'cold

discomfort' regression does not approach statistical significance, ignoring the difference in sign. Data for response to cold were here more numerous than in the tropical surveys, since the investigation was of a new cooling plant. This result is therefore good evidence for the view that sensitivity to heat and to cold are equal in the comfort range.

There is very striking agreement between the slopes of these regressions and the corresponding values in the tropical surveys. The warmth discomfort regression has exactly the same slope as that published by Webb, which has been shown above to be not significantly different from those calculated for the data of Ellis. Similarly, the cold discomfort regression has a slope that does not differ significantly from the value published by Webb. The corresponding figures are shown for comparison in Table 2.5. It may be seen that the data of Webb shows more heterogeneity, possibly because the survey was carried out under less controlled conditions, but this has been allowed for in the calculation of the standard deviations on which the statistical comparisons are based. However, none of the values of chi-square in Tables 2.4 and 2.5 approach statistical significance.

Although the responses of American surgeons and operating theatre staff to changes in Effective Temperature are thus shown to be the same as for a wide variety of subjects in the tropics, the preferred levels of temperature differ greatly. The median level of thermal stress, at which 50% of the American subjects reported discomfort due to heat, is  $8.9 \pm 0.5.F.^{\circ}$  below the median level for the tropical subjects, and the median level for discomfort due to cold is  $11.9 \pm 0.7.F.^{\circ}$

below the corresponding figure. These large differences are almost certainly due to long-term acclimatisation, determined by the previous thermal experience of the subjects.

The difference between the level of thermal stress at which 50% were too hot and the level at which 50% were too cold may be termed the 'median range'. Its value for the American subjects was  $8.0 \pm 0.6.F.^{\circ}$ , and for the tropical subjects,  $5.0 \pm 0.6.F.^{\circ}$ . The difference between these two median ranges,  $3.0 \pm 0.85.F.^{\circ}$ , is significant at the 0.01 level. This is statistical proof of an observation made by Webb (1959), that his distribution of the percentage comfortable versus thermal stress index 'seemed to be both sharper and lower than those obtained in cooler climates'. The maximum percentage comfortable was 68% at  $78.7^{\circ}F.$  for Webb's subjects, 86% at  $68.5^{\circ}F.$  for the American subjects. The most reliable estimate of the optimum temperature is to determine the centre of the median range, since the point of intersection of two probit regression lines is greatly influenced by small errors in the slope of each line.

### 3. British factory workers in summer.

The survey of Hickish (1955) was carried out in Britain during the summer months, and involved questioning a large number of light industrial workers while they were actually at work. Since it concerns subjects acclimatised to British temperatures, it is of interest in the present connection. However, unlike the tropical or American surveys examined above, it covers lower levels of temperature and humidity and higher levels of air velocity than are actually found in operating theatres. Possibly as a result of this, Hickish was led to the same conclusion as

Bedford, that dry-bulb air temperature was an adequate index of thermal stress. He laid great emphasis on the occurrence of a discontinuity in the relationship between the mean thermal vote and dry-bulb temperature, and called this the upper limit of thermal comfort. Such a discontinuity is extremely difficult to locate with any accuracy unless very large numbers of subjects have been questioned. The data were published as a vote distribution against dry-bulb temperature and this made possible the probit analyses whose results appear in Table 2.6. For comparison, the data of Webb (1959), which were published in admirably full detail, were recalculated as probit regressions against dry-bulb temperature; the results of these calculations appear in Table 2.7.

It can be seen that in thus neglecting the effects of the other thermal variables, significant heterogeneity has been introduced to the data of Webb (cf. Table 2.5.), though no systematic departure from a straight line can be seen in graphical representation. In addition, the slopes of the probit regressions against dry-bulb temperature are significantly lower than those against the Singapore Index, though both are expressed in Fahrenheit degrees. This result is to be expected from Webb's equations for mean thermal vote in terms of these two indices of thermal stress. In the case of the 'warmth discomfort' regression, the difference is significant at the 0.01 level, but the 'cold discomfort' slope does not differ significantly from the value against the Singapore Index. This would lead one to suspect that the sensitivity of Webb's subjects to cold as measured by dry-bulb temperature was higher than to heat similarly measured. The two regression coefficients in question appear in Table 2.7. A calculation

shows that the probability of their observed difference arising by chance is greater than 0.05. The most one can say is that even this apparently large difference between sensitivity to heat and to cold does not disprove the view that they are equal. Similarly, the large difference between the regression coefficients for the data of Hickish, which are shown in Table 2.6, does not approach statistical significance.

Considering the results of the probit analysis of the warmth discomfort data of Hickish in more detail than is given in Table 2.6, it can be shown that the existence of the discontinuity referred to by Hickish depends on two points, at 74°F. and at 80°F, which deviate from the regression significantly at the 0.01 level but not at the 0.001 level. Evidently the straight probit regression gives quite a good description of the data; the calculated regression coefficients do not differ significantly from the corresponding ones of Webb in Table 2.7. In Table 2.8 the 'warmth' regression results for Webb and for Hickish are set out for comparison. Again, the regression coefficients agree closely; the probability of the observed difference arising by chance is greater than 0.30. Thus it may be seen that the sensitivity of British factory workers to heat and to cold is closely similar to the sensitivity of Webb's tropical subjects, despite the fact that the two groups are acclimatised to very different temperatures.

#### 4. Summary.

The following conclusions can be drawn from the discussions of the calculated probit regression results in Section 2.4:-

1. Normal Effective Temperature, Basic Effective Temperature and the Singapore Index, used where they are appropriate, are comparable in

all respects when related to subjective responses.

2. Group sensitivity to heat and to cold appears to be equal in and near the comfort range. A given increase in temperature will produce an increase in the probit of the proportion too hot equal to the simultaneous decrease in the probit of the proportion too cold.

3. Acclimatisation to widely different temperatures does not alter the sensitivity of groups of subjects to changes in temperature. A given increase in temperature will produce the same increase in the probit of the proportion too hot and decrease in the probit of the proportion too cold whatever their state of acclimatisation in the range 60-90°F.D.B.

## 2. 5. The relationship between the median range and the preferred temperature for a group.

This sub-section will consider again the results presented in the previous sub-section, and will extrapolate from them to predict the results of other surveys.

The median range for the British subjects was  $14.6 \pm 1.1^{\circ}\text{F.}^{\circ}$ , the centre being at  $68.6^{\circ}\text{F.}$  The median range for the tropical subjects was  $4.3 \pm 1.0^{\circ}\text{F.}^{\circ}$ , with the centre at  $81.0^{\circ}\text{F.}$ , these figures referring to dry-bulb temperature. The data of Houghten and Cook (1939) can be transformed to dry-bulb temperature, working backwards on the Effective Temperature nomogram. This is only possible because the relative humidity was constant at 50% and the air velocity at 20 feet per minute. The median range then becomes  $10.5 \pm 0.6^{\circ}\text{F.}^{\circ}$ , with the centre at  $72.6^{\circ}\text{F.}$



Graph 2.4 shows the distribution of the percentage comfortable in these three surveys, obtained as smoothed curves by the transformation of the calculated probit regressions equations. It may at once be seen that the medium range decreases systematically with increasing optimum temperature for the group. The form of the relationship is shown in the Graph 2.5. From this it is possible to predict the medium range for a group if the optimum temperature for the group is known. If, further, a figure can be assumed for the slope of the probit regression, the entire distribution of subjective response is defined. Since the figures for the slopes in Tables 2.6 and 2.7 have been shown not to differ significantly from each other, it is legitimate to take their mean as a reasonable prediction of the slope for a hypothetical response distribution. The mean is  $0.27 \pm 0.05/F^{\circ}$ .

As an example, it is instructive to calculate the distribution for the data of Bedford (1936), given only that the optimum dry-bulb temperature was about  $64^{\circ}F$ . This survey was of British factory workers in winter, wearing heavier clothing than in any of the three surveys used to derive the expression. It is for this reason that it has not been considered in detail. From Graph 2.5 it can be seen that the predicted median range is  $17.9.F.^{\circ}$ . Bedford (1964) quotes a range within which more than 86% were comfortable. Using the mean slope of  $0.27/F^{\circ}$ , the width of this range is calculated to be:

$$\left\{ 17.9 - \frac{2(5 - 3.92)}{0.27} \right\} = 9.9 F^{\circ},$$

since the probit of 14% is 3.92, and of 50%, 5.00. It should be noted that it is permissible here to take '14% too hot' as the upper limit, and '14% too cold' as the lower limit of the required range only because the calculated probit of the proportion too cold at the upper end (and too hot at the lower end) is 1.25, which corresponds to less than 0.1% and is therefore quite negligible. The predicted range within which 86% of Bedford's subjects could be expected to be comfortable, is therefore calculated to be 59-69 °F. Bedford quotes the range 60-68 °F, in close agreement. His figures were derived from a histogram with groupings of 1.F.°, and are thus not more accurate than this.

By means of a similar calculation, using the mean slope of 0.27/ F° and the fact that the probit of 10% is 3.72, it may be calculated that the '10% range' predicted by this method will be :

$2 \left\{ 5 - \frac{3.72}{0.27} \right\} \text{ F}^\circ$  narrower than the median range for a hypothetical distribution, i.e. 9.5 F° narrower. When this is drawn in Graph 2.5 it can be seen that the '10% range' will be zero when the optimum temperature is about 74 °F. This means that when a group of subjects are acclimatised so that their optimum temperature lies above 74° F, fewer than 80% will be comfortable even at the optimum. In the case of Webb's subjects, for instance, only 43% were comfortable at the optimum temperature of 81° D.B. The remainder were equally divided between those too hot and those too cold. If the above relationship is generally true, the higher the preferred temperature for a group, the smaller the proportion comfortable at the optimum. In the last

thirty years preferred temperatures have increased considerably; the consequences could be inconvenient.

The remaining surveys appearing in Table 2.1 quote their results in terms of Effective Temperature. Similar calculations based on the figures in Tables 2.4 and 2.5 lead to the relationship shown in Graph 2.6 between the median range and optimum temperature for a group when both parameters are quoted in terms of Effective Temperature. The mean slope is here  $0.38 \pm 0.05/F.^{\circ}$  (E.T.), and leads to a prediction that the '10% range' will be  $6.8 F.^{\circ}$  (E.T.) less than the median range, and thus zero at  $73^{\circ}F.$  (E.T.). When a group of subjects are acclimatised so that their optimum temperature lies above  $73^{\circ}F.$  (E.T.) the prediction is that fewer than 80% of their number will be comfortable, even at the optimum. It may also be seen that for an optimum temperature of  $66^{\circ}F.$  (E.T.), the '10% range' is only  $2.F^{\circ}$ ; this means that the environment must be controlled to within  $1.F^{\circ}$  at  $66^{\circ}F.$  (E.T.) if fewer than 10% are to complain of either heat or cold. Using the relationship shown in Graph 2.6, ( $X = 0.29 (96 - T_{OPT.})$ , where X is the width of the median range and  $T_{OPT.}$  is the optimum Effective Temperature for a group), and the mean value of the probit regression coefficient,  $0.38/F^{\circ}$  (E.T.), the predictions set out in Table 2.9 may be made. They agree closely with the results of the actual surveys, which are also shown in the table, the limits of the predicted ranges being in every case within  $\pm 0.7F.^{\circ}$  (E.T.) of the figures found by experiment.

Table 2.10 shows the equations derived from the re-calculations

of published results that appear in Section 2.4. They predict with considerable accuracy the response distributions of groups of people acclimatised to temperatures in the range  $65 - 85^{\circ}\text{F}$ , providing that they are lightly clothed and not performing much physical work. They do not hold good for European visitors to the tropics; a reason for this is suggested in sub-section 2.6. They may be used to predict the response distributions that will be obtained when a group of people have become acclimatised to a particular temperature. Thus if an enclosure is to be maintained at a given temperature, these equations can be used to define the limits of permissible variation. They may be of use in the design of control equipment, and also in deciding in advance the temperature which a group should be 'conditioned' to prefer.

#### Summary.

Equations have been derived which predict the response distributions of groups of people acclimatised to temperatures in the range  $65 - 85^{\circ}\text{F D.B.}$ . The preferred, or optimum, temperature for the group has been shown to have a systematic influence on the distribution parameters. In general the equations should be taken to apply to conditions rather warmer than ideal, to which a group has habituated if not acclimatised.

#### 2.6. Acclimatisation and subjective sensation.

Ellis (1952) reported the surprising result that men who had been twelve months in the tropics were less tolerant of heat than

the same men after six months, and that a period of a week spent in a cooler climate had no effect on their thermal responses. This suggests at once that physical acclimatisation was playing a considerably smaller part than were changes in mental attitude towards the heat. On first arriving, men would expect to be uncomfortably hot almost all the time. As time went on they presumably achieved a measure of physical adjustment, such as marginally increased capacity to sweat, altered behavior and activity patterns, and so on, but as they became able to be comfortable some of the time, they would become correspondingly intolerant of conditions to which they could not adjust.

Section 2.4 showed that the subjects in the surveys of Ellis (1952), Ellis (1953) and Webb (1959) had all by habituation reached the stage where 50% would call conditions below 82 °F (E.T.) 'reasonably comfortable'. However, the results in Table 2.3 B show that 50% of their number experienced a sensation of warmth at 75.3°, 78.2° and 79.6 °F (E.T.) respectively. These figures are significantly different from each other at the 0.001 level. Examination of the original data shows that the subjects in each survey had been in the tropics less than one year, less than two and a half years and more than ten years respectively. This shows a slight but significant acclimatisation over a long period.

The comfort ranges found by Ellis in his two surveys were much wider than those found by Webb or than those predicted by the equations of Table 2.10. It has been shown that the upper

limits of the median ranges in these three surveys co-incide exactly at 82° F (E.T.). The anomalies are thus due to tolerance of cold. The subjects in Ellis' surveys were Europeans who might hesitate to describe any temperature above 70 °F as 'too cold'. The subjects in Webb's survey, who were either indigenous to Singapore or had lived there a very long time, were in no such artificial situation. Thus although their physical acclimatisation was better, they were used to being comfortable and more intolerant of deviations from the ideal than the Europeans who had recently arrived in the tropics and were therefore used to being uncomfortable. Thus it may be seen that acclimatisation to heat can have the paradoxical effect of reducing the comfort range as defined by subjective response.

#### Summary

A long-term physical acclimatisation to heat is demonstrated from the published literature. It is shown to be associated with reduced subjective tolerance of deviations from the ideal temperature conditions.

Table 2.1. Survey results examined in Section 2.

Data from the following surveys are recalculated by probit analysis:

| Reference.             | Subjects questioned in survey.              |
|------------------------|---------------------------------------------|
| Ellis (1952)           | British naval personnel, tropics, shipboard |
| Ellis (1953)           | British civilians, tropics.                 |
| Hickish (1955)         | British factory workers, summer.            |
| Houghten & Cook (1939) | American surgeons, theatre staff, summer.   |
| Webb (1959)            | Residents of Singapore.                     |

The response distributions of the following surveys are compared with theoretical predictions based on the above recalculations.

| Reference                  | Subjects questioned in survey    |
|----------------------------|----------------------------------|
| Bedford (1936)             | British factory workers, winter. |
| Newton, et al (1958)       | American office workers, summer. |
| Partridge & Maclean (1935) | Canadian school children.        |
| Rummel, et al (1939)       | American office workers, summer. |
| Yaglou (1926)              | American subjects.               |
| Yaglou & Drinker (1928)    | American subjects, summer.       |

Table 2.2. Forms of questionnaire; weighting of response categories

| Weighting for present purpose | Response categories              |                                     |                  |
|-------------------------------|----------------------------------|-------------------------------------|------------------|
|                               | Bedford (1936)<br>Hickish (1955) | Houghten & Cook (1939)              | Webb (1959)      |
| 3                             | much too warm                    | (Decidedly hot)x<br>Decidedly warm  | Excessively hot  |
| 2                             | Too warm                         | Slightly warm                       | Hot<br>Warm      |
| 1                             | Comfortably warm                 |                                     | Comfortably warm |
| 0                             | Comfortable                      | Ideal comfort                       | Comfortable      |
| -1                            | Comfortably cool                 |                                     | Comfortably cool |
| -2                            | Too cool                         | Slightly cool                       | Cool<br>Cold     |
| -3                            | Much too cool                    | Decidedly cool<br>(Decidedly cold)x | Excessively cold |

x Not obtained.

Note: Only those replies within the central zone (-1,0,+1) mention the word 'comfort'. In assigning weights intended to lead to comparable values of the Mean Thermal Vote, the distinctions between 'warm' and 'hot', and between 'cool' and 'cold' have been ignored as being too ambiguous.



Table 2.3. Probit analysis of three tropical survey results

A. The regression of the probit of % 'uncomfortable due to warmth (+2, +3), on thermal stress.

| Source       | Thermal Stress Index | Slope(S.D)       | Median(S.D.)     | 10% Value (S.D)  | $\chi^2$                         |
|--------------|----------------------|------------------|------------------|------------------|----------------------------------|
| Ellis (1952) | Basic E.T.           | 0.40 $\pm$ 0.04  | 80.5 $\pm$ 0.9°F | 77.0 $\pm$ 1.0°F | -                                |
| Ellis (1953) | Normal E.T.          | 0.356 $\pm$ 0.05 | 82.4 $\pm$ 0.4°F | 78.8 $\pm$ 0.3°F | <sup>x</sup><br>24.2<br>on 5d.f. |
| Webb (1959)  | Singapore Index      | 0.39 $\pm$ 0.05  | 81.2 $\pm$ 0.3°F | 77.9 $\pm$ 0.5°F | 13.5<br>on 9d.f.                 |

B. The regression of the probit of % reporting any sensation of 'warmth' ( 1, 2, 3), on thermal stress.

| Source       | Thermal Stress Index | Slope(S.D)      | Median(S.D)       | 10% Value (S.D)  | $\chi^2$                           |
|--------------|----------------------|-----------------|-------------------|------------------|------------------------------------|
| Ellis (1952) | Basic E.T.           | 0.28 $\pm$ 0.02 | 75.3 $\pm$ 0.3°F  | 70.7 $\pm$ 0.5°F | <sup>x</sup><br>60.0<br>on 12 d.f. |
| Ellis (1953) | Normal E.T.          | 0.29 $\pm$ 0.01 | 78.2 $\pm$ 0.04°F | 73.8 $\pm$ 0.2°F | 11.9<br>on 10d.f.                  |
| Webb (195 9) | Singapore Index      | 0.34 $\pm$ 0.04 | 79.6 $\pm$ 0.2°F  | 75.8 $\pm$ 0.5°F | 14.2<br>on 11d.f.                  |

x Indicates statistically significant heterogeneity.

Table 2.4 Probit analysis of data from Houghten & Cook (1939)

(Probit of % uncomfortable versus Effective Temperature)

| Discomfort<br>due to: | Slope<br>(S.D.)  | Median<br>(S.D.)             | 10% value<br>(S.D.)          | $\chi^2$          |
|-----------------------|------------------|------------------------------|------------------------------|-------------------|
| Warmth<br>( 2, 3)     | $0.39 \pm 0.05$  | $72.3 \pm 0.4^\circ\text{F}$ | $69.1 \pm 0.3^\circ\text{F}$ | 2.67<br>on 6 d.f. |
| Cold<br>(-2, -3)      | $-0.34 \pm 0.05$ | $64.3 \pm 0.5^\circ\text{F}$ | $68.1 \pm 0.5^\circ\text{F}$ | 1.25<br>on 7 d.f. |

Table 2.5. Probit analysis published by Webb (1959)

(Probit of % uncomfortable versus Singapore Index)

| Discomfort<br>due to: | Slope<br>(S.D.)  | Median<br>(S.D.)              | 10% value<br>(S.D.) x          | $\chi^2$          |
|-----------------------|------------------|-------------------------------|--------------------------------|-------------------|
| Warmth<br>( 2, 3)     | $0.39 \pm 0.05$  | $81.2 \pm 0.25^\circ\text{F}$ | $(77.9 \pm 0.5^\circ\text{F})$ | 13.5<br>on 9 d.f. |
| Cold<br>(-2, -3)      | $-0.40 \pm 0.06$ | $76.2 \pm 0.5^\circ\text{F}$  | $(79.4 \pm 0.7^\circ\text{F})$ | 11.0<br>on 8 d.f. |

x The calculation of the 10% value has been carried out from the published figures; an assumption is involved in the calculation of the standard deviation. Reference to this is made in the text.

Table 2.6 Probit analysis of data from Hickish (1955)

(Probit of % uncomfortable versus Dry bulb temperature).

| Discomfort<br>due to: | Slope<br>(S.D.)  | Median<br>(S.D.)             | 10% value<br>(S.D.)          | $\chi^2$              |
|-----------------------|------------------|------------------------------|------------------------------|-----------------------|
| Warmth<br>( 2, 3)     | $0.26 \pm 0.02$  | $75.9 \pm 0.4^\circ\text{F}$ | $70.9 \pm 0.4^\circ\text{F}$ | $34.1^x$<br>on 9 d.f. |
| Cold<br>(-2-3)        | $-0.33 \pm 0.06$ | $61.3 \pm 1.0^\circ\text{F}$ | $65.2 \pm 0.5^\circ\text{F}$ | $0.9$<br>on 2 d.f.    |

x Indicates statistically significant heterogeneity.

Table 2.7. Probit analysis of data from Webb (1959)

(Probit of % uncomfortable versus Dry bulb temperature).

| Discomfort<br>due to: | Slope<br>(S.D.)  | Median<br>(S.D.)             | 10% value<br>(S.D.)          | $\chi^2$               |
|-----------------------|------------------|------------------------------|------------------------------|------------------------|
| Warmth<br>( 2, 3)     | $0.18 \pm 0.05$  | $83.1 \pm 0.7^\circ\text{F}$ | $75.8 \pm 2.2^\circ\text{F}$ | $47.6^x$<br>on 13 d.f. |
| Cold<br>(-2,-3)       | $-0.32 \pm 0.06$ | $78.8 \pm 0.7^\circ\text{F}$ | $82.8 \pm 0.5^\circ\text{F}$ | $19.9^x$<br>on 9 d.f.  |

x Indicates statistically significant heterogeneity.

Table 2.8. Probit analysis of data from Hickish (1955) and Webb (1959)

(Probit of % reporting any sensation of 'warmth' versus Dry bulb temperature)

| Data From                        | Slope<br>(S.D.) | Median<br>(S.D.) | 10% value<br>(S.D.) | $\chi^2$                       |
|----------------------------------|-----------------|------------------|---------------------|--------------------------------|
| Hickish (1955)<br>( 1, + 2, + 3) | 0.22±0.02       | 71.5±0.2°F       | 65.7±0.5°F          | 16.8 <sup>x</sup><br>on 3 d.f. |
| Webb (1959)<br>( 1,+2,+3)        | 0.17±0.05       | 83.1±0.9°F       | 75.6±2.7°F          | 24.5 <sup>x</sup><br>on 5 d.f. |

x Indicates statistically significant heterogeneity.

Table 2.9. Prediction and comparison of the results of other surveys.

| Source                      | Optimum<br>E.T. | Criterion<br>% comfortable | Predicted<br>range, E.T. | Published<br>range, E.T. |
|-----------------------------|-----------------|----------------------------|--------------------------|--------------------------|
| Bedford (1964)<br>p. 97.    | 60°             | 86%                        | 57.6-62.4°               | 57-63°                   |
| Yaglou<br>(1926)            | 67°             | 50%                        | 62.8-71.2°               | 63-71°                   |
| Patridge &<br>Maclean(1935) | 66.5°           | 50%                        | 62.2-70.8°               | 61.5-71.5°               |
| Yaglou &<br>Drinker(1926)   | 70.8°           | 50%                        | 67.1-74.4°               | 66.5-75°                 |
| Rummel et al<br>(1939)      | 71.7°           | 50%                        | 68.2-75.2°               | 68.4-75°                 |
| Newton et al<br>(1938)      | 70.0°           | 50%                        | 66.2-73.8°               | 66.9-73.6°               |

Table 2.10. Comfort vote distributions

When  $P_H$  = Probit of the proportion reporting discomfort due to warmth.

$P_C$  = Probit of the proportion reporting discomfort due to cold.

$T_{OPT}$  = Optimum temperature to which the group are acclimatized.

$T$  = Temperature in  $^{\circ}F$ .

- the following equations define the predicted family of curves:

Effective Temperature.

$$P_H = 0.38 T - 0.325 T_{OPT} - 0.29$$

$$P_C = -0.38 T + 0.435 T_{OPT} - 0.29$$

Dry bulb temperature

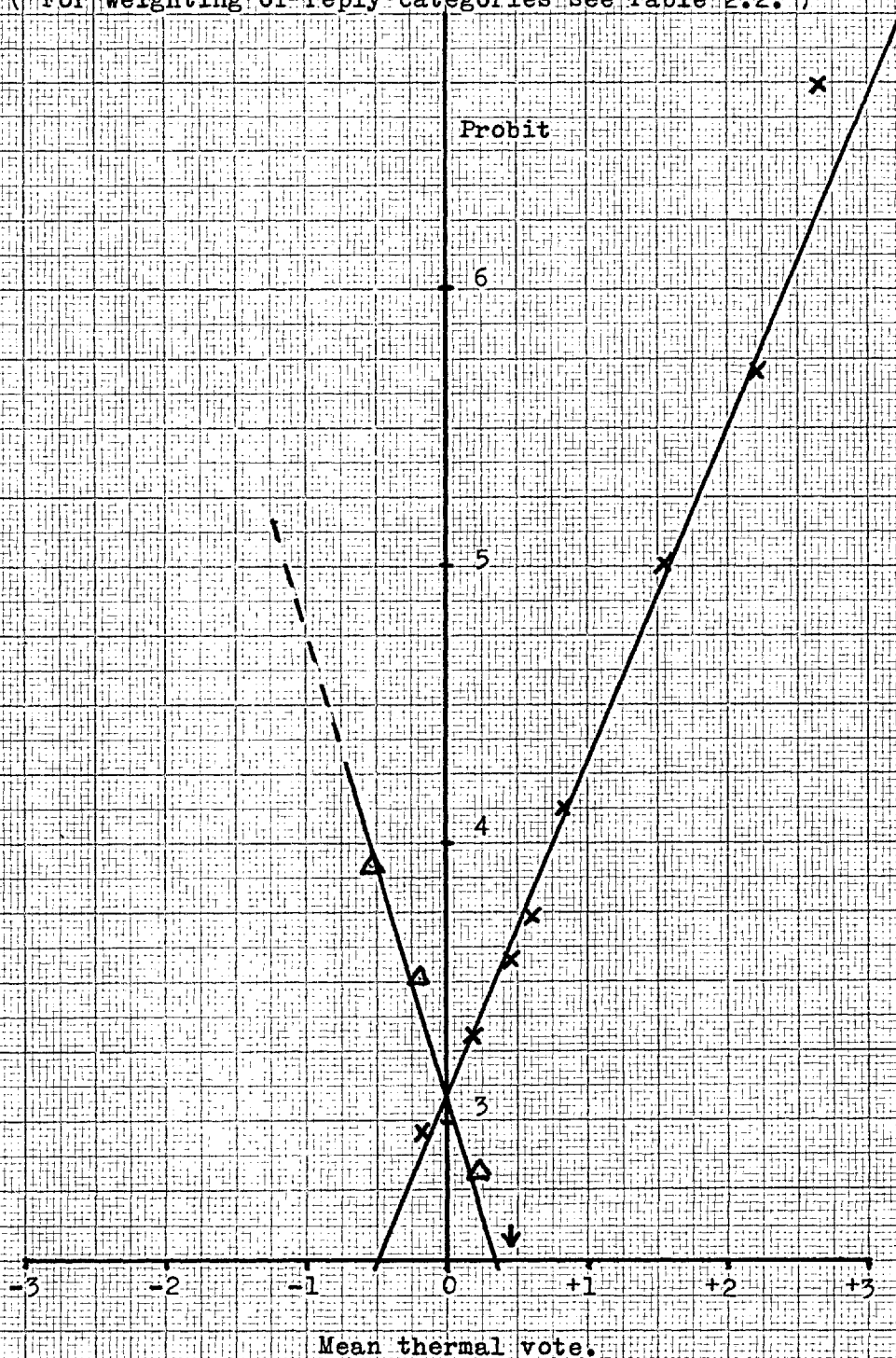
$$P_H = 0.27 T - 0.159 T_{OPT} - 4.50$$

$$P_C = -0.27 T + 0.381 T_{OPT} - 4.50$$

GRAPH 2.1. DATA FROM HICKISH (1955).

Probit of proportions "too hot" (+2,+3) and "too cold" (-2,-3)  
versus Mean thermal vote.

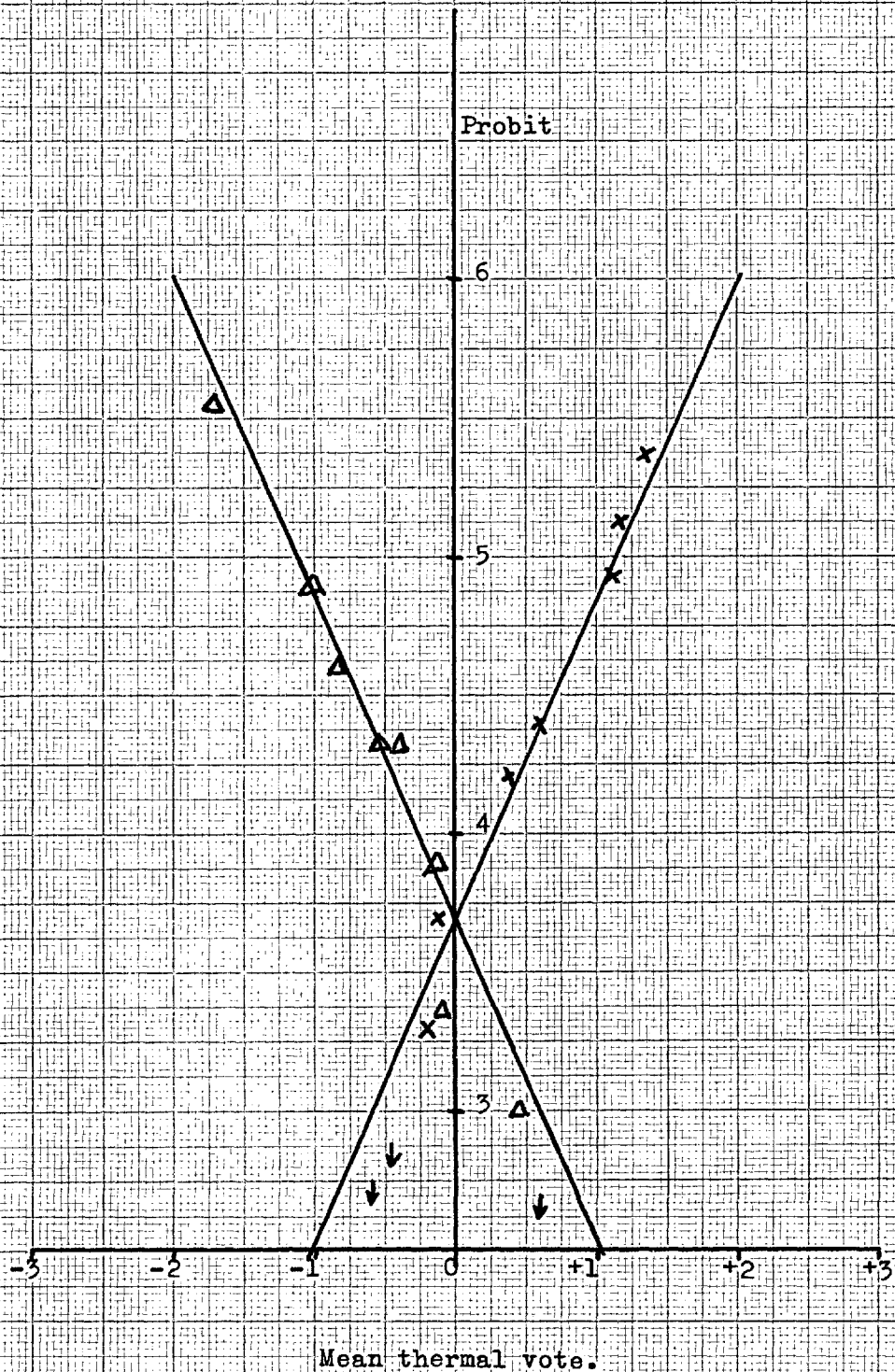
( For weighting of reply categories see Table 2.2. )



GRAPH 2.2. DATA FROM HOUGHTEN AND COOK (1939).

Probit of proportion "too hot" (+2,+3) and "too cold" (-2,-3)  
versus Mean thermal vote.

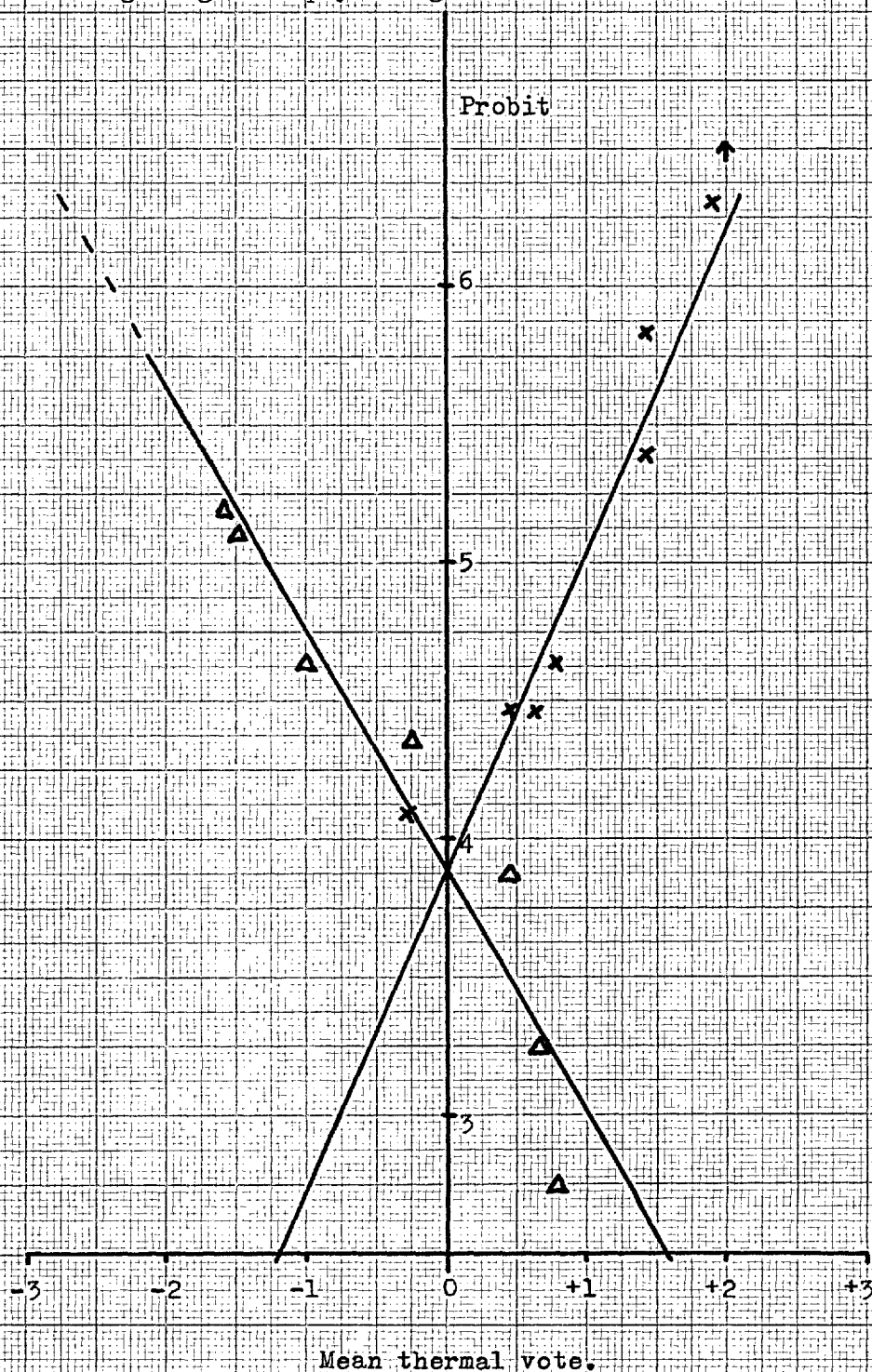
(For weighting of reply categories see Table 2.2.)



GRAPH 2.3. DATA FROM WEBB (1959).

Probit of proportion "too hot" (+2,+3) and "too cold" (-2,-3)  
versus Mean thermal vote.

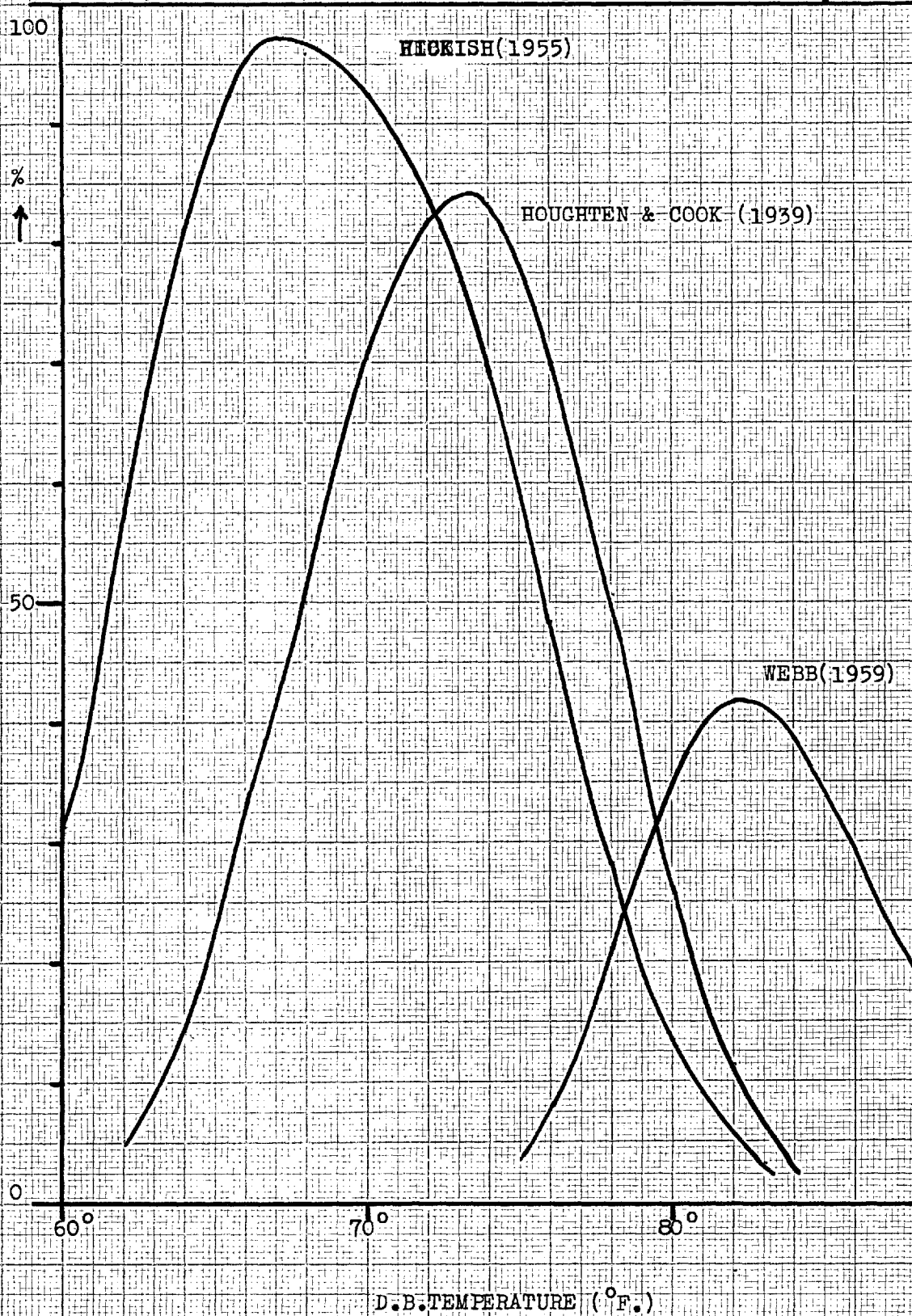
( For weighting of reply categories see Table 2.2. )





GRAPH 2.4. PERCENTAGE COMFORTABLE v. D.B. TEMPERATURE.

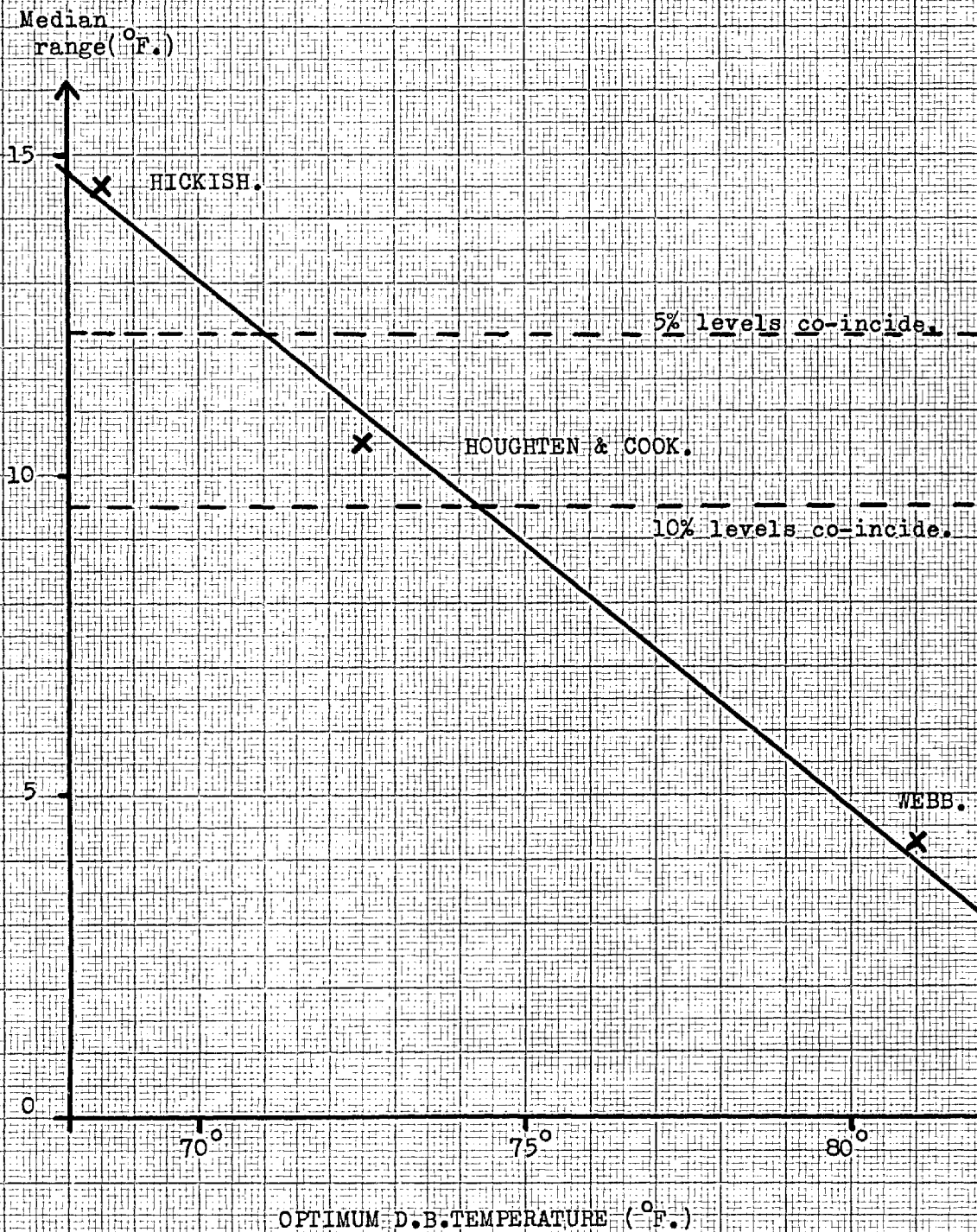
Obtained by transformation of calculated probit regression equations



GRAPH 2.5. MEDIAN RANGE v. OPTIMUM D.B. TEMPERATURE.

Represents the following equation :-

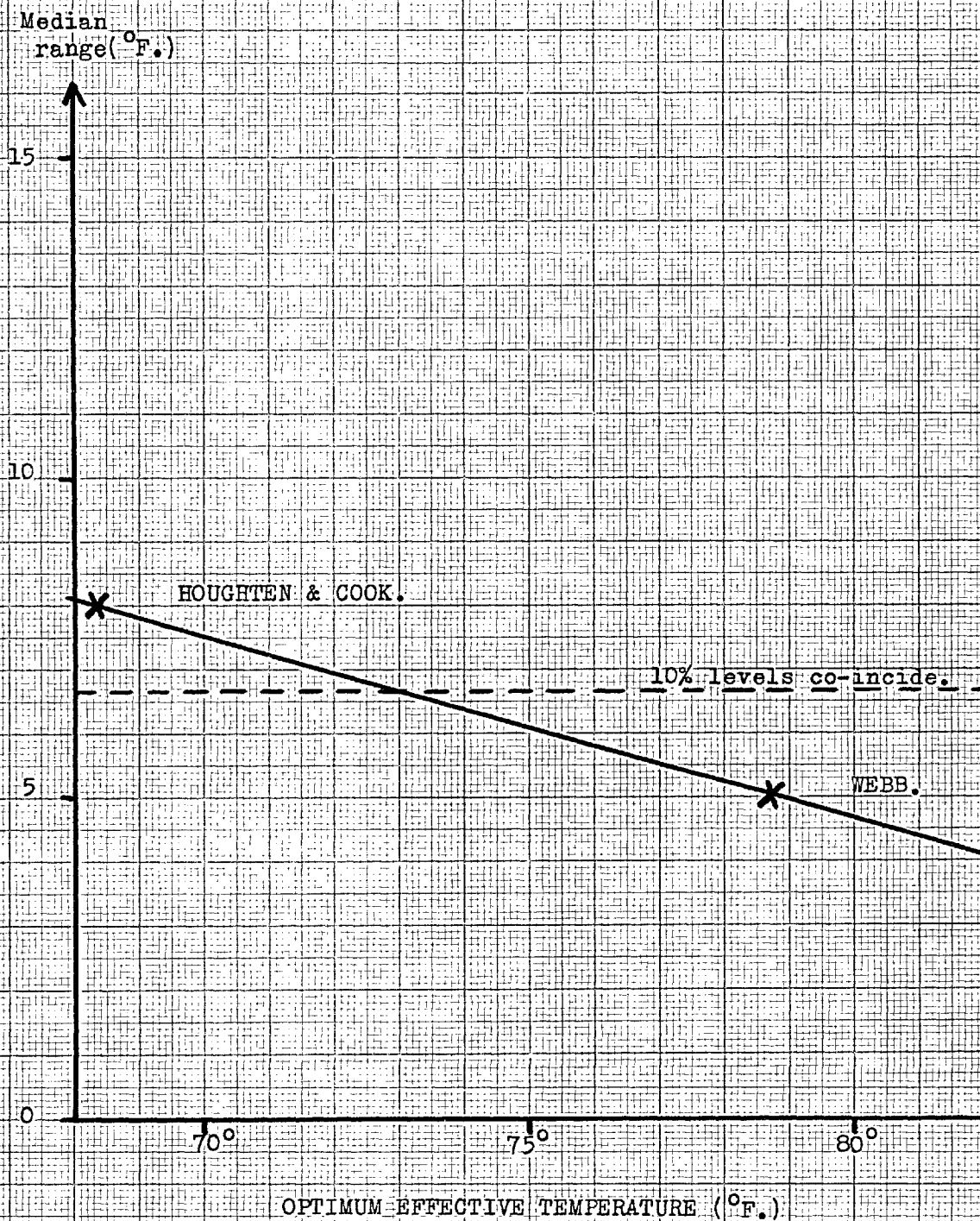
$$\text{Median range} = 0.82(85.8 - T_{\text{opt.}})$$



# GRAPH 2.6. MEDIAN RANGE v. OPTIMUM EFFECTIVE TEMPERATURE.

Represents the following equation :-

$$\text{Median range} = 0.29(96 - T_{\text{opt.}})$$



SECTION 3METHODS.

### 3. 1. Temporal scheme.

The work described in this thesis was carried out between May 1963 and October 1966, based at St. Mary's Hospital Medical School, London, and for an initial period at the Central Public Health Laboratory, Colindale, London, where six months were spent in the development of suitable instruments. From December 1963 to December 1965, an intensive series of visits to a large number of operating theatres was carried out, and in the remaining time the data was transcribed and computations performed on the IBM 1401/7090 system at the Centre for Computing and Automation, Imperial College, London. Additional computations were later performed on an identical machine in Stockholm while the author was working at the Swedish National Institute for Building Research.

### 3. 2. Organisation.

During the initial period, design studies were carried out on the various forms of instruments to be used. These are described in the following sub-sections. The author took part in a survey of air-borne cross-infection in surgery in order to become familiar with the routine of working in an operating theatre and to study the feasibility of the proposed scheme of measurement.

Forms were designed and duplicated to standardise the measurements and notes that were to be made. It was planned to study at the same time the method of working of staff in different layouts of operating suite and to this end the author was accompanied on most visits by a nurse, who also assisted in the questioning of the surgical team in the thermal survey.

In the available time, two alternative methods of investigation

were possible: either one could choose a very small number of theatres and study them intensively, or one could include as many as possible on a survey basis. The former method would make it possible to carry out more elaborate measurements, involving a degree of preparation of the theatre and collaboration by the surgeons quite impracticable in a brief visit. For instance, the climate in the theatre could be controlled for the purpose of the experiment, recording instruments could be installed and surgeons could conceivably be persuaded to wear monitoring instruments themselves. It was decided to adopt the latter method, that of brief visits to a large number of theatres, for the following reasons. Firstly, in view of the diversity of types of theatre suite in use, the results of experiments performed in a few selected theatres, however well chosen, could not be generalised to apply on a national scale. Secondly, a very great deal of work has been done on thermal comfort both in climate chambers and in working situations, and the findings are apparently in conflict with the general views of surgeons. It was thought important that the present survey should study thermal conditions in theatres where work was proceeding as normally as possible, without altering control settings and without remaining long enough to alter the attitude of the surgical teams. Surgeons are used to miscellaneous visitors and apparatus in their theatres, but not to working in a climate chamber. Thirdly, so little is known of the reasons for inter-personal variation in thermal preference that a survey of Bedford's type in which a large number of subjects are questioned infrequently was thought preferable to one in which a number of supposedly typical subjects are studied intensively.

The co-operation of the consultants of thirteen hospitals in and near the London area was obtained, and visits commenced in December 1963. It was planned to spend three working days in each suite, thus covering a possible six half-day operation sessions on each visit. Three such visits were to be made to each suite, at different times of the year separated by about four months. A preliminary visit was made on each Monday, when contact was made with the staff and the surgical scheme for the week was as far as possible obtained. In some cases the visit was necessary to locate the hospital itself. (On one occasion the team presented themselves initially at the gates of an adjacent prison.)

It was found that most surgery of the elective type tended to be performed in the middle of the week. Naturally, in busy hospitals, all available time was used, but in general it was found that a greater volume of work could be covered by visiting on Tuesday, Wednesday and Thursday. Thus Friday was usually available for a certain amount of compilation, and each week could be devoted entirely to a particular hospital. Some weeks of the first year were set aside for re-calibration of the instruments and for contingencies such as the closing of a suite or the repair of instruments. Visits had to be arranged at least three months in advance, and it was found that the above scheme worked very flexibly. Three hospitals in Scandinavia were visited during the summer, for the customary three days each.

As the actual process of data collection became more routine, it was found possible to include more items of information and the survey was expanded to include them. In the second year, visits were made to eleven

hospitals outside the London area as well as to seven more within reach of London. A completely new series of concurrent measurements of skin temperature and of sweat rate began in the spring and continued to the end of the year. A pursuit meter of a new design was constructed and on about one hundred occasions performance measures were obtained from surgeons. At the same time, the thermal questionnaire procedure was continued, and this formed at all times the main part of the survey, for while it was almost always possible to take the readings required and to interview the surgical team, however briefly, the variations of plan and unexpected contingencies that are normal in surgery often made it impossible to do more. At all times the data collection was altered to fit in with the progress of the work, even to the extent of cancelling it altogether if an emergency occurred. At no time were unreasonable requests made of surgeons, and in this way a very great deal of co-operation was in fact obtained.

### 3. 3. Instrumentation.

Measurements of the four main thermal parameters - temperature, humidity, air-velocity and thermal radiation - were required. They were to be related to the thermal sensation of the members of the surgical team, including the anaesthetist, and should thus be taken as close as possible to the person to be questioned and to the time to which questioning would refer. Thus readings would be taken very close to the table, at different heights, and during actual operations. The time available for such measurements would often be very limited, for they were always to be taken during a quiet period in the middle of an



operation, after the initial movement of staff and before the increased activity at the closure. This period could be as short as ten minutes even in a thirty minute operation. As far as possible, members of the team were to be questioned every two hours, or twice in a four-hour session. It would usually be possible to foresee the approximate length of each operation and to select the longer operations for measurement. For each person, sets of readings of the four thermal variables were required at heights of 6 ft., 3 ft. and 6 ins. above the floor. The three sets of readings taken as close as possible to the group at the table could be used for all those in the group. One set of readings was to be taken within the central group, on the table and close to the incision. A further three sets of readings were to be taken near the anaesthetist, that is at the periphery unless the theatre was unusually large.

It can at once be seen that conventional instruments would not be capable of fulfilling the above requirements. Neither the whirling hygrometer nor the keta thermometer could be used within the central group, because of the risk of breach of sterility by touching the towels or the gowns, or indeed of causing injury to the surgeons in the case of the hygrometer. In addition, the time required for these measurements, which could not be taken simultaneously by one person, would be too long. The globe thermometer, even in the 'accelerated' version of Hollon and Crookford (1959), would take far too long to reach a reading, and would be too bulky as well.

Various forms of instrument were considered. To minimise the actual work of writing down readings, it was decided to record at least two of

the four automatically. To decrease the time constants, a considerable degree of minituarisation was clearly required. The sensing elements most suitable for small, highly portable apparatus were thermistors, available commercially in many forms, and eventually the solution adopted was to base all four measurements on battery-powered circuits incorporating these elements.

The design studies for the instrumentation were carried out in 1963, before registration for this thesis. The work was done under the supervision of Dr. O.M. Lidwell, who was responsible for the final design and construction of the equipment, and a report has been published by Lidwell and Wyon (1968).

### 3. 4. Thermometer.

A form of ventilated Assman thermometer commercially available ('Hygrophil' - Ultrakust Gerätebau) was chosen as the basis for the equipment. It is in the form of a pistol, in which a battery operated fan draws air along the 'barrel' from a precisely determined measuring area at the tip, causing it to pass over two glass-encased thermistors which are completely shielded from thermal radiation by the shiny metal casing. One thermistor is dry, the other kept wet by means of a wick leading from a distilled water reservoir. The encasement in glass is such that the very fast variations of temperature found when naked thermistors are exposed to a high velocity are smoothed out, while the time constant remains adequately short. Either thermistor can be included in a bridge circuit, and three ranges are provided for each. The bridge circuit and meter are located in a separate casing connected by a 3 ft.

cable to the 'pistol'. Graduations are in  $0.5^{\circ}\text{F.}$  steps; more accurate measurement is rendered meaningless by the variations of this order that take place in seconds in the turbulent air of an occupied theatre. The time to reach a dry-bulb reading is only five or ten seconds, while the full wet-bulb depression is reached after twenty to forty seconds, depending on the magnitude of the final depression. The 'pistol' part of the equipment is light enough to be held steadily in position for two or three minutes, and the noise made by the battery-powered fan is very low. The 'barrel' can be extended by means of a 10 ins. length of tube, so that when held at arm's length the point of measurement - the tip of the extended barrel - can be three feet from the observer.

The anemometer and radiometer were constructed in such a way that their sensing elements could be located at the tip of the thermometer barrel (Fig. 3.1.), connected to the necessary measuring circuits by a multicore cable. These circuits were conveniently located together with the meter part of the Assman thermometer in a single chassis that was supported by a strap round the neck of the observer and carried at waist height against the body. (Fig. 3.2.) When not in use, the pistol could be placed in a rack on the front of the unit, enabling the observer to write down the readings obtained. The unit could conveniently stand on a table or shelf at the periphery of the theatre in between sets of measurements and while attaining thermal equilibrium. A noise meter was also incorporated in the assembly, using a desk microphone and the transistor amplifier of the radiometer, the output being recorded on the paper chart. Readings were taken during representative operations in

nearly every session while the instrument was thus standing at the periphery of the theatre. A description of this part of the instrument and of the results obtained is to be found as Section 6.1. of this thesis.

The assembly of instruments and the construction of the anemometer and radiometer have been fully described by Lidwell and Wyon (1968), so a superficial description will suffice here.

### 3. 5. Anemometer.

In order that the sensing element should be both extremely small and non-directional, a naked thermistor bead was suspended by its leads in a Y-shaped support. The bead was heated electrically to a temperature well in excess of ambient temperature, thus rendering corrections for ambient temperature changes unnecessary. The change in resistance of the bead when cooled by air velocities from 5-100 feet per minute were measured by means of the out-of-balance current changes in a resistance bridge, the bead forming one of the four arms. A mercury battery provided the necessary voltage, and the current, which varied almost linearly with air velocity in the range used, could be measured either on a moving coil meter or on a miniature paper chart recorder. Before each series of measurements the instrument was calibrated by balancing the bridge at zero air velocity and constant current. This was accomplished by enclosing the element in a box, and adjusting both voltage and balancing resistance in an iterative sequence, using the moving coil meter to monitor first the current through the thermistor, then the out-of-balance current in the bridge, while adjusting the former to a pre-set value and the

latter to zero. The sensitivity was chosen so that 0-100  $\mu$ A on either meter or recorder represented roughly 0-100 feet per minute air velocity. Calibration curves were obtained every four months by using a small wind tunnel to compare the readings with those of a standard instrument. A gradual change was observed in the bead characteristics, thought to be due to the burning on of fine dust particles.

The element was held about  $1\frac{1}{2}$  ins. above the tip of the barrel, well clear of the air movement generated by the intake of air to the barrel. It was enclosed in a 1 in. diameter spherical wire cage, with only four vertical bands and one horizontal, sufficient to provide protection against accidental damage, but not sufficient to interfere in any way with readings of air velocity. It is true that a very sharp 'shadow' could be cast by a wire when the instrument was undergoing calibration in a laminar flow wind tunnel, but this was avoided in calibration and did not arise in measurements, since no such accurately directional flow was to be measured. It was found to be possible to avoid spurious readings of air velocity due to unsteady positioning of the instrument. Readings were obtained as low as 5 feet per minute while the instrument was hand-held. Below this value the out-of-balance current was negative, and this formed an effective threshold for the instrument that was not altered by unsteady positioning.

The variability of the air velocity was of some interest in connection with the question on 'stiffness' asked of subjects. A measure of this quantity was obtained by considering the occasions on which air velocity was measured continuously for over one minute. This only occurred at

head-height at the table, when the instruments were in position for an unusually long time to allow the radiometer to settle to a large reading under the operating lamp. Thus only a proportion of the data could be used. Variability in these cases was recorded as the average deviation from the mean, regardless of sign, in feet per minute. No definite form could be assumed for the distribution of air velocity about the mean; in some cases it was clearly bi-modal, oscillating between two values in a turbulent fashion. It was felt that the average deviation gave an unambiguous, sensitive measure of variability, whereas the standard deviation would have been insensitive, its use justified only if the distribution were normal.

### 3. 6. Radiometer.

The basic difficulty in designing this instrument can be briefly stated. It is that in order to register quickly, the sphere onto which thermal radiation impinges must be very small; the cooling effect of air movement on a sphere that is small enough - about 2mm. in diameter - is so great that the temperature difference between the sphere and the air surrounding it is both unsteady and too small for accurate measurement. The solution adopted was to enclose the 2mm. sphere in a 1 in. diameter polythene bubble. This allowed thermal radiation to impinge on the central sphere, warming very little itself, and reduced the cooling effect of air movement to such an extent that the air velocity correction for the instrument was almost identical with that for a normal 6 in. unshielded sphere. Polythene is unusual in that it transmits radiation to a uniformly high extent over a very wide range of wavelengths (Schulze 1962). It has been used on a larger scale to shield

whole-sky radiometers from wind in meteorological applications, though these instruments have a solid angle acceptance of only  $2\pi$  steradians (Funk 1959). The support of the present instrument was effectively a circle of diameter  $\frac{1}{2}$  in. at a distance of 1 in., subtending a solid angle of only 0.0039 of the whole sphere, so the solid angle acceptance of the instrument was effectively  $4\pi$ . The sphere was at the end of the barrel of the Assman thermometer, supported horizontally by the thin wire members of the cage on which the polythene bubble was fixed.

The temperature of the 2 mm. sphere, which was black and contained a thermistor element at the centre, was measured electrically by means of a 2 kHz. AC bridge. Another thermistor, exposed to the air but shielded from thermal radiation by a silvered cover, formed one arm of the resistance bridge in order to compensate for different ambient temperatures. The out-of-balance current of the bridge was amplified by means of a two-stage transistor amplifier, and the rectified final current was measured on either the meter or the recorder referred to above. Before each series of measurements, the instrument was placed in a metal box, where the radiation temperature was equal to the air temperature, and allowed to reach equilibrium. The balance of the bridge and the gain of the amplifier were adjusted to standard values, using the meter to monitor the out-of-balance current with and without a standard resistance switched into one arm of the bridge in parallel with the black bead to simulate a change in resistance. The equilibration time in the box was rather long, particularly when the instrument had been brought in from outside on a cold day. This was due partly to temperature effects on the amplifier; it was not temperature-compensated since it was intended for use in a temperature controlled

environment. The silvered temperature compensating thermistor was rather more massive than the black bead, due to its cover. An improved version of this radiometer, described by Lidwell and Wyon (1968), incorporates a small, rapidly reacting air temperature compensator in the air stream of the Assman thermometer, well shielded from direct radiation. Alternatively, the black bead temperature can be directly estimated using a stepped resistor. It would probably have been better in the present survey to have omitted the compensator in this way. Calculation of the radiant excess temperature could then have been carried out digitally using the independent measurement of air temperature obtained simultaneously on the Assman thermometer.

This was the method adopted for air velocity compensation. Readings of air velocity were always taken at the same time as the radiometer readings. A correction curve was derived from experiments in a wind tunnel, and it was found possible to fit an expression of the form  $K = a + b \log V$ , where  $K$  is the correction factor,  $V$  is the air velocity, and  $a$  and  $b$  are constants. The corrected radiant excess temperature was then obtained by dividing the reading in microamperes by this factor, which ranged from 1 to 0.5 with increasing air velocity. Uncorrected readings were used in data transcription, and punched onto Hollerith cards, the correction taking place at the stage of computing. Thus the expression had only to be written once for it to be performed 2,500 times as a 'transgeneration' in storage prior to each computer analysis.

In spite of the variable air velocities usually encountered, the reading of the radiometer was steady, enabling an accurate reading to be taken. As the instrument attained equilibrium during a measurement,



the reading was displayed on the paper chart recorder, together with the reading of air velocity. (The recorder was a commercially available pressure-sensitive paper model (Amprobe DC100), modified to have two channels. The needle was free swinging, pressed against the paper from beneath every 4 sec. A miniature switching device caused the radiometer to be connected for three successive readings, the anemometer for two, thus automatically coding the two values.) The observer was able to watch the radiometer reading settle to a steady value while monitoring the simultaneous recording of air velocity. Thus the time for each reading could be minimised and the influence of sudden changes in radiation temperature (which were rare) and of sudden changes in air velocity could be seen and the procedure altered to take account of them and to obtain a meaningful set of readings on each occasion.

The radiometer reading could vary from - 30 to + 70 microamperes, and the final range of corrected radiant excess temperatures was from - 1.5 to + 11°F. The highest readings were always obtained at the level of the surgeon's head, in the direct beam of the lamp. The reading beneath the lamp at this height but out of the direct beam was usually about half this value. The time to obtain a reading of + 30 microamperes was about two minutes, but readings less than this took a shorter time. The reference numbers were written onto the paper chart to identify the readings and link them to the appropriate notes and the readings of wet and dry-bulb temperature that were written down by the observer at the same time. The transcription of the readings so obtained was a very lengthy procedure.

### 3. 7. Documentation.

The form of analysis determined the way of recording the data. The basic unit of information was chosen as a 'person-occasion', each such unit to form one case in the multiple regression analysis. This choice was made necessary by the observational nature of the experiment. Very seldom do two members of a surgical team have identical experience of a session, and it was thought that by taking careful account of differences in the number and type of operations attended, in the length of time spent at the table, in clothing and similar factors, some of the variability 'between people' and between occasions for the same person, could be explained. It was not possible to treat a 'person' as the basic unit, as there was no way of ensuring that each person would be encountered the same number of times. In the event, more than half of the subjects were encountered only once, whereas some were encountered as many as ten times.

A considerable amount of duplication of data is implied by this choice of basic unit. Firstly, a set of readings of the four thermal variables taken at the table must be used for all those who were standing at the table when the readings were taken and who were subsequently questioned about that period. Readings of noise and counts of the staff movement must be used for all those present; dates, theatre and hospital identification were the same; readings relating to the environment external to the theatre apply to all working at the time in the theatre, and so on. Individual accounts must be prepared of each person's experience of the session and of the personal details of age, sex, race, build, height and clothing. In practice, such a clerical exercise is

out of the question in the course of attending and keeping track of the progress of a session. There is usually nowhere at all to do paperwork, even for the surgeon, and one is kept fully occupied accounting for the surprisingly large numbers of people walking about a theatre (sometimes as many as twenty individuals would enter and leave during a session), taking the readings, recording the details and times of the operations performed, intercepting and interviewing the staff. The only solution was to write down everything only once, in the most convenient way possible, on forms that could be filled in on a hand-held clipboard, and then to perform the duplication at a later stage. This solution was adopted reluctantly; it would have been preferable to be able to punch the records directly from the field sheets. Special summary cards were prepared, and the data for each person-occasion was brought together on those cards in a form suitable for punching.

Since the field sheets formed the framework for the standardised collection of data, it is suitable at this point to consider each one separately in sufficient detail to show what data was collected and how it was recorded in a meaningful way. Examples of the field sheets used are shown as Figs. 3.3.-3.10. The hospital, theatre, date and session were always written at the top of each sheet in the space provided, and a completely new set of sheets was used for each separate session.

### 3. 7. 1. Operation Data. (Fig. 3.3.)

The name of each operation actually performed was written down in the way it appeared on the operating list. The start and finish times were written down to the nearest minute. An operation was deemed to start when the skin preparation was applied, since this marked the

start of the sterile procedure at the wound site. Similarly, it was deemed to finish at the conclusion of the sterile procedure, usually when the dressing was applied. Both these are definite events, which can be exactly timed. The number of scrubbed staff at the table was recorded, and if an observer was gowned and standing with the table staff throughout an operation, he also was included. During each operation the occurrence of 'mistakes' and 'complications' was recorded. A 'mistake' was deemed to occur when any unintended incident interrupted the operating procedure. For example, if an air cylinder failed in use and occasioned a pause while it was replaced, or if a necessary instrument was dropped, occasioning a pause while it was re-sterilised. If either of these happened in a way not causing disturbance or delay it was ignored. The dropping of an instrument such as a skin clip, replaceable at once from the sterile tray, usually causes no disturbance at all and would not be recorded as a mistake. A 'complication' was deemed to occur if the operation at any stage became more difficult than had been expected, necessitating further surgical steps. Thus if an appendicectomy revealed carcinoma, or a patient went into cardiac failure, a complication was recorded, but if a laparotomy revealed carcinoma it was not, since this could have been one of the possibilities envisaged by the surgeon when starting the operation. The purpose of recording these two rather difficult items was to investigate their effect on the surgeon's perception of the thermal environment, not in any sense to record medical data per se. In addition, estimates were made of the 'emotional tension' in the theatre, on a three point 'tense, normal, relaxed' scale, and of the 'tempo' of work, on a three point

'hurried, normal, slow' scale. It was found to be surprisingly easy to make these estimates, which in all cases were relative to the normal conditions for that team in that theatre and not to any absolute standards. Thus when a surgeon was recorded as working slowly, he may still have been working a great deal faster than another surgeon recorded as hurrying, since speeds of working vary so much between individual surgeons. The purpose of these items was again to see whether these facets of behaviour on a particular occasion could be shown to influence the perception of the environment and thus perhaps account for some of the variation found between occasions for the same person.

On the same sheet the names of the staff present were recorded, and a record kept of which operations they had attended. Space was provided for summarising these details into a record of the 'session up to Q' (questioning) for each person. The summaries were prepared at the stage of compilation. At this point each operation was classified as major, average or minor and assigned a 'difficulty category' of 2, 1 or zero respectively. The categories were based on the scale of charges for private surgery recommended by the Ministry of Health (Statutory Instrument, 1953), and naturally many objections can be raised to measuring the difficulty of an operation in guineas. The fact is that a supposedly minor operation can turn out to be of exceptional difficulty, and vice versa, depending on sometimes quite minor features of the task and on the particular skills or experience of the surgeon. No satisfactory estimate of the difficulty of an operation can be made, certainly not by an unqualified observer. At

the same time, it was felt that it would be less than useful to ask the surgeon himself if an operation had been difficult, since the reply would have depended on the personality of the surgeon and on his attitude to such questions.

For each person-occasion the summary consisted of the duration in minutes of the total operating time up to questioning, the time-weighted mean difficulty, the total number of mistakes and of complications occurring in the operations completed prior to questioning, the appropriate 'tension' and 'tempo' estimates for the period, and the time-weighted mean number of scrubbed staff at the table. Frequently the same summary could be used for a number of people who had all been present for the same operation and had all been questioned at the same time, but in a long list a great number of combinations were possible. These represented real differences of experience, however, and it was therefore considered worthwhile to go to these lengths.

### 3. 7. 2. Physical Measurements. (Fig. 3. 4.)

On this sheet were recorded the measured dry-bulb temperature at each of three heights above the floor, at each place and each time a set of readings was taken. The occasion was identified by means of the exact time and by means of a brief note in the space provided, such as 'after operation 1' or 'during operation 6'. The numbers I to IV identify readings belonging to the same set, which may have been taken at slightly different times but were intended to cover the same period. At head height and within the central group ('on table'), the wet-bulb temperature was also measured. Space was provided on the form for the readings of air speed and of radiant excess temperature that were always

taken at the same time as the temperature readings. These were written automatically on the paper chart and were interpreted and transcribed at the stage of compilation. At the time of measurement, an identifying letter was written on the chart and in the appropriate column on the form, so that readings could be linked reliably to the correct time and temperature. The compilation procedure involved deriving the relative humidity from the temperature readings and transcribing the chart readings onto this form.

The chart readings of radiant excess temperature were easily read off, since the readings were always continued until a steady value of radiant excess temperature had been reached. They were read in microamperes above or below the experimentally determined zero, and written onto the form as uncorrected values of radiant excess temperature, 10 microamperes being written as  $1\text{F}^{\circ}$ . Thus they were recorded to the nearest  $1/10 \text{ F}^{\circ}$  - not because they were as accurate as this but because they were to be corrected digitally for air velocity, and rounding-off errors would have been introduced had this not been done. When coding, three degrees F. were added and the decimal point removed, in order to avoid negative values and so as to be able to punch each reading in only two columns of a Hollerith card.

The interpretation of the air velocity readings presented more problems. In general, the separate readings were read off and their mean determined, but where systematic variation was present, the final air velocity reached was used because it was this value that was associated with the equilibrium value of the radiant excess temperature, and thus this value that would be used to correct the radiometer

reading for air velocity. The mean variation of air velocity was determined where appropriate, as has been mentioned above, but in the majority of cases too few readings were available for a reliable estimate of this quantity to be made. It was expected that air velocity would in the theatre situation be a variable having little thermal significance, since on other grounds air velocities are kept as low as possible, and this turned out to be the case. Thus it was not thought necessary to be too rigorous in the measurement of air velocity. Nevertheless, all readings were corrected according to the calibration curves obtained periodically from wind-tunnel experiments, in order to avoid introducing systematic errors. Each separate reading of air velocity was probably accurate to within one or two feet per minute, but the variation about the mean could be as high as 50 per cent. with such low air velocities. The readings of air velocity were entered as feet per minute in two punched columns for each value. In the handful of cases where the measured and corrected value was over 100 feet per minute, the figure entered was 99. No values were obtained below 5 feet per minute, for the reason referred to in the discussion of the effective threshold of the instrument, and this ensured that the correction factor for the radiometer, which involved the logarithm of the air velocity, remained within reasonable bounds.

If two sets of readings had been taken prior to questioning, the second set was always taken, as the questioner had always requested the subject to defer his answers to the later part of the session if he felt that that was different from the earlier part, or if the readings indicated that a marked change of thermal conditions had in fact taken



place. This happened very infrequently.

Rough measurements of light values were taken in some theatres and recorded on these sheets. Some use of them is made in Section 10., where the measuring technique is also described.

### 3. 7. 3. Personal Data (Fig. 3.5.)

For every member of the surgical team present during a session, a summary of personal details and clothing was completed as one row of this sheet. The subject's name, 'status' (surgeon, assistant, scrubbed nurse or anaesthetist) and sex were written down. An estimate of age was made, later to be grouped to the nearest five years for punching. It was usually possible to be as accurate as this. The subjects' race was written down as one of six broad categories, but in the analysis distinction was made only between 'North Europeans' and others in order to have sufficiently large groups. The build of a subject was assessed and written down as one of five categories (fat, thickset, normal, slim and thin). The population average was subsequently found to be very close indeed to 'normal', so apparently any marked bias was avoided. Similarly a subject was classified as above, equal to, or below normal height. Such estimates are not difficult to make with a fair degree of reliability. If the subject was wearing glasses during the session, this was recorded. Details of clothing were recorded in words; informal questioning during the interview served to elicit details of extra items that were not visible. As mentioned above, female staff were usually questioned by a nurse, male staff by the author. Their clothing details were coded onto five columns of the punch card.

It later proved to be impossible to decode the data into a usable form by means of the transgenerations that were available with the multiple regression program. This was a mistake, due to a desire to retain all the data. A special program was used later to decode the data onto a third card in the form of the number of layers of clothing and whether an apron was worn. This form of recording would have been better in the first place.

#### 3. 7. 4. Responses (Fig. 3. 6.)

This sheet was completed while interviewing each subject. The time of questioning was written down, and the occasion (e.g. 'after operation two') to relate this data correctly to the relevant details of the session prior to questioning. The subject's name and status were recorded, each subject being assigned a block of four rows in order to keep together the records of successive questionings. In practice a subject was rarely questioned more than twice in a session unless it lasted all day. The average duration of the session up to questioning was 120 minutes of actual operating time.

The results of the interview consisted of five 'votes' on multiple choice scales, one observation and four 'opinions' in the form of 'yes or no' responses to direct questions. The sequence of questioning is shown in Table 3.1. It was strictly adhered to in wording and sequence, and little supplementary explanation was necessary to make clear to subjects the meaning of the questions. Sometimes it was necessary to emphasise that the questions referred to the subject's

own subjective sensations and not to some supposed optimum. As mentioned above, if the subject expressed the opinion that the conditions had changed during the session, he was asked to refer in his replies to the later part, which was usually felt to be more stressful. Actual changes of conditions occurred very seldom indeed and questioning was usually delayed until conditions had been steady for at least an hour to avoid ambiguity. Care was taken to keep subjects unaware of the actual temperature or humidity, to avoid the danger of obtaining only a stereotyped response to the figure itself. Thermometers in the theatre were either removed or turned to the wall, electrical thermometers were switched off, and if these measures proved impossible, doubt was cast on the reliability of such instruments. If direct questions were put about the readings, it was explained that for the purpose of the experiment subjects should not know the actual figures before reporting their subjective sensations, and no information was given until after questioning. The discrepancy between the supposed figure and that measured was commonly very great; the majority would have automatically answered 'too hot' if they had known the temperature was above 70°F, whereas in ignorance of the exact reading quite large numbers were subjectively comfortable up to 80°F. This was a crucial part of the experiment, and neglect of this aspect could have led to very misleading results.

The rationale of using such subjective scales has been discussed in the introduction and the thermal scale has been extensively tested in Section 2. The five point scales for 'stuffy/fresh' sensation and for perception of air movement have not been used in this form,

and the results are in any case specific to the wearing of surgical clothing, in particular a mask and rubber gloves. It is interesting that most people found no incongruity in judging whether a theatre was 'stuffy' while wearing a mask. The questioning took very little time, ten questions requiring only simple answers being sufficient to obtain the appropriate score on each of the five scales.

Prior to and during questioning, the extent to which the subject was sweating was observed by the interviewer and noted in the appropriate space as the 'P-estimate'. The scale is given in Table 3.1. As subjects were always questioned before leaving the theatre or immediately afterwards, this estimate does refer to their physiological equilibrium during the operation.

The questions on noise, humidity, overcrowding and staff movement were then put to the subject and the answers 'yes' or 'no' were recorded. Any spontaneous remarks were also written down, and although no use has been made of these in a formal way, they have been very useful in forming a general impression.

It was often convenient to question a surgeon while he was scrubbing for the next operation. In most cases, a more elaborate questionnaire would have taken too long. By using only this brief, simple form of interview, lasting at most a minute, it was possible to avoid delaying the subject and thereby reducing his willingness to co-operate and give considered replies. Another advantage was that one person could question a number of people in the rather short pauses between operations when questioning was at all possible.

### 3. 7. 5. Environment external to theatre. (Fig. 3.7.)

At a convenient stage in the session, usually during a long operation when it was possible to leave the theatre briefly without losing track of the events, a series of spot readings of wet and dry-bulb temperature were taken in the other rooms of the theatre suite, and of the outdoor conditions, usually through a window. At the stage of compilation the relative humidity was derived and summaries made up for each staff category of the average temperature and humidity in the rooms used for resting between operations, of the rooms from which that staff category could enter the theatre and of all the rooms entered by that category. For instance, anaesthetists rarely entered the sterilising rooms, which could be quite hot, and surgeons rarely entered the anaesthetic rooms, which could be quite cold. Such differences could conceivably lead to different subjective judgements of the temperature in the theatre, by contrast if not by thermal effect on the heat balance. Unfortunately these records were not always taken, particularly in the early part of the survey, and thus it was impossible to include them in the main analysis. They are analysed by a special technique for missing data in Section 6.4.

The outside temperature at 9 a.m. on each day was written in at compilation from meteorological records, and the mean temperature for the preceding 18 days. The barometric pressure and tendency were also included, but no correlation with response could be shown with over 2,500 pairs, so no further mention will be made of them. No consistent record of weather was kept.

### 3. 7. 6. Surface temperatures (Fig. 3.8.)

Readings of surface temperatures in the theatre were taken on a number of occasions in each suite, using a specially constructed instrument (Lidwell and Wyon 1968). These readings could not always be taken at the same time, and sometimes not at all. They were subject to time errors, therefore, and were unsuitable for direct analysis. They were used only to check that no great departure from air temperature was encountered and that the radiometer reading in the centre of the room was therefore a valid measure of radiant heat exchange with the surroundings. This was always found to be the case, and no further reference will be made to these readings.

### 3. 7. 7. Staff Movement records.

The recording of staff movement was done by the nurse in much greater detail than was actually required by the thermal survey. The data was used to derive patterns of staff movement and quantitative 'traffic diagrams' for different theatre layouts in another connection. The method used was to have a 12 x 12 double entry form, and to assign to each door an identification number, with additional numbers for key points in the theatre. The form was entered at the row corresponding to the door or position from which a person moved and a mark was made in the column corresponding to the door or position to which the person moved. Different symbols were used for different staff categories. Very considerable skill and attention was required to keep an adequate record of the movements of up to fifteen people. It was only feasible during actual operations, as between operations there was too much movement to follow. Observation periods usually lasted an hour.

For the purpose of the present survey, only total entries and exits per hour and movements within theatre per hour were written onto the summary cards referring to each observation period, together with the total number of different people involved in the movement, i.e. who were at some time during the period present in the theatre. The intention was to investigate whether thermal stress affected the perception of this aspect of the environment, and vice versa. The results are set out as Section 6.2.

### 3. 7. 8. Sweat rate measurements. (Fig. 3.9.)

This form was only partially used. The sweat rate data was derived and copied onto the summary card appropriate to the period of measurement, from which a special summary of relevant conditions was made up, and punched onto separate Hollerith cards. A description of the technique of making these measurements can be more conveniently set out in Section 8, which deals exclusively with this part of the survey.

### 3. 8. The summary card. (Fig. 3.10.)

The eight field sheets that have been described above in Sections 3.7.1.-3.7.8. served to record all the relevant data. There remained the problem of compiling the 'raw' data into a form suitable for analysis. It has already been explained why it was impossible to design the survey so that punching of the data could be carried out from the original records; the summary cards were used to bring together the relevant data for each person-occasion, code it numerically and set it out in a format suitable for punching directly onto Hollerith cards. It may be seen that the card groups the data into logical fields, clearly labelled

to facilitate the transference of data from field sheets to summary card. Within the fields, the data is arranged in columns numbered from 1-80 to correspond to the columns of the Hollerith cards used. Within each column there are two spaces, one for the raw data and one for the numerical code that would in fact be punched. No coding was done in transferring the data onto the summary card, in order to minimise errors and facilitate checking. One person, a clerical assistant employed for six months for the purpose wrote in the data from field sheets to summary cards. The author then checked every column on every card back to the original records, working together with a third person. The data was then coded numerically into the adjacent square, in a different colour to avoid confusing the punch operators. Thus the raw data and the code were immediately adjacent, and it was easy to verify the coding. This stage was reached about five months after the end of the data collection and the punching and verification took a further six weeks for two operators working part time.

The card was designed to group the data into a form taking as few columns as possible. Even so it was necessary to use two 80 column cards for each 'person-occasion', which made card sorting very difficult. The two cards were linked by means of the identification number in columns 1-4. Every subject had been assigned a three-digit reference number, and the fourth digit identified how many times that person had been questioned previously. Thus a 'person-occasion' unit was identified completely by the reference number. These summary cards were prepared during the first year of the survey, and in fact more than



999 different people were eventually interviewed. The eleventh and twelfth position of column one was punched to obtain the extra reference numbers. Only two people were questioned more than ten times, and they were assigned new reference numbers for the additional replies, thus retaining column four as a number between 0 and 9. Certain key responses were duplicated on the second card to make it possible to cross-tabulate them with the physical measurements appearing on that card by means of a card sorting machine. It is arguable that it would have been better to do all cross-tabulation and frequency distributions by computer program, so that leader and trailer (X and Y) cards could have been kept together from punching onwards. In fact, though preliminary sorting was done on the individual cards by means of a readily accessible card sorting machine, later cross-tabulation was carried out on the paired cards by means of the BMD.09.D. library program.

The need to use two punch cards for each unit made it possible to include 39 blank columns in the format in case they were needed. 26 of these were in fact used, for such additional data as movement, season, variation of air velocity, a duplicated status variable on the Y card, etc. Care was taken to avoid missing data in the variables to be used for the main analysis. It will be seen in the topics covered by Section 6 that handling incomplete data was considerably more complicated.

Table 3. 1.

| <u>Sequence of questioning</u> |                                                                    | <u>Allocated score</u> |
|--------------------------------|--------------------------------------------------------------------|------------------------|
| <u>S-Vote</u>                  | <u>Do you think it is stuffy in the theatre?</u>                   |                        |
| Yes:                           | <u>Slightly stuffy or much too stuffy?</u>                         | 1, 2                   |
| No:                            | <u>Is it too fresh?</u>                                            |                        |
|                                | No:                                                                | 0                      |
|                                | Yes: <u>slightly or much too fresh?</u>                            | - 1, - 2               |
| <u>T-Vote</u>                  | <u>Is the temperature comfortable</u> {                            |                        |
|                                | at head height?                                                    | T <sub>1</sub>         |
|                                | for your body?                                                     | T <sub>2</sub>         |
|                                | for your feet?                                                     | T <sub>3</sub>         |
| Yes:                           | <u>Is it ideal, or would prefer it slightly warmer or cooler?</u>  |                        |
|                                | Warmer                                                             | - 1                    |
|                                | Neither, ideal                                                     | 0                      |
|                                | Cooler                                                             | 1                      |
| No:                            | <u>Is it too hot or too cool?</u>                                  |                        |
|                                | Too hot: <u>slightly too hot or much too hot?</u>                  | 2, 3                   |
|                                | Too cool: <u>slightly too cool or much too cool?</u>               | - 2, - 3               |
| <u>W-Vote</u>                  | <u>Would you like more air movement or less?</u>                   |                        |
|                                | (Repeat: <u>Did you find it either stagnant or too draughty?</u> ) |                        |
|                                | More (stagnant): <u>Slightly more or much more?</u>                | - 1, - 2               |
|                                | Neither:                                                           | 0                      |
|                                | Less (draughty): <u>Slightly less or much less:</u>                | 1, 2                   |
| <u>P-estimate</u>              | Forehead dry                                                       | 0                      |
|                                | Forehead damp                                                      | 1                      |
|                                | Forehead wet, beads of sweat                                       | 2                      |
|                                | Forehead wet, wiping necessary                                     | 3                      |
|                                | Forehead wet and clothing wet                                      | 4                      |

Table 3. 1. (Continued)

| <u>Sequence of questioning</u> |                                                                      | <u>Allocated score</u> |
|--------------------------------|----------------------------------------------------------------------|------------------------|
| N-Vote                         | Did you think it was (excessively) noisy<br>in theatre?              | 0/1                    |
| H-Vote                         | Did you think it was (excessively) humid<br>in theatre?              | 0/1                    |
| O-Vote                         | Did you think it was (excessively) over-<br>crowded in theatre?      | 0/1                    |
| M-Vote                         | Did you think there was too much movement<br>in and through theatre? | 0/1                    |
| D-Vote                         | Would you prefer (do you prefer) daylight<br>in theatre?             |                        |
|                                | Yes:                                                                 | 0                      |
|                                | No; Indifferent                                                      | 1                      |
|                                | Prefer no day-<br>light                                              | 2                      |

Fig. 3.1. Tip of radiometer, showing anemometer bead above.

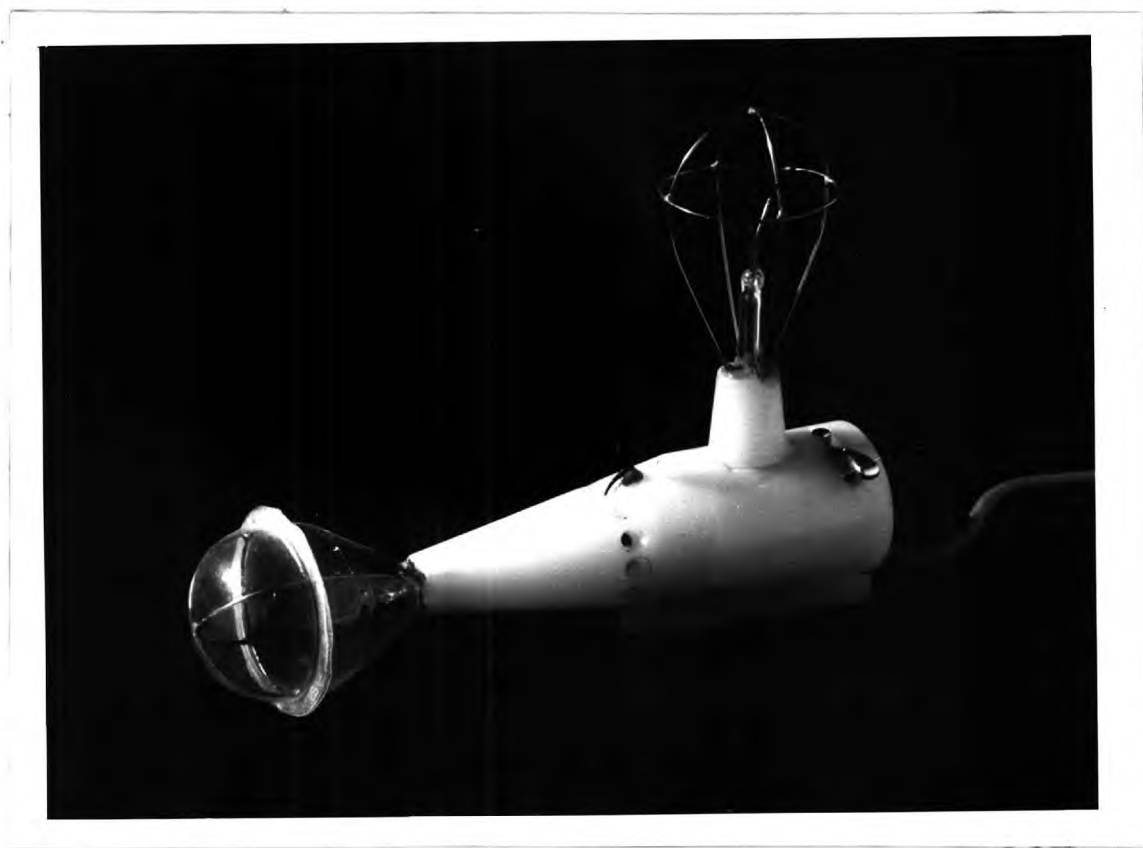


Fig. 3.2. General view of instrument assembly.



OPERATION DATA 106

[illegible]

|         |                | PERIPHERY |    |     |    | AT TABLE |    |     |    | ON TABLE     |    |     |    |
|---------|----------------|-----------|----|-----|----|----------|----|-----|----|--------------|----|-----|----|
|         |                | I         | II | III | IV | I        | II | III | IV | I            | II | III | IV |
| 16"     | Occasion       |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Time           |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Dry temp.      |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Wet temp.      |           |    |     |    |          |    |     |    |              |    |     |    |
|         | % Humidity     |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Air speed      |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Radiant excess |           |    |     |    |          |    |     |    |              |    |     |    |
|         | No. at table   |           |    |     |    |          |    |     |    |              |    |     |    |
| (HEAD)  | Comments       |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Time           |           |    |     |    |          |    |     |    | LIGHT VALUES |    |     |    |
|         | Dry temp.      |           |    |     |    |          |    |     |    | Time         |    |     |    |
|         | Air speed      |           |    |     |    |          |    |     |    | Task         |    |     |    |
|         | Radiant excess |           |    |     |    |          |    |     |    | Local        |    |     |    |
|         | No. at table   |           |    |     |    |          |    |     |    | Back ground  |    |     |    |
|         |                |           |    |     |    |          |    |     |    | Day-light    |    |     |    |
|         |                |           |    |     |    |          |    |     |    | Variations   |    |     |    |
| (BODY)  | Time           |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Dry temp.      |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Air speed      |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Radiant excess |           |    |     |    |          |    |     |    |              |    |     |    |
|         | No. at table   |           |    |     |    |          |    |     |    |              |    |     |    |
|         |                |           |    |     |    |          |    |     |    |              |    |     |    |
|         |                |           |    |     |    |          |    |     |    |              |    |     |    |
|         |                |           |    |     |    |          |    |     |    |              |    |     |    |
| 6"      | Time           |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Dry temp.      |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Air speed      |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Radiant excess |           |    |     |    |          |    |     |    |              |    |     |    |
|         | No. at table   |           |    |     |    |          |    |     |    |              |    |     |    |
|         |                |           |    |     |    |          |    |     |    |              |    |     |    |
|         |                |           |    |     |    |          |    |     |    |              |    |     |    |
|         |                |           |    |     |    |          |    |     |    |              |    |     |    |
| (FEET)  | Time           |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Dry temp.      |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Air speed      |           |    |     |    |          |    |     |    |              |    |     |    |
|         | Radiant excess |           |    |     |    |          |    |     |    |              |    |     |    |
|         | No. at table   |           |    |     |    |          |    |     |    |              |    |     |    |
|         |                |           |    |     |    |          |    |     |    |              |    |     |    |
|         |                |           |    |     |    |          |    |     |    |              |    |     |    |
|         |                |           |    |     |    |          |    |     |    |              |    |     |    |
| Remarks |                |           |    |     |    |          |    |     |    |              |    |     |    |

PERSONAL DATA, CLOTHING.

[illegible]



[illegible]

| READINGS                 |     |         |     |              | DERIVED SUMMARIES |      |                  |      |                 |    |                     |          |          |      |          |              |
|--------------------------|-----|---------|-----|--------------|-------------------|------|------------------|------|-----------------|----|---------------------|----------|----------|------|----------|--------------|
| AREA                     | No. | TEMP.   |     | R.M.         | STATUS<br>Cat.    | REST |                  |      | ENTRY           |    |                     | ADJACENT |          |      |          |              |
|                          |     | DRY     | WET |              |                   | No.  | T.               | R.M. | No.             | T. | R.M.                | No.      | T.       | R.M. |          |              |
| . Changing               | 1   |         |     |              | S,<br>S.A.        |      |                  |      |                 |    |                     |          |          |      |          |              |
| . Rest                   | 2   |         |     |              |                   |      |                  |      |                 |    |                     |          |          |      |          |              |
| crub-up                  | 3   |         |     |              |                   | Mean |                  |      |                 |    |                     |          |          |      |          |              |
| . Room                   | 4   |         |     |              | An.               |      |                  |      |                 |    |                     |          |          |      |          |              |
| uice                     | 5   |         |     |              |                   |      |                  |      |                 |    |                     |          |          |      |          |              |
| erilising                | 6   |         |     |              |                   | Mean |                  |      |                 |    |                     |          |          |      |          |              |
| eatre<br>corridor        | 7   |         |     |              | S.N.              |      |                  |      |                 |    |                     |          |          |      |          |              |
| spital<br>corridor       | 8   |         |     |              |                   |      |                  |      |                 |    |                     |          |          |      |          |              |
| tside                    | 9   |         |     |              |                   | Mean |                  |      |                 |    |                     |          |          |      |          |              |
| INTERNAL                 |     | Hosp. T |     | Outside<br>T | Mean T            |      | Hospital<br>R.M. |      | Outside<br>R.M. |    | Mean R.M.           |          | Pressure |      | ↑ ↓      | Wea-<br>ther |
| ENVIRONMENT              |     | 65      | 66  | 67 68        | 69                | 70   | 71               | 72   | 73              | 74 | 75                  | 76       | 77       | 78   | 79       | 80           |
| CATEGORIES               |     |         |     |              |                   |      |                  |      |                 |    |                     |          |          |      |          |              |
| CILIARY AREAS, RELEVANT  |     |         |     |              | TEMPERATURES      |      |                  |      |                 |    | RELATIVE HUMIDITIES |          |          |      |          |              |
| TO FOLLOWING CATEGORIES: |     |         |     |              | Rest              |      | Entry            |      | Adjacent        |    | Rest                |          | Entry    |      | Adjacent |              |
|                          |     |         |     |              | 49                | 50   | 51               | 52   | 53              | 54 | 55                  | 56       | 57       | 58   | 59       | 60           |
| ARGLEONS, ASSISTANTS     |     |         |     |              |                   |      |                  |      |                 |    |                     |          |          |      |          |              |
| AELECTHICISTS            |     |         |     |              |                   |      |                  |      |                 |    |                     |          |          |      |          |              |
| RUE-NURSES               |     |         |     |              |                   |      |                  |      |                 |    |                     |          |          |      |          |              |

| DATE:             | Position  | READINGS  |      |           |      |           |      |
|-------------------|-----------|-----------|------|-----------|------|-----------|------|
|                   |           | Time I:   |      | Time II:  |      | Time III: |      |
|                   |           | Occasion: | Mean | Occasion: | Mean | Occasion: | Mean |
|                   | WALLS     |           |      |           |      |           |      |
|                   | FLOOR     |           |      |           |      |           |      |
|                   | CEILING   |           |      |           |      |           |      |
|                   | LAMP      |           |      |           |      |           |      |
|                   | RADIATORS |           |      |           |      |           |      |
| AREA OF RADIATORS |           |           |      |           |      |           |      |
| AREA OF LAMP      |           |           |      |           |      |           |      |

|                        |             |  |  |  |  |  |
|------------------------|-------------|--|--|--|--|--|
| DISC :                 |             |  |  |  |  |  |
| WEIGHT (AFTER)         |             |  |  |  |  |  |
| WEIGHT (BEFORE)        |             |  |  |  |  |  |
| GAIN                   |             |  |  |  |  |  |
| POSITION OF DISC       |             |  |  |  |  |  |
| NAME                   |             |  |  |  |  |  |
| REFERENCE NO.          |             |  |  |  |  |  |
| TEST                   | START       |  |  |  |  |  |
|                        | FINISH      |  |  |  |  |  |
|                        | DURATION    |  |  |  |  |  |
|                        | OCCASION    |  |  |  |  |  |
| RATE mg/hr             |             |  |  |  |  |  |
| MEASURED<br>CONDITIONS | DRY TEMP.   |  |  |  |  |  |
|                        | WET TEMP.   |  |  |  |  |  |
|                        | R.H.        |  |  |  |  |  |
|                        | AIR VEL.    |  |  |  |  |  |
|                        | RAD. EXCESS |  |  |  |  |  |
| E.T.                   |             |  |  |  |  |  |
| CLOTHING               |             |  |  |  |  |  |
| DURATION OF OP. TIME   |             |  |  |  |  |  |
| MEAN DIFFICULTY        |             |  |  |  |  |  |
| REMARKS                |             |  |  |  |  |  |

FIG. 3.10 SUMMARY CARD.

| REFERENCE        |       |          |       |                  |        |        |      |                 |            |          |      |     |    |       |    |  |  |  |  |  |  |  |  |
|------------------|-------|----------|-------|------------------|--------|--------|------|-----------------|------------|----------|------|-----|----|-------|----|--|--|--|--|--|--|--|--|
| SUBJECT          |       |          | RESP. | CARD             |        |        |      |                 |            |          |      |     |    |       |    |  |  |  |  |  |  |  |  |
| 1                | 2     | 3        | 4     | 5                | 6      | 7      | 8    | 9               | 10         | 11       | 12   | 13  | 14 | 15    | 16 |  |  |  |  |  |  |  |  |
|                  |       |          |       | X                |        |        |      |                 |            |          |      |     |    |       |    |  |  |  |  |  |  |  |  |
|                  |       |          |       |                  |        |        |      |                 |            |          |      |     |    |       |    |  |  |  |  |  |  |  |  |
| 17               | 18    | 19       | 20    | 21               | 22     | 23     | 24   | 25              | 26         | 27       | 28   | 29  | 30 | 31    | 32 |  |  |  |  |  |  |  |  |
|                  |       |          |       |                  |        |        |      |                 |            |          |      |     |    |       |    |  |  |  |  |  |  |  |  |
| OCCASION         |       |          |       | VERBAL RESPONSES |        |        |      |                 |            |          |      |     |    |       |    |  |  |  |  |  |  |  |  |
| DATE             | MONTH | TIME     | S     | T1               | T2     | T3     | W    | P               | N          | H        | O    | M   | D  | L     |    |  |  |  |  |  |  |  |  |
| 33               | 34    | 35       | 36    | 37               | 38     | 39     | 40   | 41              | 42         | 43       | 44   | 45  | 46 | 47    | 48 |  |  |  |  |  |  |  |  |
|                  |       |          |       |                  |        |        |      |                 |            |          |      |     |    |       |    |  |  |  |  |  |  |  |  |
| THEATRE          |       | CLOTHING |       |                  |        | NOISE  |      | ILLUMINATION    |            |          |      |     |    |       |    |  |  |  |  |  |  |  |  |
| NO.              | HEAD  | BODY     | FEET  | ETC.             |        |        | TASK | LOCAL           | BACKGROUND | DAYLIGHT |      |     |    |       |    |  |  |  |  |  |  |  |  |
| 49               | 50    | 51       | 52    | 53               | 54     | 55     | 56   | 57              | 58         | 59       | 60   | 61  | 62 | 63    | 64 |  |  |  |  |  |  |  |  |
|                  |       |          |       |                  |        |        |      |                 |            |          |      |     |    |       |    |  |  |  |  |  |  |  |  |
| PERSONAL DETAILS |       |          |       |                  |        |        |      | SESSION DETAILS |            |          |      |     |    |       |    |  |  |  |  |  |  |  |  |
| STATUS           | SEX   | AGE      | RACE  | BUILD            | HEIGHT | GLASS. | LIST | DURATION        | STRESS     | OCC.     | AMB. | NO. | AT | TABLE |    |  |  |  |  |  |  |  |  |
| 65               | 66    | 67       | 68    | 69               | 70     | 71     | 72   | 73              | 74         | 75       | 76   | 77  | 78 | 79    | 80 |  |  |  |  |  |  |  |  |
|                  |       |          |       |                  |        |        |      |                 |            |          |      |     |    |       |    |  |  |  |  |  |  |  |  |

| REFERENCE                   |            |          |              |             |          |                     |       |                             |      |       |    |              |    |    |    |  |  |  |  |  |  |  |  |
|-----------------------------|------------|----------|--------------|-------------|----------|---------------------|-------|-----------------------------|------|-------|----|--------------|----|----|----|--|--|--|--|--|--|--|--|
| SUBJECT                     |            |          | RESP.        | CARD        |          |                     |       |                             |      |       |    |              |    |    |    |  |  |  |  |  |  |  |  |
| 1                           | 2          | 3        | 4            | 5           | 6        | 7                   | 8     | 9                           | 10   | 11    | 12 | 13           | 14 | 15 | 16 |  |  |  |  |  |  |  |  |
|                             |            |          |              | Y           |          |                     |       |                             |      |       |    |              |    |    |    |  |  |  |  |  |  |  |  |
|                             |            |          |              |             |          |                     |       |                             |      |       |    |              |    |    |    |  |  |  |  |  |  |  |  |
| VERBAL RESPONSES            |            |          |              |             |          |                     |       | THEATRE TEMPERATURES        |      |       |    |              |    |    |    |  |  |  |  |  |  |  |  |
| S                           | T1         | T2       | T3           | W           | P        | H                   | HEAD  | BODY                        | FEET | TABLE |    |              |    |    |    |  |  |  |  |  |  |  |  |
| 17                          | 18         | 19       | 20           | 21          | 22       | 23                  | 24    | 25                          | 26   | 27    | 28 | 29           | 30 | 31 | 32 |  |  |  |  |  |  |  |  |
|                             |            |          |              |             |          |                     |       |                             |      |       |    |              |    |    |    |  |  |  |  |  |  |  |  |
| AIR VELOCITY                |            |          |              |             |          |                     |       | RADIANT EXCESS TEMPERATURES |      |       |    |              |    |    |    |  |  |  |  |  |  |  |  |
| HEAD                        | BODY       | FEET     | TABLE        | HEAD        | BODY     | FEET                | TABLE |                             |      |       |    |              |    |    |    |  |  |  |  |  |  |  |  |
| 33                          | 34         | 35       | 36           | 37          | 38       | 39                  | 40    | 41                          | 42   | 43    | 44 | 45           | 46 | 47 | 48 |  |  |  |  |  |  |  |  |
|                             |            |          |              |             |          |                     |       |                             |      |       |    |              |    |    |    |  |  |  |  |  |  |  |  |
| ANCILLARY AREA TEMPERATURES |            |          |              |             |          | ANCILLARY AREA R.H. |       |                             |      |       |    | THEATRE R.H. |    |    |    |  |  |  |  |  |  |  |  |
| REST                        | ENTRY      | ADJACENT | REST         | ENTRY       | ADJACENT | HEAD                | TABLE |                             |      |       |    |              |    |    |    |  |  |  |  |  |  |  |  |
| 49                          | 50         | 51       | 52           | 53          | 54       | 55                  | 56    | 57                          | 58   | 59    | 60 | 61           | 62 | 63 | 64 |  |  |  |  |  |  |  |  |
|                             |            |          |              |             |          |                     |       |                             |      |       |    |              |    |    |    |  |  |  |  |  |  |  |  |
| EXTERNAL ENVIRONMENT        |            |          |              |             |          |                     |       |                             |      |       |    |              |    |    |    |  |  |  |  |  |  |  |  |
| HOSPITAL T.                 | OUTSIDE T. | MEAN T.  | HOSPITAL RH. | OUTSIDE RH. | MEAN RH. | PRESSURE            | R1/F2 | WEATH.                      |      |       |    |              |    |    |    |  |  |  |  |  |  |  |  |
| 65                          | 66         | 67       | 68           | 69          | 70       | 71                  | 72    | 73                          | 74   | 75    | 76 | 77           | 78 | 79 | 80 |  |  |  |  |  |  |  |  |
|                             |            |          |              |             |          |                     |       |                             |      |       |    |              |    |    |    |  |  |  |  |  |  |  |  |

SECTION 4.

ANALYSIS.

#### 4. 1. Introduction.

This section describes a number of techniques used in the analysis of the data whose collection and recording were described in Section 3. Certain preliminary results, that were used at an early stage in making decisions on the form of the analysis, are presented, but the main results, covering as they do a very broad range of topics, can more conveniently be set out in separate sub-sections. These are grouped into Sections 5 and 6 of the thesis. Section 5 deals with the main analysis, for which complete data was available, while Section 6 deals with the examination of incomplete data on various subsidiary topics. The methods of analysis used in the examination of individual differences, objective measurements of sweat rate and skin temperature, performance measures, and preference for daylight, are set out in the appropriate sections (7, 8, 9 and 10 respectively) as they are somewhat different in kind.

The aim of the main analysis was to derive multiple regression equations that expressed an estimate of each dependent variable in terms of as many factors of the environment as could be shown to have a significant effect. The dependent variables were either the results of standard sequences of questions or of systematised observation. In all cases they were measures of response to the environment expressed on arbitrary scales and it was necessary to show in the first instance that these measures were normally distributed with respect to the main variables, especially with respect to temperature.

#### 4. 2. Examination of thermal responses.

A large amount of two-way sorting was carried out on the punch

cards whose preparation was described in Section 3. The method of probit analysis was used as in Section 2; Graph 4.1. illustrates a result obtained by this method. As predicted by the analyses of Section 2, Bedford's seven point scale of thermal comfort did result in normally distributed responses of 'too hot' and 'too cold' against temperature. Graph 4.2. shows that the 'Mean Thermal Vote' is linearly related to these probit values, again in accordance with Section 2. Similar linear relationships were found for the other measures of subjective response, and they were therefore considered to be distributed sufficiently close to normality for the purpose of the analysis. Graph 4.3. shows the relation between mean thermal vote at head-height and the dry-bulb temperature. There is no trace of the discontinuity reported by Hickish (1955) and discussed in Section 2. Mean thermal vote is thus seen to be a useful and orderly measure of response over the full data range, and is used as a metric variable in the rest of the analysis.

#### 4. 3. Treatment of other variables.

When different categories of staff are considered separately, as Graph 4.4. shows for surgeons and anaesthetists, consistent differences are seen in the response. Clearly 'staff-category' must be considered as a variable, but as it is 'measured' on a nominal scale (Siegel 1956), it cannot merely take its place in the analysis along with metric variables such as temperature or air-velocity, which are measured on interval or even ratio scales. The effect is one of constant bias, or a shift of axis, and Lidwell (1961) has shown a



useful way of deriving the correct value within the framework of a multiple regression analysis. The presence or absence of each category is treated as a separate variable taking the value zero or unity. The regression coefficient then appears as an adjustment to the constant in the equation. The categories must be mutually exclusive. The same technique is appropriate in the treatment of 'season of the year', though in this case only three variables were used - spring, summer and autumn - so that the reference condition became winter, when all three 'variables' took the value zero. A number of other non-metric variables were included in exactly the same way. Among them were sex, race and the presence or absence of glasses worn by the subject. Age and duration of exposure were measured in years and minutes respectively and present no problem. Build and height were estimated variables, and the level of measurement was no more than ordinal, but as both arbitrary scales are approximations to underlying interval scales, they have been treated as metric variables for the purpose of the analysis.

The form of regression equation to which the data was fitted is given in Section 4.4; it assumes a linear effect for all metric variables. The assumption was tested for the main thermal variables in Section 3, and is probably an acceptable approximation for the small effects produced by the metric variables considered in this section.

#### 4.4. Computer programs.

The multiple regression analyses were carried out by means of the computer program BMD.02R of the Biomedical Series (1965). It is a sequential analysis by which successive terms are added to the

equation in the order in which they make the greatest reduction in the residual sum of squares. The decision as to which variables are 'significant' can be made at a later stage by considering each estimated regression coefficient in relation to its variance, or the program can be instructed to stop adding variables when the reduction in the sum of squares falls below a specified level of significance. The output includes the mean and variance of all the variables and the correlation matrix. The form of the equation derived is  $E = aX_1 + bX_2 + \text{etc.}$  where E is an estimate of the dependent variable,  $X_1, X_2 \dots X_i$  are independent variables, and a, b, c, etc. are the calculated regression coefficients.

#### 4. 5. Vapour pressure of water.

It was originally intended to use relative humidity as one of the principal variables, but examination of its effect by means of three-way sorting produced the results shown in Graph 4.5. They suggest the need for a cross-product term in temperature and relative humidity; this leads to ambiguous results in a multiple regression analysis of this kind. Graph 4.6. shows that when the same data is re-plotted in terms of vapour pressure, an expression of the form  $T_1\text{-vote} = aT + b.V.P. + \text{etc.}$  is appropriate. It was therefore decided to use vapour pressure instead of relative humidity as a measure of the water content of the air. This decision was taken reluctantly, as relative humidity is a more familiar quantity and is in fact the variable that is controlled by most humidifying equipment. In addition, only dry-bulb temperature and relative humidity had been

punched on the data cards, making it necessary to use a modified form of the Kirchoff-Rankine-Dupré formula to generate saturated vapour pressure, and hence the vapour pressure is millimetres of mercury.

The formula used was:

$$\log_e \text{SVP} = 20.810 - \frac{2458}{459+T}, \quad \text{where SVP is}$$

the saturated vapour pressure in mm. Hg., and T is the dry-bulb temperature in Fahrenheit degrees. The accuracy achieved in the data range was better than 0.03 mm. Hg. This calculation was carried out by computer each time the data was used.

#### 4. 6. Radiometer readings.

A similar calculation was required in order to correct the reading of the radiometer for the effect of air velocity. An experimentally obtained relation was used, as given by Lidwell and Wyon (1968), but a numerical approximation was obtained graphically and is shown in Graph 4.7. The form of the equation was:

$$R = \frac{R^1}{0.722 - 0.178 \cdot \log_{10} V}$$

where R = Radiant excess temperature in Fahrenheit degrees

$R^1$  = Radiometer reading in microamperes

V = air velocity in feet per minute.

The radiant excess temperature thus obtained was used as an independent variable in the regression equation, much as the radiant excess temperature is added arbitrarily to the dry-bulb temperature in the Corrected Effective Temperature scale. (Bedford (1964)).

#### 4. 7. Air velocity.

The effect of air velocity was apparently very slight. Graph 4.8. shows the relation between the percentage of surgeons and surgical assistants reporting a sensation of 'uncomfortably hot' at head-height against the air velocity in feet per minute, for three temperature ranges. There is no evidence for the inclusion of a cross-product term in temperature and air velocity, but equally the evidence is not sufficient to decide on any particular functional relationship with air velocity. However, there is a considerable amount of evidence to suggest that heat loss by conduction-convection from the human body varies as the square root of the air velocity. This is well summarised by Lee (1958). This function of air velocity was used by Webb (1959) in deriving a factorial equation for mean thermal vote. As has been pointed out in Section 2, Webb's mean thermal vote is not the same as Bedford's mean thermal vote as used in the present work, but the reasoning behind the choice of the square root of the air velocity is the same as that used by Bedford (1964) in forming a similar factorial equation. A laboratory experiment carried out by Turner (1955) on a single subject lends some support to this choice. In this experiment the subjective sensation evoked by gusts of air at different temperatures and velocities was investigated. It was found that the difference in temperature between the surrounding air and the gust varied linearly with the square root of the air velocity for threshold sensations of warmth or cold. Turner found that increasing the area of skin exposed to the gust affected this relationship, but only for very small areas; an area of skin as great as the 80-100 cm.<sup>2</sup> exposed by surgical clothing

was as sensitive as much larger areas of skin. This work is more relevant to the perception of air velocity per se. than to the effect of air velocity on mean thermal vote. However, taking all the evidence together, it was decided to use the square root of the air velocity as a measure of this factor in the regression equations for thermal responses.

#### 4. 8. Observed sweating.

In addition to obtaining subjective responses to thermal stress, the interviewer made observations of forehead sweating every time a subject was questioned. Ellis (1952) has used observations of chest sweating made by subjects themselves, and Webb (1959) asked subjects to record the extent to which they were sweating. In neither case was the result used in other than an illustrative way. Houghton and Cook (1939) observed forehead sweating by operating theatre staff, but the small number of observations (51) made their results of little predictive value. However, their work appears to be the most relevant to the present case, and provides a useful pilot study of the feasibility of constructing a usable scale of 'sensible perspiration' for use in an operating theatre situation. Assigning numerical values to the categories of observation defined in Section 3 results in an index, denoted here by P, whose dependence on dry-bulb temperature is shown in Graph 4.9. The regression is essentially linear, the anomalous point below 65° being due to only 41 observations in the total number of over 2,500. Most importantly, there is no tendency to 'saturation' at the highest temperatures encountered. Graph 4.10 shows the result of an application of probit analysis to the categories

of P. Again the results are very closely linear, demonstrating that the observations are normally distributed with respect to temperature. It is interesting to note that 50% of the predominantly male subjects in this sample were observed to have 'damp' foreheads even at 70°F.

It was decided on the basis of these results to use 'P' as a dependent metric variable in a way analogous to the use of the mean thermal vote.

#### 4. 9. Special techniques of analysis.

##### 4. 9. 1. 'Z-cards'.

As detailed in Section 3, the data available for mechanical processing was contained on pairs of punched cards in order to accommodate all the information relevant to each case. For a number of reasons it was necessary to 'generate' from each pair a single card bearing processed and selected data for particular purposes. These third cards have been called 'Z-cards' as opposed to the X and Y cards of the original pairs. In practice, two sets of 'Z-cards' were generated for different purposes, but no distinction will be made between them as the principle was the same. Z-cards were generated by program BMD. 09.S. of the Biomedical Series (1965), by which a very wide range of operations can be performed and the results located as required in the columns of mechanically produced output cards. Input can be in the form of up to ten cards for each case.

The reasons for the use of Z-cards were the following:

##### 4. 9. 2. Incomplete data.

Certain variables, dealt with in Section 6 of this thesis, were incomplete in the sense that they were not recorded for all cases. The

programs in use had no facility for selecting a sub-sample of data for analysis, so this operation had to be performed by card-sorting prior to analysis. It was not possible to select sub-samples of the paired cards by this method, but if all the data needed for the analysis was transferred to the Z-cards, sub-sampling could take place by sorting the Z-cards into input packs for each analysis of incomplete data.

#### 4. 7. 3. Predicted votes.

In order to increase the precision of the analyses of the incomplete data, they were performed for the most part with 'deviation from the predicted vote' as dependent variable. The predicted votes were the values calculated from the regression equations obtained in the main analyses, their coefficients based not on a sub-sample, as used for the incomplete data, but on all the data available. Thus variation due to variables that were always recorded was removed prior to the analysis of the effect of the incomplete data. For this purpose, predicted votes were generated for each case and punched on the Z-cards.

#### 4. 9. 4. Index temperatures.

Predicted votes can be used to derive an Index temperature for each combination of conditions; Index temperature is defined as that temperature that would under standard conditions lead to the same predicted vote as the measured conditions. This is the principle of the Effective Temperature scale and of the Singapore Index. In the present case it was thought useful to choose reference conditions close to the mean values observed in order to avoid unreal extrapolation. The standard conditions chosen were 50% relative humidity, mean radiant

temperature equal to air temperature, and 25 feet per minute air velocity. The value of the Index Temperature is linearly related to the predicted vote on which it is based, so it was not necessary to generate Index Temperature explicitly on the Z-cards. Distributions of response against Index Temperature were constructed by sorting the Z-cards with respect to the predicted vote and the recorded vote for each case.

#### 4. 9. 5. Mean thermal response, $T_0$ .

Some time after the original data cards had been punched, it was decided to combine the three thermal votes obtained,  $T_1$ ,  $T_2$  and  $T_3$ , into a single measure of thermal response. This was defined as  $T_0 = 1/3 (T_1 + T_2 + T_3)$ , and generated on each Z-card. It would have been simpler to have included it on the original data cards. However, the result of a sorting operation on the Z-card pack is shown in Graph 4.11.  $T_0$  can be seen to reflect in an orderly way the combined thermal responses at each of the three bodily levels. It can, of course, only vary in units of  $1/3$  for each case, but a particular value of  $T_0$  can arise in a large number of ways; for example  $T_0 = 11/3 = 3.67$  can arise from votes of 3, 4, 4 (No discomfort), 5, 3, 3 (Uncomfortably hot in one area of the body) or even 6, 4, 1 (Uncomfortably hot in one area, uncomfortably cold in another). It was found that only seven cases out of over 2,500 exhibited this 'contradictory' pattern, and they were therefore discarded. A 'comfort range' of  $T_0$  can be defined as 2.33 - 3.67, within which less than 50% of subjects report any discomfort at all. Outside the range an increasing proportion of subjects are uncomfortable



at head, body or feet, or in more than one of these areas.  $T_0$  is used in the analysis as a metric variable. It is in fact more continuous and therefore a better approximation to a metric variable than mean thermal vote itself.

#### 4. 9. 6. Decoding

Certain variables such as clothing, mistakes, etc. had been recorded on the original data cards in a coded form. It had been thought that the transgenerations available on the regression programs would make it possible to decode them prior to analysis, but this proved not to be the case. The much wider range of operations available in the BMD.09.S. program enabled this mistake to be remedied, and the decoded data was punched on the Z-cards in a usable form.

GRAPH 4.1. PROBIT OF PROPORTIONS HOT & COLD v. D.B. TEMPERATURE.

Numbers of observations on which the points are based :-

(3)

(64)

(527)

(1267)

(623)

(111)

PROBIT.

5

"TOO COLD"

"TOO HOT"

4

OPTIMUM FOR "ALL STAFF" :-

66.6°F.

3

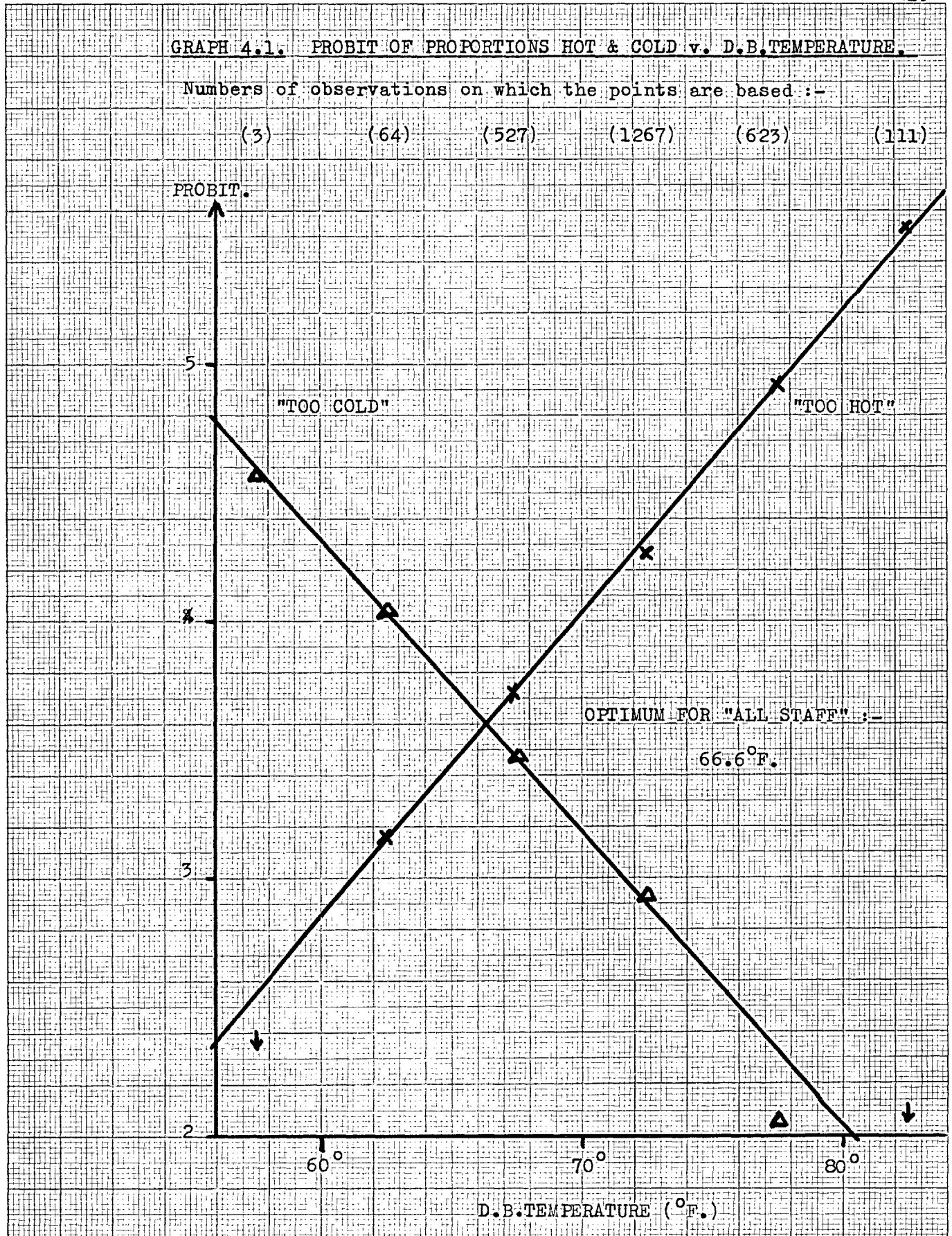
2

60°

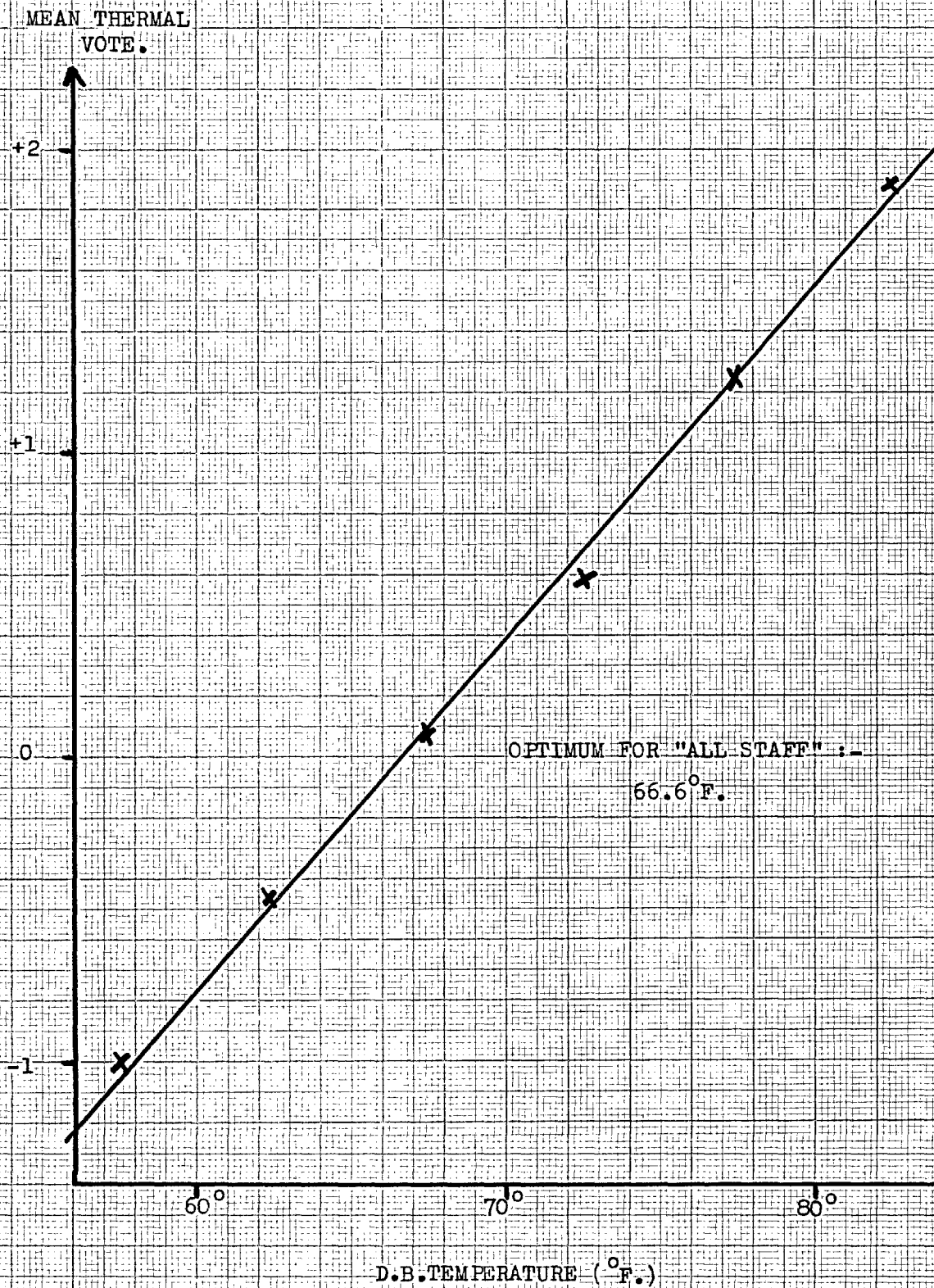
70°

80°

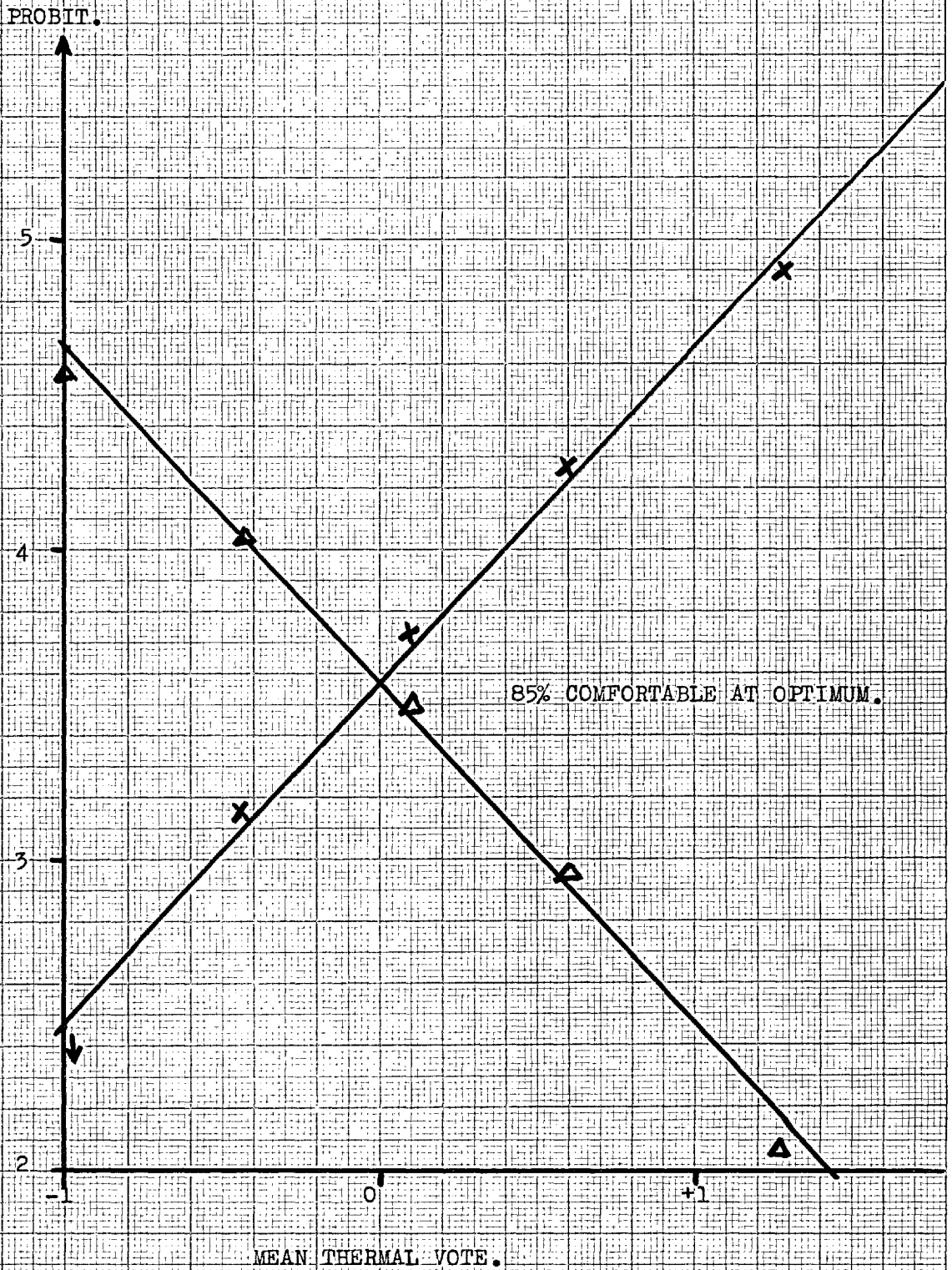
D.B. TEMPERATURE (°F.)



GRAPH 4.2. MEAN THERMAL VOTE v. D.B. TEMPERATURE.

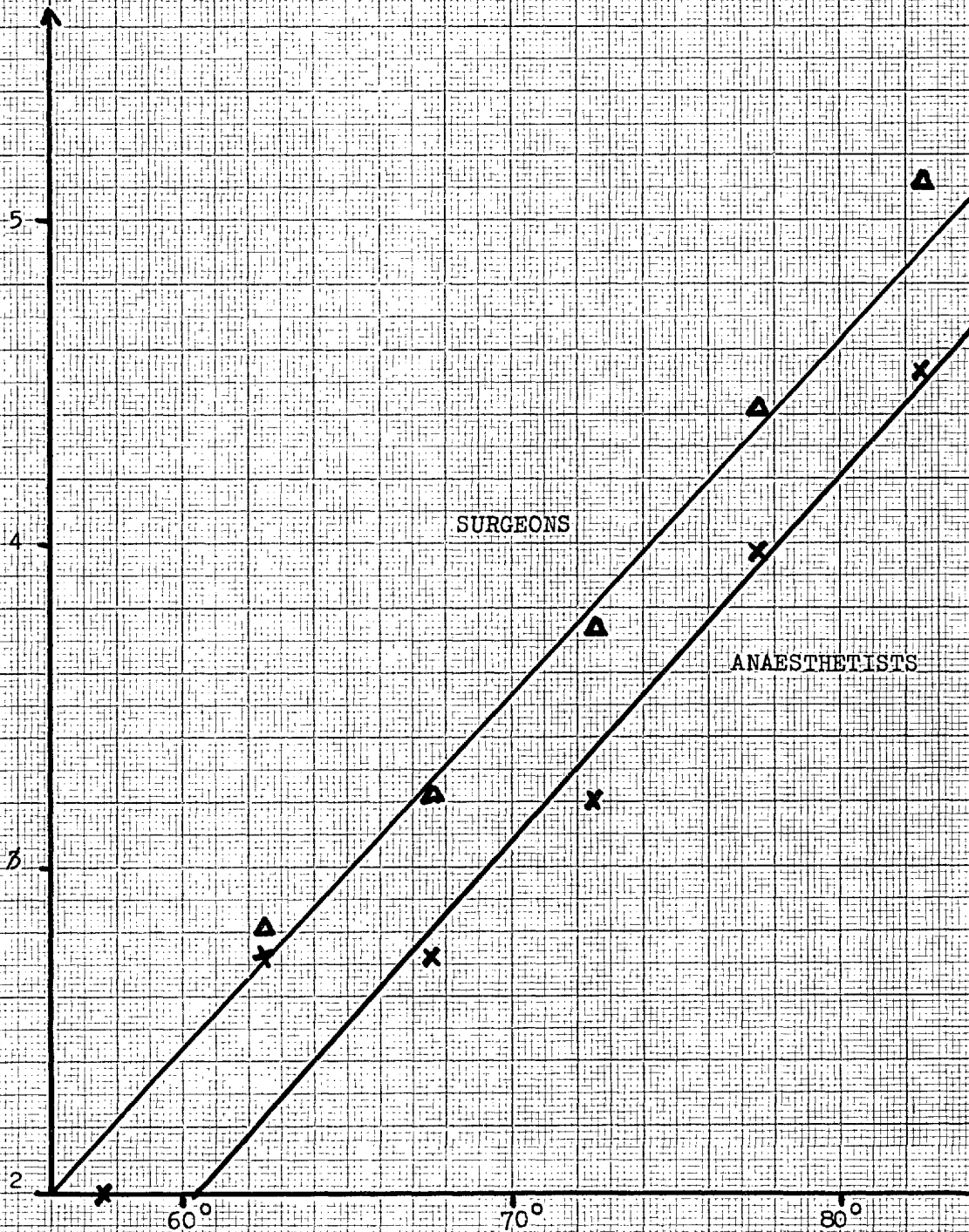


GRAPH 4.3. PROBIT OF PROPORTIONS HOT &amp; COLD v. MEAN THERMAL VOTE.



GRAPH 4.4.  $T_1$  - MEAN THERMAL VOTE v. D.B. TEMPERATURE.

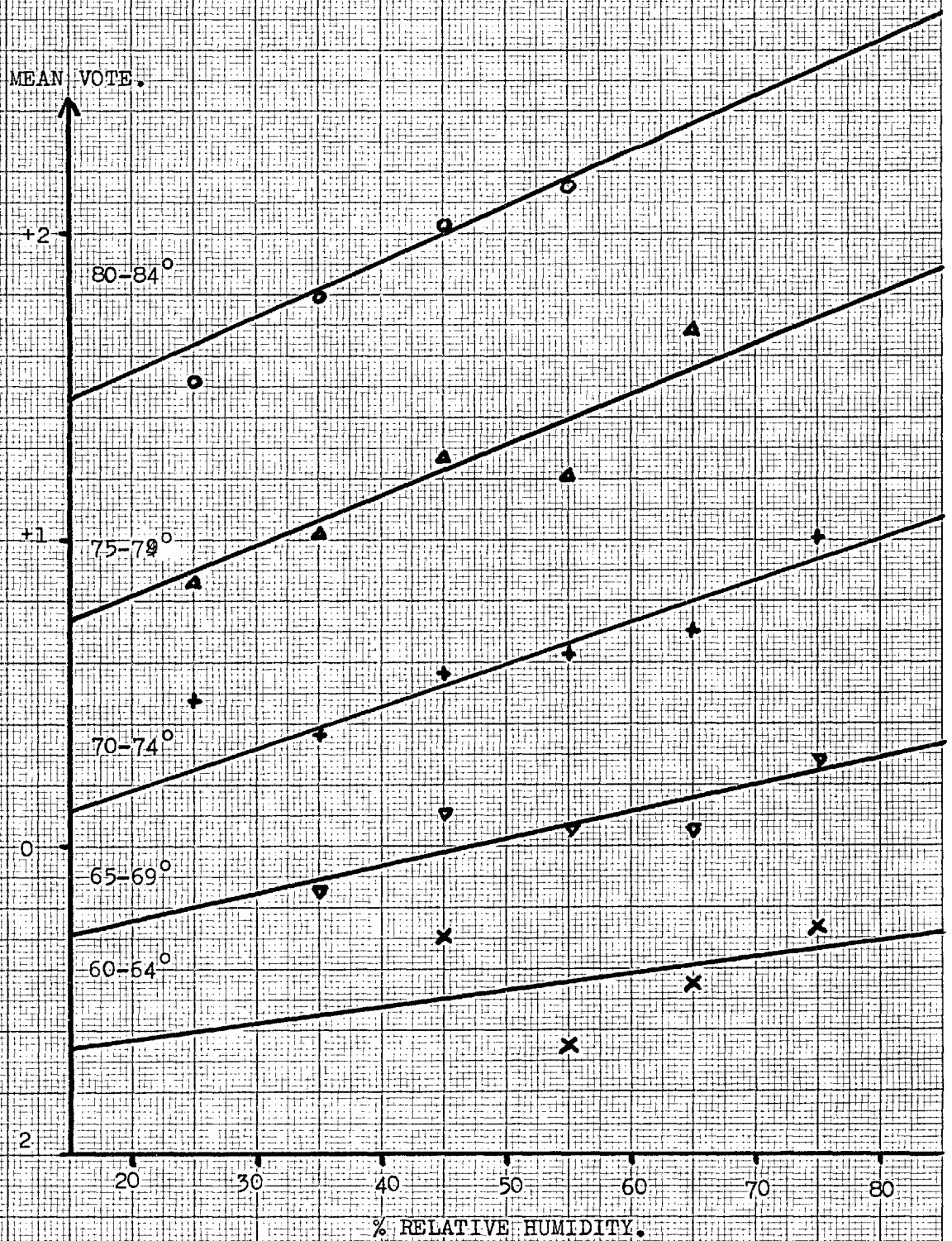
MEAN THERMAL  
VOTE.



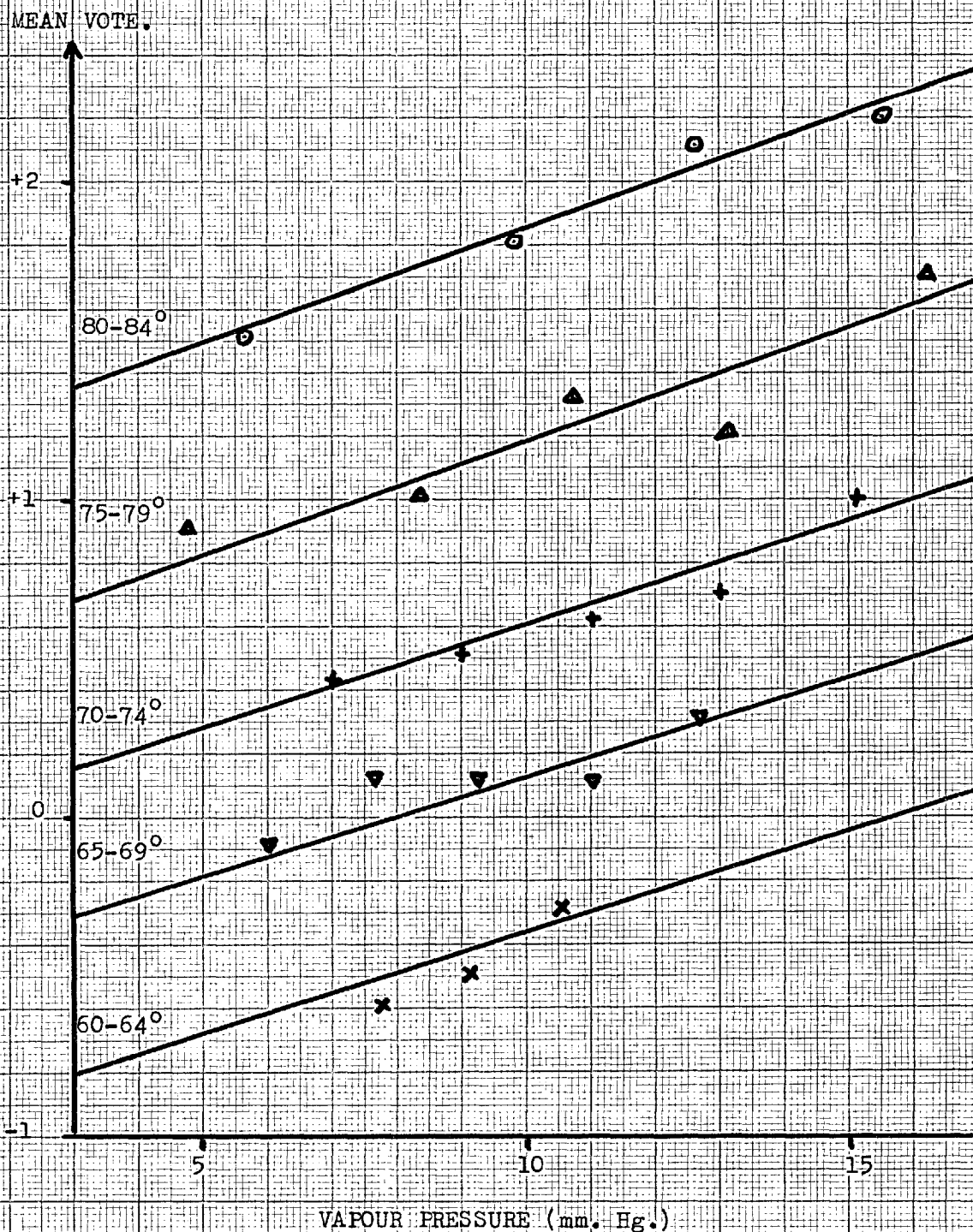
D.B. TEMPERATURE (°F.)



GRAPH 4.5  $T_1$  - MEAN VOTE v. % RELATIVE HUMIDITY.  
-IN TEMPERATURE BLOCKS.



GRAPH 4.6 T<sub>1</sub> - MEAN VOTE v. VAPOUR PRESSURE OF WATER.  
IN TEMPERATURE BLOCKS.

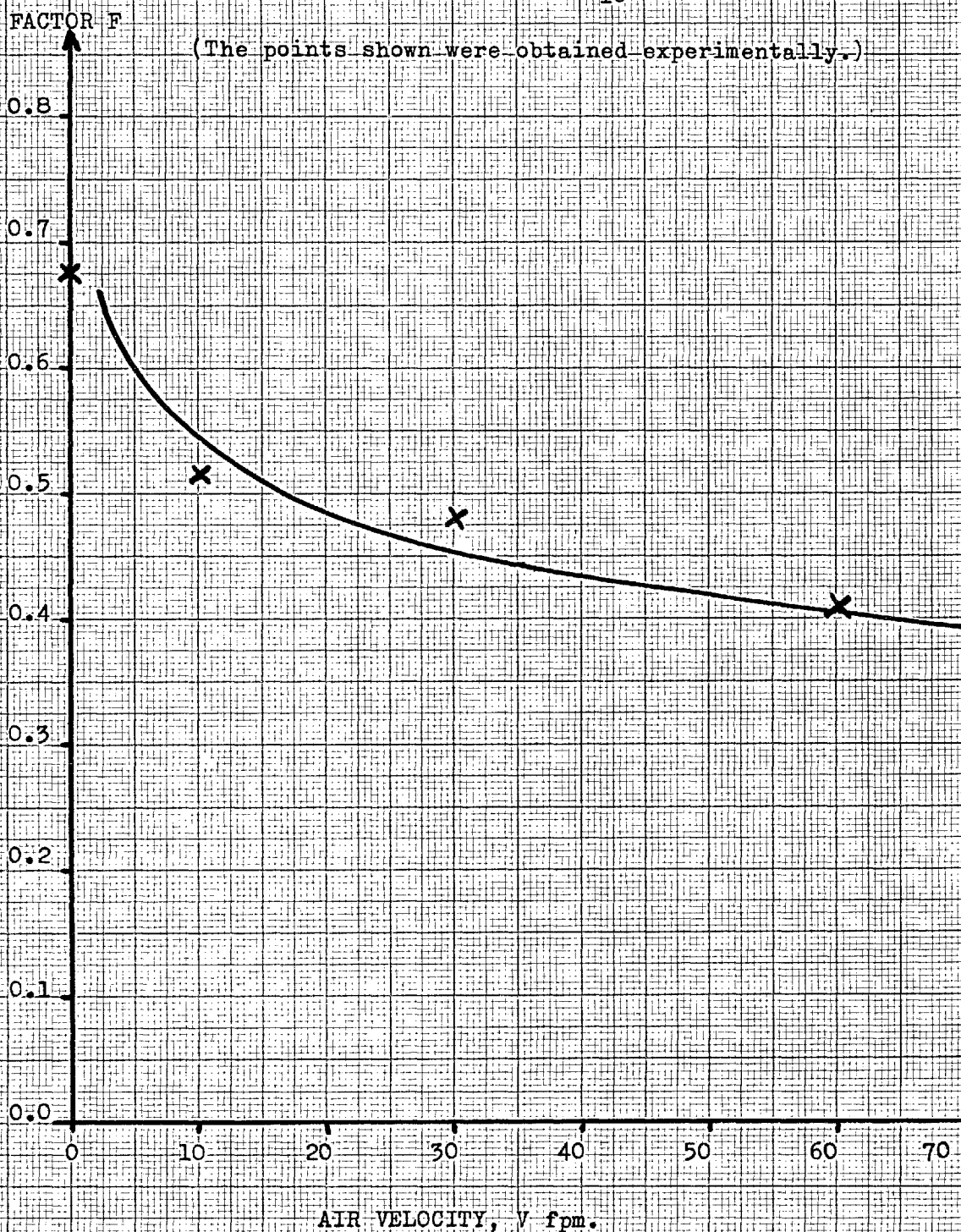


GRAPH 4.7. RADIOMETER CORRECTION FACTOR.

The curve shown is given by :-

$$F = 0.722 - 0.178 \log_{10} V$$

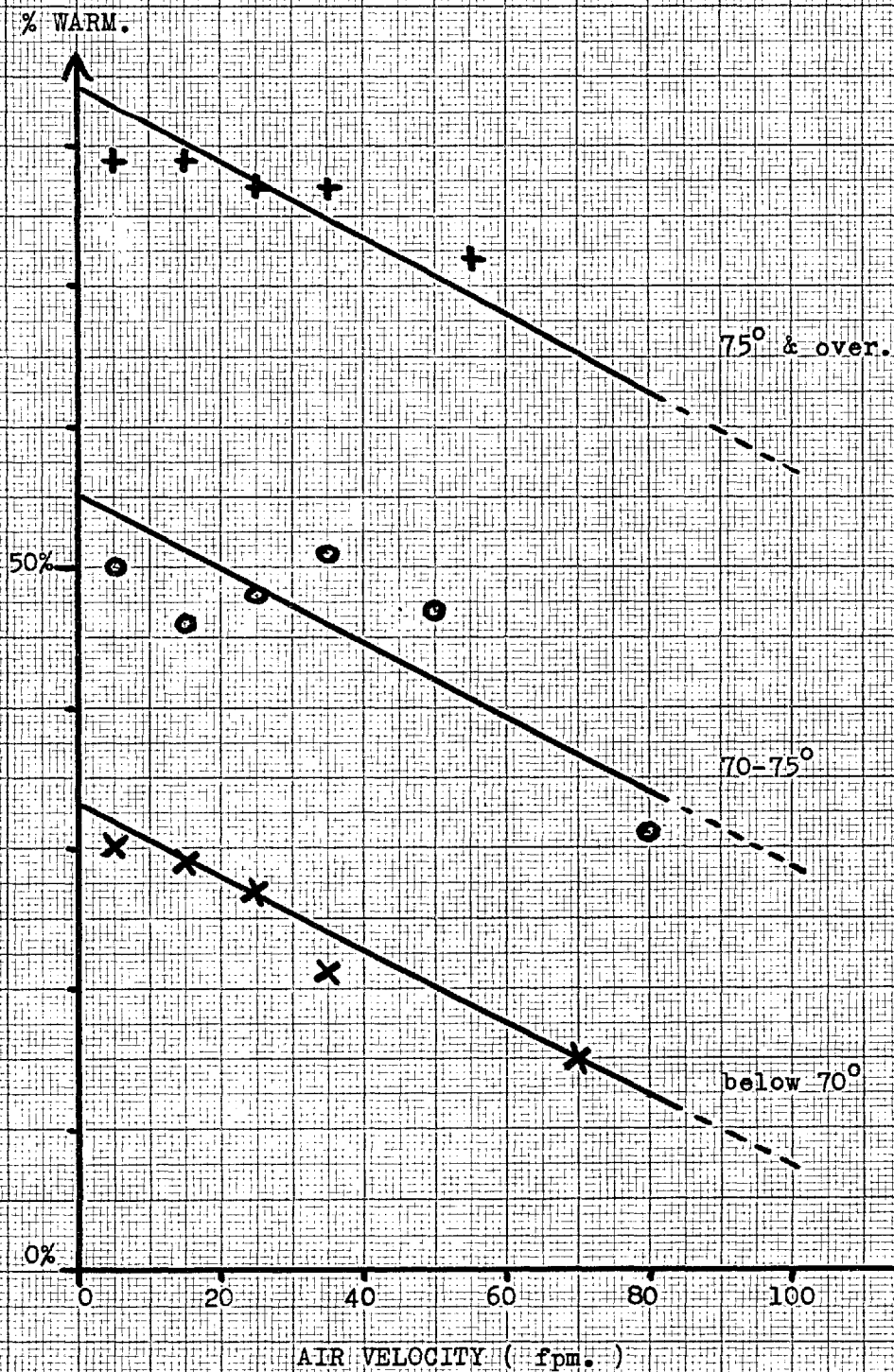
(The points shown were obtained experimentally.)





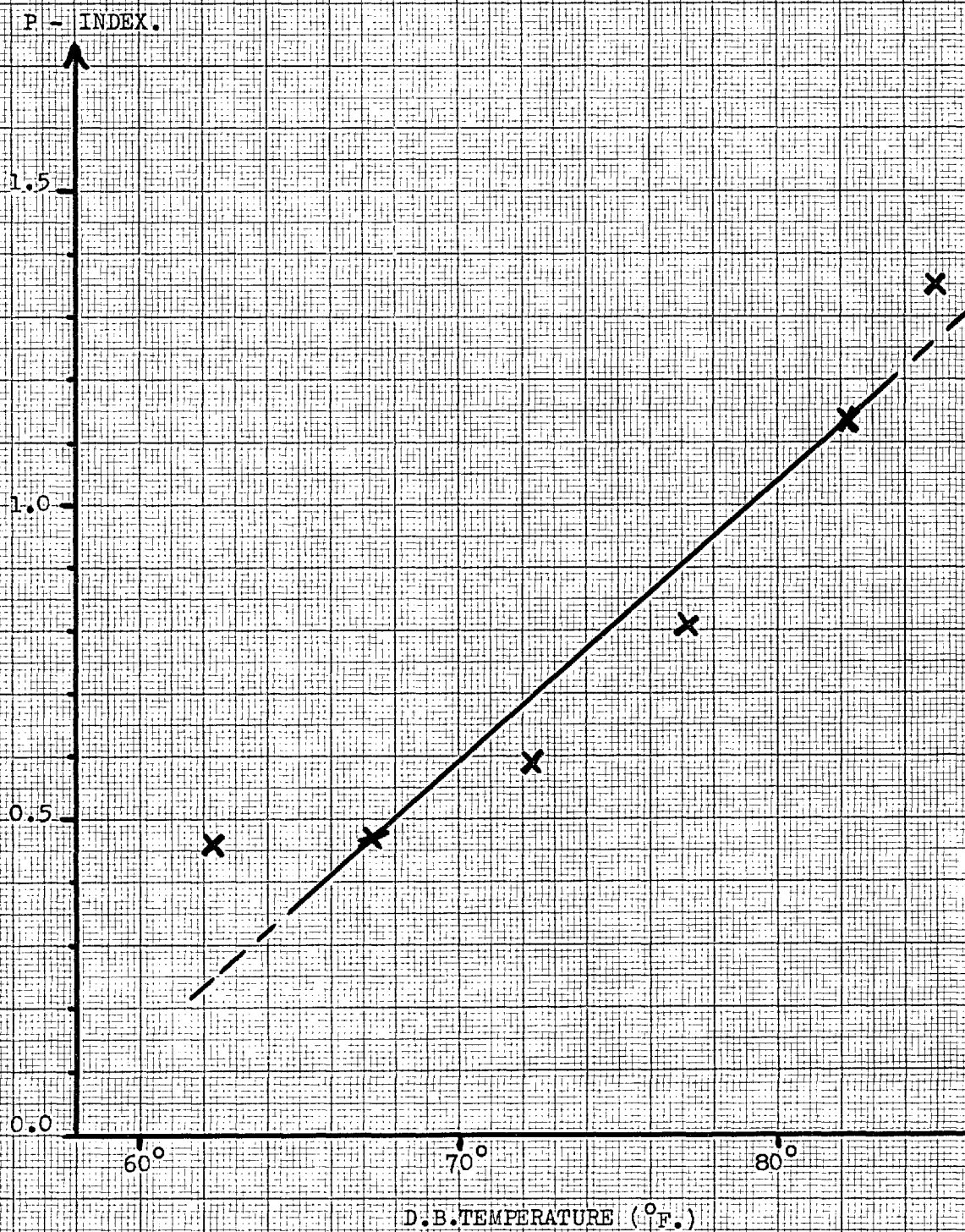
GRAPH 4.8. % WARM (+1,+2,+3, ON  $T_1$ ) v. AIR VELOCITY.

IN TEMPERATURE BLOCKS. ( SURGEONS & ASSISTANTS ONLY.)



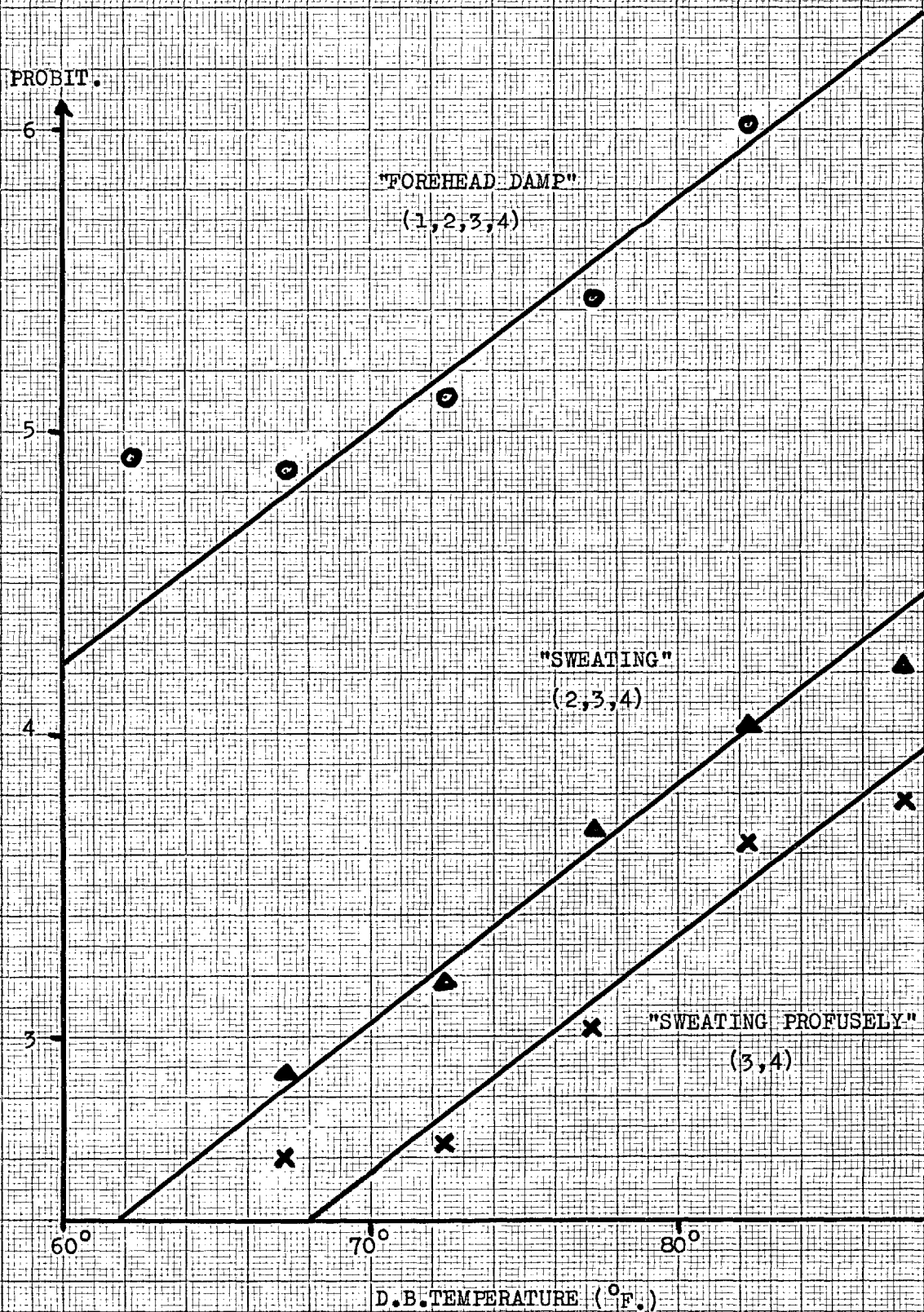
GRAPH 4.9. OBSERVED SWEATING ( P-INDEX ) v. D.B. TEMPERATURE.

( Surgeons, assistants &amp; anaesthetists only. )

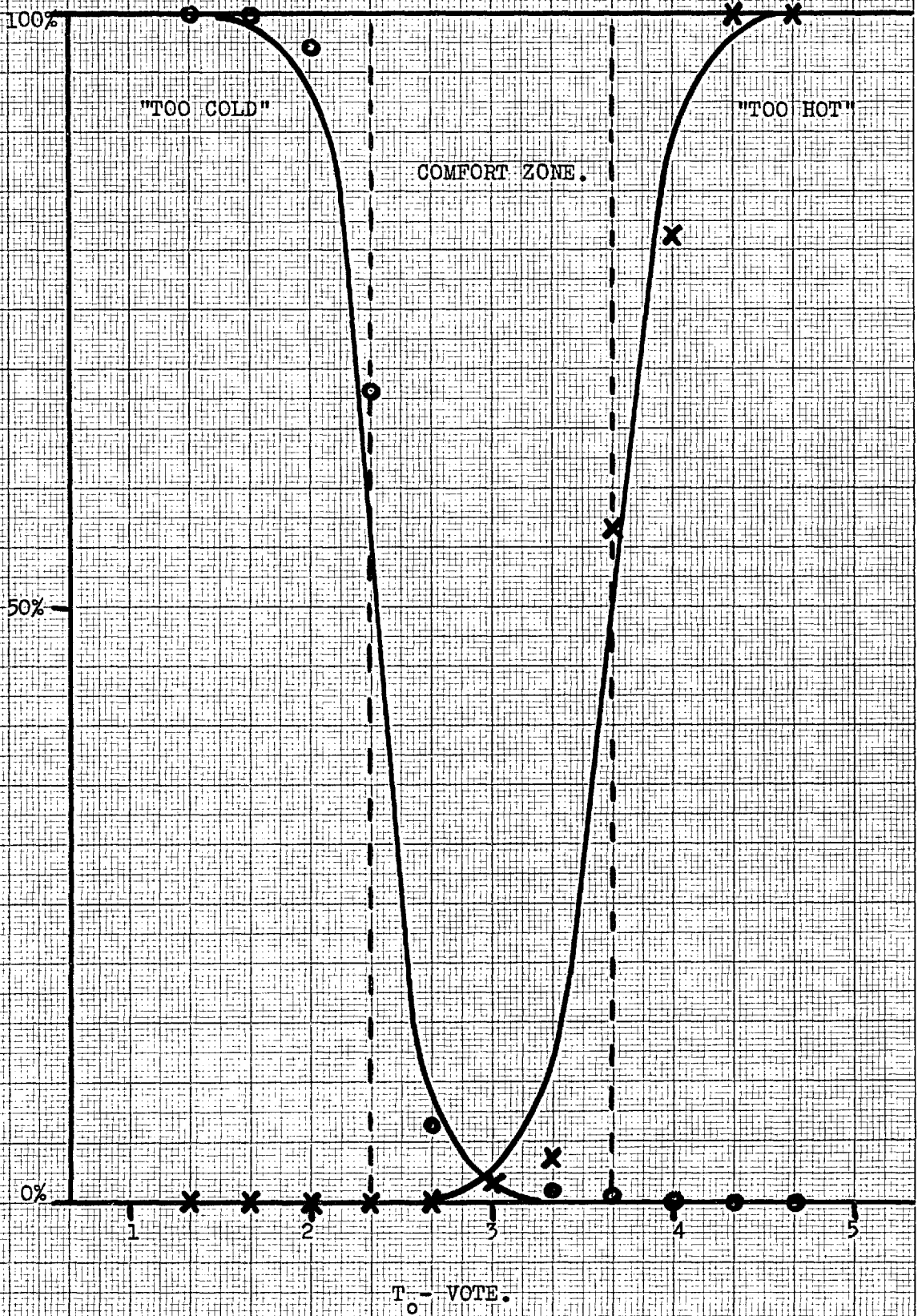


GRAPH 4.10. PROBIT OF PROPORTION SWEATING TO 3 LEVELS V.  $^{\circ}\text{F. (D.B.)}$

( Surgeons, assistants & anaesthetists only. )



GRAPH 4.11. PROPORTION HOT & COLD v.  $T_o$ -VOTE.



SECTION 5.

RESPONSES TO THE THERMAL ENVIRONMENT.



## 5. 1. Mean thermal votes and observed sweating.

### 1. Data ranges.

This sub-section contains the most important results obtained in the survey. It deals with the verbal responses  $T_1$ ,  $T_2$  and  $T_3$ , their mean  $T_0$ , discussed in Section 4, and the sweating index  $P$ . Table 5. 1. 1. gives the means, and standard deviations where appropriate, of all the variables that could be shown to have a significant effect on one or more of these responses. From these figures, derived from over 2,500 cases, a number of calculations may be made; for example, that 95% of the observations at head height were made in the temperature range 64-81°F, and the air velocity range 5-50 feet per minute. The mean water vapour pressure recorded corresponds very closely to a relative humidity of 50% at the mean temperature of 72.6°F. The mean thermal vote,  $T_1$ , considered as a continuous variable, exceeded 4.5 (the boundary between 4 - comfortably warm, and 5 - too warm) on about 20% of occasions, while the temperature at head height exceeded 75°F. on about 25% of occasions. However, causal relationships cannot be deduced at this stage, as all the thermal variables are intercorrelated. Table 5-1-2 gives a section of the total correlation matrix derived in the course of the analysis. In the table,  $T_1$  and  $P$  are related to values of the environmental variables recorded at head height,  $T_2$  and  $T_0$  to values recorded at body height, and  $T_3$  to values recorded near the floor. 35 of the 36 correlation coefficients tabulated are significant at the 0.01 level. It is clear that a multiple regression analysis is required. However, it can be seen that all five responses

are correlated more closely with temperature than with any other thermal variable.

## 2. Regression equations.

Table 5-1-3 shows the regression equations derived by means of the program RMD.02.R., for the four parameters of the physical environment only. The multiple correlation coefficients are listed together with the correlation coefficients of each response with temperature alone, reproduced from the previous table for comparison. In every case the regression accounts for a larger proportion of the variance; the improvement is greatest for  $T_0$ , but even so represents only a change from 25% to 30% in the proportion of variance attributable to the measured variables. However, all the regression coefficients listed exceed twice their standard deviation and are therefore significant at the 0.05 level. This was the test applied for the significance or otherwise of the effect of each parameter. In the case of  $T_1$  and  $P$ , the effect of air velocity was not significant at this level. From the values tabulated in Table 5-1-1 it can be seen that the air velocity was in fact lowest when measured at head height, the mean of  $\sqrt{V}$  corresponding to only 21 feet per minute, which is half the threshold value for perception of air movement on the face (Boutjor 1924). It is of interest that the effect on  $P$  should also be non-significant, since this is not dependent on the subjective sensation of draught. The effects of all four parameters were, with these exceptions, significant for all five dependent variables. The magnitude of the effects of individual parameters other than temperature will be discussed below. Their combined effect has been shown above

to be small in terms of prediction, but is not necessarily to be neglected in terms of thermal effect in some situations.

### 3. Comparison with other thermal indices.

In order to assess the value of the regression equations, comparison may be made with other thermal indices in terms of the resultant correlation coefficients for the present body of data. Table 5-1-4 shows the result of such comparison. In terms of their success in predicting the value of  $T_1$  and P for each of over 2,500 cases, Equivalent Temperature, Effective Temperature and the Singapore Index are all better than dry-bulb temperature but worse than the regression equations. Globe thermometer temperature is worse than dry-bulb temperature for  $T_1$ , and better for P, but is worse than the regression for both responses. This result is to be expected, partly because the regressions represent by definition the optimum combination for the particular body of data, but also because the regressions combine all four parameters of the physical environment while none of the thermal indices used here combine more than three.

The equations used for generating the values of the thermal indices are given in Table 5-1-10, and may be of some peripheral interest. In particular, the derived factorial expression for Effective Temperature in the data range (Equation 3 in the table) may be of use to other workers. It was derived by means of a multiple regression analysis with Effective Temperature (as given by the approximate Equation 4) as the dependent variable and the 2,500 sets of values of the thermal parameters as the independent variables. Equation 4 was derived geometrically from the



Effective Temperature nomogram and involves the fitting of straight lines to the appropriate area of the air velocity correction grid. (O.M. Iddwell 1966, personal communication.) It is somewhat cumbersome to use, and the factorial Equation 3 will estimate the resulting Effective Temperature with a standard deviation of  $0.16^{\circ}\text{F}$ .

#### 4. Identification of other significant factors.

One of the objects of the present survey was to identify and test any other factors that might be influencing the perception of the thermal environment by operating theatre staff. Table 5-1-5 shows the regression equations derived in an exactly similar way to those of Table 5-1-3, but allowing all measured variables to enter the equations. Those that were measured but did not enter fell short of the criterion for significance. In this category are time of day, number at table, height, the wearing of glasses and the difficulty of the operation. Reference to the last named and to other more esoteric variables that were not included in the main analysis will be made in Section 6. Some results relevant to the main responses appear later in the present sub-section (Table 5-1-8).

The multiple correlation coefficients for the more extensive regression equations exceed for every response those achieved by the regression equations in physical variables only. However, the largest, 0.576 for  $T_o$ , represents only an increase from 30% to 33% in the proportion of variance attributable to the measured variables. This is a small return for the inclusion of seven additional variables. On the other hand, the improvement for P represents a change from under 7% to over 24% in the proportion of variance attributable to the

regression. Clearly some of the ten additional factors are important in causing forehead sweating. To identify which are the most important, it is necessary to know which entered first in the sequential regression analysis. For  $T_1$ ,  $T_2$  and  $T_0$ , the non-metric variable 'Anaesthetist' entered before all the thermal variables had been included, while for  $P$  the non-metric variables 'Surgeon', 'Surgical Assistant' and 'Sex' entered in that order, 'Surgeon' entering before Temperature and 'Surgical Assistant' before vapour pressure. In Table 5-1-9 use is made of this information to produce regression equations which include few variables but result in multiple correlation coefficients only slightly less than those including all variables. They represent steps in the sequential analyses, and could have been identified by setting a lower limit to the acceptable reduction in the total sum of squares due to the addition of a further variable. They have been used to derive the Index Temperatures that are discussed below.

##### 5. Qualitative effects.

The inclusion of 'status' variables, effectively adjusting the additive constant in the equation, can evidently lead to greater reductions in the residual variation than is achieved by including some additional thermal data. This effect was indicated by the preliminary sorting results given in Section 4. Anaesthetists tend to feel colder than other staff categories, surgeons and their assistants tend to sweat more, while females tend to sweat less. These effects are in accord with experience, though they might have been thought to be less important than radiation or air velocity in determining an individual's response. Other effects in accord with expectation are

that females feel cooler; people of non-European (mostly coloured) race sweat less, though they do not feel cooler; thin people have colder feet and sweat less than fat people; a longer stay in a theatre leads to more sweating but not to an increase in the sensation of heat. Less expected, perhaps, is the finding that the older members of operating teams feel the heat less, and actually sweat less; sensations of heat are greater in spring and summer than in autumn and winter; feet feel colder and sweating is greatest in autumn. It should be emphasised that the above results take account of the correlation between variables; they could perhaps be stated with the rider 'other things being equal'. For example, the findings on age are not affected by the fact that assistants and nurses tend to be younger than surgeons and anaesthetists, for this effect has been 'partialled out'. Similarly, 'people feel hotter in summer' is a trivial statement unless it is realised that the actual temperature effect has been removed - people feel hotter in summer at the same temperature.

#### 6. Quantitative effects.

Some idea of the magnitude of these effects can be gained by calculating, from the relative size of the regression coefficients, what change in the variable would be necessary to produce the same change of response as a specified change of temperature. Alternatively, where appropriate, the change in temperature necessary to produce the same effect as a specified change in the variable can be calculated. The results of such calculations are shown in Table 5-1-6. It is worth noting the way in which the effects of the measured variables on

subjective thermal responses are mirrored by their effects on the observed forehead sweating, P. This close correspondence between subjective and objective measures of thermal strain supports the validity of both. The detailed effects are discussed below.

The effect of water vapour pressure is such that a change corresponding to a decrease of 10% in the relative humidity is equivalent to a drop of 1°F. at 68°F. This is much greater than the negligible effect of humidity at this temperature that was found by Koch et al (1960) for normal conditions of occupancy, and nearly twice as great as the effect reported by Miura (1931) for experiments on five subjects. An increase of 1°F. can be counteracted by an increase of air velocity from 25 to 30 feet per minute. The effect of radiant heat, between  $\frac{1}{3}$  and  $\frac{1}{2}$  that of ambient temperature, is in agreement with the figure of  $\frac{1}{3}$  generally accepted (Koch et al 1960). The anomalous value for sensation at head height, where radiation apparently has only half that effect, may be due to expectation; in the special case of working at the operating table, radiation is expected and perhaps allowed for in reporting thermal sensation. The measurement was made at the point of maximum intensity of the beam, whereas most of the members of a team keep their heads clear of this point for most of the time. This would also tend to reduce the apparent effect of thermal radiation. When clear of the direct beam, the radiation received from the hot lamp casing appears to be only about half the maximum intensity, according to a number of spot readings taken in empty theatres with the same instrument. The same

result was obtained in a domed theatre with spotlights studding the roof instead of a conventional operating lamp, and is likely to be generally true.

There is thus apparently little scope for mitigating the effects of a high temperature by altering the other thermal parameters. A reduction of the humidity from 50% to 30%, accompanied by a doubling of the air velocity from 25 to 50 feet per minute, would be equivalent only to a drop of 3°F. in the temperature, in terms of its effect on thermal sensation or forehead sweating. Such changes might well be unacceptable on bacteriological or other grounds.

Individual differences increase the difficulty of satisfying all the occupants of a theatre. The effects tabulated in Table 5-1-6.B. are additive, and can lead to surprisingly large differences of predicted response. For example, a fat surgeon would feel uncomfortably hot at a temperature 8°F. below that at which his thin female anaesthetist would experience a similar sensation. In terms of sweating, the difference between these individuals rises to 27°F., and to over 30°F. if the anaesthetist is coloured and the surgeon is not. Though this is admittedly an extreme example, the difference of 12.3°F. between surgeon and anaesthetist, in terms of the temperature at which they begin to sweat, is a constant factor with serious implications. The fact that older members of the team sweat less than younger members is an indication that the cause of forehead sweating is probably psychological tension. It is unlikely to be a physiological effect, as it is accompanied by a reduction of the

sensation of heat; if older men were markedly less able to sweat, they would tend to feel hotter, not cooler.

The effect of season of the year is interesting. Though small, it is significant, and disproves the assertion often made that high temperatures are better tolerated in summer. A possible reason is that a hot working environment may be welcome in winter when most rooms are too cold. Conversely in summer, when one tends to be too hot elsewhere, the feeling is that it should at least be cool where one is expected to perform surgery. The effect of physiological acclimatisation would have been to counteract this tendency; some evidence for acclimatisation is perhaps provided by the increased sweating observed in autumn, and the feeling in that season that feet were cold, given that acclimatisation to heat would be at its greatest at the end of summer.

#### 7. 'Optimum' temperatures.

From the regression equations it is possible to work out the temperature at which thermal sensation would be equal to 3, ideally comfortable, for the mean observed values of the other variables. For this purpose,  $P$  is of no use, as there is no preferred level of sweating. As shown in Section 2, the optimum as determined by the mean thermal vote is usually the point at which the maximum number are comfortable. However, this is not necessarily a useful concept in operating theatres. In an office or a factory, 'the greatest comfort of the greatest number' is a useful criterion, but in the operating theatre the comfort of the surgeon is arguably of

paramount importance. It may be more useful to consider only the proportion of surgeons that are too hot, and this is done in the following sub-sections. For completeness, the 'optima' are tabulated in Table 5-1-7 for the different status categories. The most reliable is probably the figure of 66.1°F. for  $T_0$ , the overall thermal vote, for surgeons. It is rather close to the optimum derived by simple card sorting in Section 4. (cf. Graph 4-1) for all staff. In passing it is worth noting the trend to prefer higher temperatures from surgeon to assistant to anaesthetist, the close similarity between the figures for assistants and for nurses, and the tendency for preferred temperatures to increase from head to body to feet in opposition to any realistic thermal gradient. It would seem that in any theatre that is cold enough at head height, there is a risk of cold feet. However, these figures give no indication of the distribution of comfort votes about the optimum, or even of the proportion comfortable at the optimum. Distributions will be considered below, when the remaining significant variables have been discussed.

#### 8. 'Thermal' effects of other variables.

Table 5-1-8 tabulates the change of temperature necessary to produce the same effect as certain environmental changes. These effects are derived and discussed in Section 6, but the results are relevant to the main responses under discussion in this section. The theatre was felt to be hotter when the atmosphere was tense, and more sweating was in fact observed. These effects are of considerable magnitude. There was more sweating during major operations and when there were frequent entries and exits to the theatre. There was less sweating

when the staff moved freely in the theatre, and when the maximum noise level, almost always due to talking, was higher; these circumstances occur when the atmosphere is more relaxed. The variability of air velocity had a marginal effect in the expected direction of decreasing the sensation of heat. There were fewer complaints of heat when there had been 'mistakes' in procedure. No explanation is offered for this other than that it may have been due to over-compensation or it may have been due to distraction. It was not a large effect, and was not reflected in the observed sweating.

#### 9. Response distributions.

Using the concept of Index Temperature introduced in Section 4, the four thermal variables can be combined into a single figure, that of the equivalent ambient temperature under standard conditions of humidity, radiation and air velocity. 'Equivalent' is used here in the sense of 'producing the same response'. The standard conditions chosen are 50% relative humidity, mean radiant temperature equal to air temperature and air velocity 25 feet per minute. Using the economical equations of Table 5-1-9 to generate the predicted vote at head, body and feet ( $T_1$ ,  $T_2$  and  $T_3$ ), the distributions set out in Graph 5-1-1 are obtained. They have been transformed from probit regression analysis of the proportion too hot and too cold, in order to obtain smooth curves. One reason why the curve for comfort at the feet is so broad is that no status factor was included. The curves show in a general way the relationship between comfort at the head, body and feet, and the consequences of non-ideal conditions.



A more informative set of curves is obtained by examining the distribution of the  $T_0$  response for each status category separately. Graph 5-1-2 sets out the result of such an examination with respect to ambient temperature, treating surgical assistants and nurses as one category for the present purpose. The curves were obtained by sorting the  $T_0$  response against ambient temperature and identifying the proportions too hot and too cold by means of the arbitrarily defined comfort range of  $T_0$ ; this was introduced in Section 4, and assumes that over 50% of subjects returning a value of  $T_0$  within the range 2.3 - 3.6 inclusive are not uncomfortable in any way. These proportions were transformed to probits, the probit regression lines obtained graphically, and at each temperature the smoothed proportion comfortable was obtained by subtraction. The resulting curves are illustrative of the differences between status categories, and display also the effect deduced from published results in Section 2, namely that of a progressively smaller median range with each increase in the preferred temperature of a group. However, in view of the highly significant correlations between thermal factors and the somewhat arbitrary nature of the comfort criterion, a further refinement of method is required.

#### 10. Suggested method of presentation.

This final stage in the analysis is proposed as a method of general use in studies of thermal comfort.

Using the equation for prediction of  $T_0$  as it appears in Table 5-1-9, the Index Temperature for each set of data was derived. Treating the three status categories separately, the proportion comfortable, too cold and too hot were identified by examining the recorded values of

$T_1$ ,  $T_2$  and  $T_3$ . If one or more of these values was 0 or 1, indicating a response of 'uncomfortably cold' in one or more areas of the body, the overall response was taken to be one of 'too cold'. Similarly, those 'too hot' were identified. In practice this was done by generating a Comfort Index taking the values 0, 1 or 2 after logically testing the three recorded values. It will be recalled that anomalous vote combinations had already been excluded, i.e. those simultaneously too hot and too cold. It is clear that this procedure is more rigorous than most; those recorded as comfortable had stated that they were comfortable in each of three areas of the body, in response to three direct questions requiring in the first place a 'yes' or 'no' answer. The proportions too hot and too cold were transformed to probit values, and the linear probit regression lines against Index Temperature are plotted in Graphs 5-1-3, 5-1-4 and 5-1-5 for surgeons, assistants and nurses, and anaesthetists respectively. On the same graphs are plotted the percentage comfortable at each Index Temperature, obtained by transformation of the regression lines to percentages and subtracting. It should be noted that the ordinate for these lines is linear in percentage, whereas the ordinate for the probit regression lines is linear in probit values; the abscissa is Index Temperature in  $^{\circ}\text{F}$ . throughout.

These graphs contain all the relevant information. At each Index Temperature it is possible to obtain an accurate prediction of the proportions too cold, comfortable and too hot, in marked contrast to the usual presentation of mean thermal vote or proportion comfortable.

An example of the utility of this presentation is the possibility of setting an upper limit to the temperature of operating theatres in terms of the proportion uncomfortably hot. If no more than 5% of surgeons are to be uncomfortably hot, the Index Temperature should not exceed 65.3°F., as shown on Graph 5-1-3. With the mean amount of radiation recorded at body height, 2.1°F. above air temperature according to Table 5-1-1, and the relation between air temperature and radiant excess temperature as set out for  $T_0$  in Table 5-1-9, this corresponds to an ambient temperature almost exactly 1°F. lower, i.e. 64.3°F. It is suggested that this is a useful criterion for operating theatre temperatures. From the graphs it can be seen that over 60% of anaesthetists would be uncomfortable at this Index Temperature, but this should be seen in relation to the fact that 33% of anaesthetists were uncomfortable even at the optimum for the group, 72°F. Indeed, since only 1.3% of anaesthetists would be too hot at 65.3°F., increasing the clothing worn by the remainder would raise the proportion comfortable at 65.3°F. to well above the present maximum of 67% at 72°F. At 65.3°F., 28% of assistants and nurses would be uncomfortable; at the optimum for their group, 67.5°F., 26.5% were uncomfortable. Thus an Index Temperature of 65.3°F. would enable a very high proportion of the occupants of a theatre to be comfortable, while ensuring that no more than 5% of surgeons were uncomfortably hot. It appears in fact to be the optimum temperature for surgeons, but so few surgeons were uncomfortably cold that the descending portion of the curve represents an extrapolation.

If some other criterion is adopted, the consequences can quickly be derived from the information presented in these graphs.

#### 11. Relation to the results of Section 2.

It is of interest to relate these experimentally obtained distributions to the theoretical predictions made in Section 2 as a result of the analysis of published data. Taking the optima of the three graphs as the Index Temperature at which the proportion comfortable is at a maximum, one obtains the figures c.  $65.0^{\circ}$ ,  $67^{\circ}$  and  $72^{\circ}\text{F.}$  for surgeons, assistants and nurses, and anesthetists respectively. The predicted median ranges are, from Graph 2-5,  $17.1^{\circ}$ ,  $15.5^{\circ}$  and  $11.3^{\circ}\text{F.}$  The median ranges obtained experimentally were c.  $19^{\circ}$ ,  $15.9^{\circ}$  and  $10.4^{\circ}\text{F.}$  With the exception of the figure for surgeons, these figures are in close agreement with the predicted values. For surgeons, absence of adequate data for the portion of the graph below the 'optimum' renders any measurement of median range highly speculative, and the agreement obtained is therefore adequate.

However, although the median ranges for each group agree quite well with the findings of Section 2, the shapes of the distributions are not well predicted by the equations of Table 2.10. For example, the regression coefficient between the probit of the proportion too hot and the temperature is 0.16 for surgeons, 0.15 for assistants and nurses, and 0.19 for anaesthetists. The figure used in Table 2.10 is 0.27, the mean of widely but not significantly different values. This would lead to predicted distributions much narrower than those actually found, with fewer people uncomfortable at the optimum. It may be that the shape of the distribution varies with some factor

such as task involvement, but no conclusions can be drawn from these results or from the data considered in Section 2.

It is worth noting that the predicted figures were based on the analysis of results for ambient temperature, not Effective Temperature. Since Index Temperature is defined in terms of conditions close to the mean, this choice is more appropriate. Had the definition of Index Temperature been in terms of fully saturated, still air, the alternative choice would have been appropriate.

## 12. Distribution of observed sweating.

Using the equation for P in Table 5-1-9, an Index Temperature can be derived for each observation of this response. The observed values of P are related to Index Temperature in the form of cumulative frequency distributions in Graph 5-1-6. On the same graph, the regression of mean P on Index Temperature is shown. The ordinate for this line is not related to that of the frequency distributions. 'Mean P' is proposed as a valuable measure of thermal response. In the range 60-90°F. it can be seen to vary in an orderly way.

The frequency distributions were obtained by transformation of probit regression lines, drawn for the 'proportion sweating to each criterion level' as for Graph 5-1-0. At the suggested maximum Index Temperature, 65.3°F., no forehead would be observed as 'wet-beads of sweat' (criterion 2), but 25% of foreheads would be observed as 'damp'. In general it can be seen that sweating is not a serious problem below 80°F., at which Index Temperature 10% were sweating to criterion 2, and 3% to criterion 3 ('forehead wet, requires frequent wiping') i.e. profuse sweating.

13. Summary of sub-section 5. 1.

Analysis of the main responses yielded the following results:

1. The variation of dry-bulb temperature was shown to account for at most 25% of the variation of response.
2. Regression equations in all four thermal parameters were shown to account for at most 30% of the variation of response.
3. Regression equations including all measured variables were shown to account for at most 33% of the variation of response, but to be particularly successful in improving the prediction of observed sweating.
4. A large number of non-thermal factors were shown to affect significantly the perception of temperature and the observed sweating. Quantitative evaluation of their effect was possible; combinations of non-thermal factors were shown to be capable of producing unexpectedly large effects.
5. Response distributions were presented in a new way; it was suggested that they convey more information than the current methods of presentation.
6. An objective method of determining the maximum temperature for operating theatres was proposed; if no more than 5% of surgeons were to be uncomfortably hot, the ambient temperature should not exceed 65.3°F. with a relative humidity of 50%, a mean radiant temperature equal to air temperature, and an air velocity of 25 feet per minute. This corresponded to an air temperature of 64.3°F. with the mean observed radiation excess of 2.1°F. Under these conditions nearly twice as many anaesthetists would

be uncomfortable as at the optimum for the group, but by wearing more clothing the proportion could be reduced to below the present optimum figure.

7. Observed forehead sweating was shown to be a useful index of thermal strain. It was shown that sweating was not a widespread problem below 80°F.

## 5. 2. Subsidiary response: the impression of 'stuffiness'

### 1. Introduction.

A common complaint in operating theatres where conditions are unsatisfactory is that the room is 'stuffy'. This common pejorative is frequently applied to over-occupied rooms, and its origin may possibly be traced to the idea of 'anthropotoxin' proposed by Pettenkofer over a hundred years ago, of which mention was made in Section 1. No satisfactory investigation of the causes of 'stuffiness' has been made; it would be an interesting and potentially valuable study. Vernon and Manley (1926) investigated the causes of sensations of 'freshness', and this may be seen as the opposite end of the scale. However, since sensations of freshness or otherwise are commonly referred to the head, and more particularly to the nose and cheeks, the theatre situation in which all those present are masked, is likely to be rather a special case.

### 2. Methods.

The present investigation included a sequence of questions resulting in a five-point stuffy/fresh scale, the wording of which has been given in Table 5.1. These questions were put to each subject

before the more specific questions on temperature, air velocity and humidity, so that the answers would reflect what was meant by the term 'stuffiness' as generally used. Had subjects been first asked to state specifically whether the temperature, air velocity and humidity were comfortable, they might have adopted a more rational and perhaps misleading approach to reporting their sensation of 'stuffiness'.

### 3. Results.

The method of analysis was exactly that used for the main responses, namely the derivation of a multiple regression equation by a sequential procedure. The use of the mean vote as a metric variable was justified in the same way as the mean thermal vote. Graph 5-2-1 shows the result of preliminary sorting on the data for surgeons and assistants. There is a good linear relationship between  $\bar{s}$ , the mean 'stuffiness' vote, and the dry-bulb temperature. The optimum temperature, at which  $\bar{s} = 3$ , is seen to be 65.2°F. At this temperature about 7% considered the conditions 'too stuffy' and 7% considered the conditions 'too fresh'.

Table 5-2-1 shows the regression equations derived. All the coefficients shown exceed twice their standard deviation. The variables entered the equation in the order in which they made the greatest reduction in the residual sum of squares, which is the order in which they appear. The table also shows the proportion of variance attributable to the regression at each step. Thus when only thermal variables were permitted to enter, the inclusion of vapour pressure and the radiation excess added only 2.5% to the 15.4% of the variance attribu-



table to the temperature alone. The effect of air velocity could not be shown to be significant. The sensation of 'stuffiness' appears to be predominantly one of feeling too hot, at least in the context of the operating theatre.

When all variables were permitted to enter, the proportion of variance attributable to the regression rose to 19.5%. In this case, when allowance had been made for the subjects who were anaesthetists, the effect of thermal radiation could not be shown to be significant. The effect of air velocity was again not significant. From this equation the 'optimum' temperature can be calculated by setting the other variables equal to their mean value in the data and the S-vote equal to 3; the result, 66.6°F., is identical with the optimum derived in Graph 4-1 for thermal sensation at head height. It may also be compared with the optima derived from the regression equations for thermal sensation and tabulated in Table 5-1-7.

The effects of the individual variables can be illustrated by calculating the equivalent temperature change from the relative size of the regression coefficients; in terms of the sensation of stuffiness, an increase of 7% in the relative humidity at the mean of 72.7°F., 50% relative humidity, would be compensated for by a fall of 1°F. This is very close to the figure of 8½% given by Bedford and Warner (1939) for the effect of humidity on sensations of freshness. However, whereas their figure implied that in their data the effect of humidity was three times as great on freshness as on thermal sensation, comparison with Table 5-1-6 shows that in the present study humidity was

almost as influential on thermal sensation as on freshness. The reason is almost certainly that there is a good deal more sweating in the theatre situation, and evaporation of sweat plays a correspondingly more important role in determining thermal sensation. Anaesthetists found conditions stuffy at a temperature nearly  $3F^{\circ}$  above the temperature at which the other occupants of the theatre experienced a similar sensation. In the previous sub-section, similar effects for thermal sensation and for observed sweating were demonstrated for anaesthetists, the bias amounting to between 1 and  $3.F^{\circ}$  for thermal sensation, and to  $5.F^{\circ}$  for sweating. The present results show that for anaesthetists, the sensation of 'stiffness' exhibited an identical bias. Women found conditions 'stuffy' at a temperature about  $2.F^{\circ}$  below the temperature at which the male occupants of the theatre experienced a similar sensation. Table 5-1-6 shows that in contrast to these results, women were more tolerant of heat when asked specifically about thermal sensation, and much more tolerant of heat in terms of observed sweating. The delayed onset of sweating is associated with an increased sensation of stiffness and the link may be causal.

The effect of 'duration of stay in theatre' was such that an additional stay of 145 minutes was equivalent to a rise of  $1.F^{\circ}$ . This effect is only about one third as great as that of 'stay' on thermal sensation. A marginal effect of clothing on sensations of stiffness was found and is given in detail in Section 6. 5.

In evaluating the success of the regression equations in

predicting the S-vote, it is of interest to compare the multiple correlation coefficients obtained, 0.425 for thermal variables only and 0.442 for all significant variables, with the simple correlation coefficients between S-vote and a number of other parameters of thermal stress. These are tabulated in Table 5-2-2. The correlation coefficient with Effective Temperature is the largest, 0.405, but falls short of the multiple correlation coefficient for temperature and vapour pressure alone,  $(0.174)^{\frac{1}{2}} = 0.417$ . This in turn is smaller than the figures for Equations 1 and 2 in Table 5-2-1.

The correlation coefficient between S-vote and T<sub>1</sub>-vote, thermal sensation at head height, was only 0.592; that is, a knowledge of thermal sensation would enable one to account for only  $(0.592)^2 = 35\%$  of the variation in predicting the sensation of stuffiness. Thus although 'stuffiness' is closely related to thermal sensation, there remains a considerable amount of unexplained variation.

#### 4. Discussion.

The sensation of 'stuffiness' in the operating theatre was clearly governed by many of the same factors that determined thermal sensation. Individual differences had a large effect, and a person who felt that a theatre was too hot might not feel it was stuffy. However, as the optima co-incide, it is probably safe to assume that if the theatre is not felt to be too hot it will not be felt to be stuffy.

#### 5. Summary.

The sensation of stuffiness was examined and a number of influential factors were identified. The results should not be taken to apply outside the operating theatre.

### 5. 3. Subsidiary response: the perception of air velocity.

#### 1. Introduction.

The air velocity in operating theatres is often extremely low. This has been a consequence of attempts to produce a downward displacement system (Williams, et al. 1962). There is some evidence (Angus and Brown 1957) to suggest that in ordinary rooms an increase of air velocity from 10 to 30 feet per minute is sufficient to cause a marked improvement in comfort. On the other hand, Baetjer (1924) found that air velocities below 40 feet per minute were not perceptible to the skin of the cheek over the whole range of temperatures encountered in occupied rooms. The present investigation provides some information on the existing air velocities in occupied operating theatres and on their effects.

#### 2. Method.

Readings of mean air velocity were obtained as described in Section 3. Subjects were questioned on their perception of the air velocity, using the sequence of questions set out in Table 3.1; this resulted in a five-point scale of response, termed the 'W-vote', with the value 5 for 'air velocity much too high', 4 for 'slightly too high', 3 for 'neither too high nor too low', and so on. These questions were asked immediately after those referring to thermal comfort at each of three levels.

#### 3. Results.

Reference to Table 5.1.1. shows that the mean square root of the air velocity at head height was 4.57, corresponding to an air velocity of 21 feet per minute; the 95% range was approximately 5-50 feet

per minute if the square root is an effectively normalising transformation. The results of the analysis in Section 5-1 show that air velocity had an almost negligible influence on thermal sensation, not reaching significance at head height. Preliminary sorting indicated that the W-vote was also almost completely unaffected by air velocity, and the result is therefore not given here. Instead, Graph 5-3-1 shows that, for surgical assistants, the air temperature did have an appreciable effect on the W-vote. The probit of the proportion voting 1 or 2 ('too little air movement') is plotted against air temperature, and similarly those voting 4 or 5 ('too much air movement'). A fairly accurate estimate can then be made of the temperature at which 50% considered the air velocity too low. The figure of 75.8°F. corresponds very closely to the figure of 76°F. given by Baetjer as the temperature at which the lower threshold of perception of air velocity was equal to 21 feet per minute. The 'lower threshold' refers to perception of air velocity by the eyes and immediately surrounding areas of skin, which is the area exposed by a mask in the operating theatre. It is reasonable to infer from this that air velocity was considered 'too low' when it could no longer be detected by the most sensitive area. However, an alternative interpretation is that complaints of 'too little air movement' were made when the subject was too hot, without regard to the actual air velocity in the very restricted range encountered.

Multiple regression analysis was performed with the W-vote as dependent variable. Table 5-3-1 shows the equation derived by this

means. All the coefficients tabulated exceed twice their standard deviation; no other variables could be shown to have a significant effect. The variables entered in the order shown, and the proportion of variance attributable to the regression at each step in the sequential procedure is shown in the table. Air velocity accounted for only 0.3% of the 16.8% attributable to the complete regression, bearing out the sorting result mentioned above.

From the relative values of the regression coefficients it can be calculated that an air velocity of 10 feet per minute at the mean temperature of 72.6°F. would evoke the same W-vote as an air velocity of 50 feet per minute at 75°F. This means that the largest difference of air velocity likely to be found in practice is equivalent only to a difference of 2.4°F. Similarly, it can be shown that in terms of the W-vote, and under the mean conditions encountered, an increase of 10% in the relative humidity was equivalent to a rise of 1.5°F. in the air temperature; anaesthetists complained of draughts at a temperature 3.8°F. higher than did other staff categories; in autumn complaints were made at temperatures 1.7°F. higher than at other times of the year.

The mean value of the W-vote was  $2.64 \pm 0.75$ ; this means that air velocities were more often considered too low than too high. Partly for this reason, and partly because the coefficient of air velocity can only be inaccurately estimated, no meaningful 'optimum' air velocity can be derived from this equation. However, by setting the W-vote equal to 3 and the other variables to their mean values, the optimum temperature

can be calculated as 65.8.°F. This is extremely close to the optimum as calculated from the thermal response equations in Section 5-1, and lends support to the view that the W-vote reflected thermal comfort and not perception of air velocity per se.

#### 4. Discussion.

The air velocities occurring in operating theatres are generally considered too low. However, subjects were unable to give meaningful estimates of their sensation of air velocity; complaints of low air velocity probably reflected a generalised feeling of heat, and the feeling that an increased air velocity would bring relief. Section 5-1 has shown that increased air velocities, within the presently occurring range, had in practice only a marginal effect on thermal sensation.

#### 5. Summary.

Sensations of air movement were examined and were shown to be related to thermal sensation rather than to the actual value of the air velocity.

### 5. 4. Subsidiary response: the perception of humidity.

#### 1. Introduction.

Although the influence of humidity on thermal sensation has been intensively studied, very little work on the perception of humidity per se appears to have been carried out. In Britain uncomfortably high or low humidities rarely occur naturally, and equipment for the control of humidity is only installed for special purposes. Operating theatres provide an important example of artificially high humidity maintained for purposes other than the comfort of the occupants.

(e.g. safety from electrostatic sparking). Previous sections have shown that the values of humidity presently occurring do not contribute substantially to thermal discomfort or to 'stuffiness', but high humidity is often blamed for feelings of discomfort in operating theatres. The present study investigated the causes of complaints of uncomfortably high humidity in operating theatres.

## 2. Method.

Subjects were asked quite simply if they considered the humidity too high for comfort, and their answer was recorded as 'yes' or 'no'. This question was put at every interview, after the questions on other factors of the thermal environment. Humidity was measured as described in Section 3.

## 3. Results.

The current recommendation (Report of a working party on anaesthetic explosions 1956) is that the relative humidity in operating theatres should not fall below 60%. The mean relative humidity measured in the present survey was 50%; the majority of operating theatres apparently fail to achieve the recommended level. Defective adjustment or operation of the humidification plant appears to be responsible for this; few theatres studied were without such plant.

The response was coded as 0 or 1, and used in this form as the dependent variable for subsequent regression analyses. These have little predictive value for individuals, but the mean for a group can be seen as the proportion considering the humidity too high. The overall mean was 0.546, indicating that over a third of the 2,566 responses were complaints of high humidity. The correlation



coefficient of this response, referred to as the H-vote, with relative humidity was 0.045, which is not significant at the 0.05 level. With vapour pressure it was 0.242, with air temperature at head height 0.326, with the P estimate 0.257, and with thermal sensation at head height ( $T_1$ ) 0.462; all these values are highly significant. Thus complaints of high humidity were associated most closely with complaints of high temperature, and only to a lesser extent with the actual observed sweating, i.e. subjects tended to complain when they thought the high humidity must be preventing the evaporation of sweat rather than when it was in fact doing so. Complaints of high humidity should therefore be interpreted as complaints of high temperature in the absence of evidence to the contrary. In support of this conclusion is the fact that complaints, of high humidity were more closely associated with the measured air temperature than with the measured vapour pressure. The multiple regression analysis set out below shows that this predominance of temperature over vapour pressure persisted when their mutual correlation had been allowed for.

The difference between relative humidity and vapour pressure was investigated by means of preliminary sorting, which showed that a given increase of relative humidity produced a progressively greater increase in the proportion complaining of high humidity as the temperature increased above 70°F. Evidently, although the majority of subjects considered that they could and did estimate relative humidity, they were not in fact doing so. For this reason, humidity was expressed as water vapour pressure and the sorting results

are shown in this form in Graph 5-4-1 for the 2,027 responses obtained from surgeons, their assistants and anaesthetists. It can be seen that complaints of high humidity increased linearly with water vapour pressure, and that a given increase of air temperature increased the proportion complaining by the same amount over the whole range of humidity. Evidently a linear regression equation in temperature and vapour pressure is appropriate, in the same way as the use of this form of analysis for thermal sensation was justified in Section 4. It is worth noting that there appears to be a marked difference between the perception of humidity above 70°F. and that below. Nearly six hundred responses were obtained below 70°, so the effect is not likely to be due to chance. It can be seen that fewer than 18% complained of high humidity below 70°, even when the water vapour pressure corresponded to 70% relative humidity. Between 70° and 75°F. this proportion was already exceeded at 7 mm.Hg., corresponding to a relative humidity below 40%. Above 75°F. the proportion did not fall below a third at any humidity.

Table 5-4-1 shows the regression equation derived by the usual sequential procedure. The variables entered in the order shown, and the proportion of variance attributable to the regression is tabulated at each step. All the coefficients listed exceed twice their standard deviation, and no other variable could be shown to have a significant effect. The multiple correlation coefficient, (.398) is lower than that derived in Section 5.2 for 'stiffness', but only marginally so. It also falls short of the correlation between H-vote and T<sub>1</sub>-vote.

The regression coefficients can be interpreted as the resulting

increments in the proportion of complaints. For instance, an increase of  $1^{\circ}\text{F.}$  would add 0.03 to the H-vote, i.e. would increase the percentage complaining by 3% for a given group. Thus a given set of conditions in which 30% of a group of anaesthetists complained of high humidity would cause 48% of a group of surgeons to make similar complaints. However, this is perhaps misleading. An alternative interpretation is in terms of the equivalent temperature change to produce a given change of H-vote; this method has been used illustratively in previous sections. Thus an increase of 10% in the relative humidity above the mean conditions produced the same change of response as an increase of  $2.1^{\circ}\text{F.}$  in the air temperature; surgeons complained of humidity at temperatures  $5.8^{\circ}\text{F.}$  below other staff categories; in spring complaints of high humidity were made at temperatures  $3.1^{\circ}\text{F.}$  lower than at other seasons of the year; subjects 20 years older than the average complained of high humidity only at temperatures  $3.2^{\circ}\text{F.}$  higher than subjects of average age.

In Section 5.1. it was shown that below  $64.3^{\circ}\text{F.}$ , fewer than 5% of surgeons experienced any thermal discomfort. From the equation in Table 5-4-1 it can be calculated that at this temperature, in seasons other than spring, fewer than 5% of surgeons complained of high humidity when the vapour pressure was below 6.4 mm.Hg., corresponding to 40% relative humidity. Thus this recommended maximum temperature for thermal comfort is unlikely to lead to many complaints of high humidity.

#### 4. Discussion.

The results of this sub-section show that complaints of high

humidity are common in operating theatres, that they are mediated by high vapour pressures rather than by high relative humidities, and by high air temperatures to a greater extent than by vapour pressure. However, no more than 16% of the variance of this response could be attributed to the recorded variables. Complaints of high humidity are likely to be infrequent below the maximum temperature of 64.5°F. recommended elsewhere on thermal comfort grounds.

#### 5. Summary.

Factors causing complaints of high humidity were identified and the magnitude of their effects was derived.

Table 5. 1. 1. Mean and standard deviation of the major variables

| <u>Variable</u>                                                                       | <u>Mean</u>                 | <u>Standard<br/>deviation</u> |
|---------------------------------------------------------------------------------------|-----------------------------|-------------------------------|
| 1. Ambient temperature (°F.)                                                          |                             |                               |
| head                                                                                  | 72.6                        | 4.0                           |
| trunk                                                                                 | 72.3                        | 4.0                           |
| feet                                                                                  | 71.8                        | 3.9                           |
| 2. Water vapour pressure (mm.Hg.)                                                     | 10.2                        | 2.4                           |
| 3. Radiation (°F. excess over<br>ambient)                                             |                             |                               |
| head                                                                                  | 4.3                         | 2.8                           |
| trunk                                                                                 | 2.1                         | 1.5                           |
| feet                                                                                  | 1.6                         | 1.6                           |
| 4. Air movement (f.p.m.) <sup>1</sup> / <sub>2</sub>                                  |                             |                               |
| head                                                                                  | 4.59 ( $\bar{x}$ 21 f.p.m.) | 1.16                          |
| trunk                                                                                 | 4.77 ( $\bar{x}$ 23     " ) | 1.21                          |
| feet                                                                                  | 5.51 ( $\bar{x}$ 30     " ) | 1.50                          |
| 5. Age (years)                                                                        | 38.6                        | 9.3                           |
| 6. Sex (proportion female)                                                            | 0.364                       | -                             |
| 7. Race(     "     European)                                                          | 0.836                       | -                             |
| 8. Build                                                                              | 2.820                       | 0.78                          |
| 9. Surgeon                   (propotion)                                              | 0.228                       | -                             |
| 10. Surgical assistant     "                                                          | 0.250                       | -                             |
| 11. Scrubbed nurse         "                                                          | 0.281                       | -                             |
| 12. Anaesthetist           "                                                          | 0.241                       | -                             |
| 13. Spring (fraction responses March-<br>May)                                         | 0.260                       | -                             |
| 14. Summer (     "     "     June-<br>August)                                         | 0.187                       | -                             |
| 15. Autumn (     "     "     Sept.-<br>Nov.)                                          | 0.292                       | -                             |
| 16. Winter (     "     "     Dec.-<br>Feb.)                                           | 0.261                       | -                             |
| 17. Stay in room (hours up to time of<br>questioning)                                 | 2.00                        | 1.11                          |
| 18. Stress                                                                            | 1.46                        | 0.73                          |
| 19. Proportion wearing glasses during<br>operation                                    | 0.287                       | -                             |
| 20. Comfort for head (T <sub>1</sub> )                                                | 3.69                        | 1.14                          |
| for trunk (T <sub>2</sub> )                                                           | 3.51                        | 1.17                          |
| for feet (T <sub>3</sub> )                                                            | 3.31                        | 0.97                          |
| 21. overall (T <sub>0</sub> = 1/3<br>(T <sub>1</sub> T <sub>2</sub> T <sub>3</sub> )) | 3.50                        | 0.94                          |
| 22. Degree of visible perspiration on<br>forehead (P)                                 | 0.58                        | 0.62                          |

Variables 6, 7, 9-16 and 19 are non-metric so that a standard deviation is not an appropriate measure of dispersion.

Table 5. 1. 2. Correlation Matrix

|                  | <u>t</u> | <u>VP</u> | <u>R</u> | <u>v<sup>1/2</sup></u> | <u>T<sub>1</sub></u> | <u>P</u> | <u>T<sub>2</sub></u> | <u>T<sub>0</sub></u> | <u>T<sub>3</sub></u> |
|------------------|----------|-----------|----------|------------------------|----------------------|----------|----------------------|----------------------|----------------------|
| t                | 1        | 0.275     | -0.159   | -0.239                 | 0.466                | 0.262    | 0.452                | 0.500                | 0.366                |
| VP               |          | 1         | NS       | -0.204                 | 0.267                | 0.202    | 0.275                | 0.290                | 0.198                |
| R                |          |           | 1        | NS                     | 0.061                | 0.118    | -0.061               | -0.076               | NS                   |
| v <sup>1/2</sup> |          |           |          | 1                      | -0.145               | -0.097   | -0.161               | -0.171               | -0.068               |
| T <sub>1</sub>   |          |           |          |                        | 1                    | 0.366    | 0.768                | 0.887                | 0.476                |
| P                |          |           |          |                        |                      | 1        | 0.375                | 0.379                | 0.218                |
| T <sub>2</sub>   |          |           |          |                        |                      |          | 1                    | 0.911                | 0.536                |
| T <sub>0</sub>   |          |           |          |                        |                      |          |                      | 1                    | 0.761                |
| T <sub>3</sub>   |          |           |          |                        |                      |          |                      |                      | 1                    |

Correlation coefficients are based on 2,566 pairs.

(. \*. Those greater than 0.051 are significant at the 0.01 level.)

Legend: t = dry-bulb temperature, VP = vapour pressure of water,

R = radiant excess temperature, v<sup>1/2</sup> = square root of air velocity

T<sub>1</sub> = Thermal vote at head height

P = observed forehead sweating

T<sub>2</sub> = thermal vote at body height.

T<sub>3</sub> = thermal vote at feet.

T<sub>0</sub> = 1/3 (T<sub>1</sub> + T<sub>2</sub> + T<sub>3</sub>)

T<sub>1</sub>, P are related to values of physical variables measured at head height.

T<sub>2</sub>, T<sub>0</sub> " " " " " " " " body "

T<sub>3</sub> is " " " " " " " " feet "

Correlations among physical variables relate to measurements at head height.

Table 5. 1. 3. Coefficients of the regression equations for prediction of subject's response

| x. | <u>Variable</u>                                             | <u>Response</u> |                |                |                |         |
|----|-------------------------------------------------------------|-----------------|----------------|----------------|----------------|---------|
|    |                                                             | T <sub>1</sub>  | T <sub>2</sub> | T <sub>3</sub> | T <sub>0</sub> | P       |
| 1. | Ambient temperature (°F.)                                   | 0.126           | 0.134          | 0.091          | 0.118          | 0.038   |
| 2. | Water vapour pressure<br>(mm.Hg.)                           | 0.066           | 0.076          | 0.048          | 0.062          | 0.033   |
| 3. | Radiation (°F.)                                             | 0.037           | 0.095          | 0.050          | 0.079          | 0.025   |
| 4. | Air movement ( $\sqrt{\text{vol. in f.p.m.}}$ )             | -               | -              | 0.073          | -              | 0.030   |
|    | Constant                                                    | - 6.340         | - 6.848        | - 3.669        | - 5.636        | - 2.694 |
|    | Multiple correlation<br>coefficient                         | 0.504           | 0.503          | 0.394          | 0.548          | 0.331   |
|    | Correlation coefficient with<br>ambient temperature<br>only | 0.466           | 0.452          | 0.366          | 0.500          | 0.262   |

The regression equations are of the form

$$\text{Predicted response} = a + b_1x_1 + b_2x_2 + \dots$$

and the table gives the values of the coefficients  $b_1$ ,  $b_2$  etc. and of the constant  $a$ . All the coefficients listed exceed twice their standard errors. - indicates that the variable was not entered into the regression, its effect on the residual sum of squares being insignificant.

Table 5. 1. 4. Comparison with other indices of thermal comfort

Values of the correlation coefficient between  
the indicated response and the index

|                                          | <u>Mean value in<br/>this data</u> | <u>T<sub>1</sub></u> | <u>P</u> |
|------------------------------------------|------------------------------------|----------------------|----------|
| Ambient temperature                      | 72.6°F.                            | 0.466                | 0.262    |
| Globe thermometer temperature            | 76.9°F.                            | 0.448                | 0.306    |
| Equivalent temperature                   | 72.8°F.                            | 0.482                | 0.300    |
| Effective temperature                    | 68.1°F.                            | 0.481                | 0.285    |
| Singapore or Equatorial Comfort<br>index | 67.0°F.                            | 0.481                | 0.281    |
| Regression (Table 5. 1. 3.)              | -                                  | 0.504                | 0.331    |

The correlation with the Singapore index was calculated for table staff only, i.e. anaesthetists were excluded from this calculation.

The definitions of the several indices are given in Bedford (1964)



Table 5. 1. 5. Coefficients of the regression equations for prediction of the subject's response

| x.  | Variable                                           | All major variables |                |                |                |        |
|-----|----------------------------------------------------|---------------------|----------------|----------------|----------------|--------|
|     |                                                    | Response            |                |                |                |        |
|     |                                                    | T <sub>1</sub>      | T <sub>2</sub> | T <sub>3</sub> | T <sub>0</sub> | P      |
| 1.  | Ambient temperature (°F.)                          | 0.120               | 0.124          | 0.091          | 0.111          | 0.036  |
| 2.  | Water vapour pressure (mm.Hg.)                     | 0.065               | 0.066          | 0.050          | 0.056          | 0.030  |
| 3.  | Radiation (°F.)                                    | 0.015               | 0.051          | 0.040          | 0.047          | 0.009  |
| 4.  | Air movement<br>( $\sqrt{\text{vel. in f.p.m.}}$ ) | -                   | -0.056         | -              | -0.047         | -      |
| 5.  | Age (for each 5 years over 25)                     | -0.048              | -0.028         | -0.064         | -0.045         | -0.041 |
| 6.  | Sex (Female)                                       | -                   | -0.124         | -              | -              | -0.263 |
| 7.  | Race (Non-European)                                | -                   | -              | -              | -              | -0.111 |
| 8.  | Build (Fat, 1. - Thin, 5.)                         | -                   | -              | -0.054         | -              | -0.042 |
| 9.  | Surgeon                                            | 0.235               | 0.188          | 0.065          | 0.184          | 0.254  |
| 10. | Surgical assistant                                 | 0.007               | -0.017         | -0.043         | 0.028          | 0.011  |
| 11. | Scrubbed nurse                                     | 0.007               | 0.188          | 0.065          | 0.028          | -0.057 |
| 12. | Anaesthetist                                       | -0.239              | -0.382         | -0.091         | -0.236         | -0.186 |
| 13. | Spring (March-May)                                 | -                   | 0.160          | -              | 0.128          | -      |
| 14. | Summer (June-August)                               | -                   | 0.166          | -              | 0.117          | -      |
| 15. | Autumn (Sept.-November)                            | -                   | -              | -0.166         | -              | 0.090  |
| 16. | Winter (Dec.-Feb.)                                 | -                   | -              | -              | -              | -      |
| 17. | Stay in room (hrs.)                                | -                   | -              | -              | -              | 0.042  |
|     | Constant                                           | -5.622              | -5.991         | -3.467         | -4.929         | -2.262 |
|     | Multiple correlation coefficient                   | 0.520               | 0.541          | 0.423          | 0.576          | 0.490  |

The form of the regression equations is as described in Table 5. 1. 3.

Table 5. 1. 6. Equivalent thermal effect of other variables.

A. Change in the specified variable required in order to produce the same effect as 1°F. drop in ambient temperature.

| <u>Variable</u>               | <u>Response</u> |       |       |       |       |
|-------------------------------|-----------------|-------|-------|-------|-------|
|                               | $T_1$           | $T_2$ | $T_3$ | $T_0$ | P     |
| Vapour pressure, mm.Hg.       | - 1.8           | - 1.9 | - 1.8 | - 2.0 | - 1.2 |
| % Relative humidity at 63°F.  | - 10            | - 10  | - 10  | - 11  | - 7   |
| Radiation, °F.                | - 8.0           | - 2.5 | - 2.3 | - 2.4 | - 4.0 |
| Air movement, fpm. at 25 fpm. | -               | 27    | -     | 30    | -     |
| Age, years                    | 12              | 22    | 7     | 12    | 4     |
| Stay, minutes in theatre      | -               | -     | -     | -     | - 51  |

B. Change in ambient temperature, °F., required to produce the same response in the specified class of individual as that observed in the population as a whole.

| <u>Class character</u> | <u>Response</u> |       |       |       |       |
|------------------------|-----------------|-------|-------|-------|-------|
|                        | $T_1$           | $T_2$ | $T_3$ | $T_0$ | P     |
| Sex (female)           | -               | 1.0   | -     | -     | 7.3   |
| Race (non-European)    | -               | -     | -     | -     | 3.1   |
| Surgeon                | - 2.0           | - 1.5 | - 0.7 | - 1.7 | - 7.1 |
| Anaesthetist           | 2.1             | 3.1   | 1.0   | 2.1   | 5.2   |
| Fat subjects           | -               | -     | - 1.2 | -     | - 2.3 |
| Thin subjects          | -               | -     | 1.2   | -     | 2.3   |

C. Change in ambient temperature, °F., required to produce the same response in the given season as obtained in winter.

| <u>Season</u>           | <u>Response</u> |       |       |       |     |
|-------------------------|-----------------|-------|-------|-------|-----|
|                         | $T_1$           | $T_2$ | $T_3$ | $T_0$ | P   |
| Spring (March-May)      | -               | - 1.3 | -     | - 1.2 | -   |
| Summer (June-August)    | -               | - 1.3 | -     | - 1.1 | -   |
| Autumn (Sept.-November) | -               | -     | 1.8   | -     | 2.5 |

Table 5. 1. 7. Preferred ambient temperatures ( $^{\circ}\text{F.}$ ) ( $T = 3.0$ )  
(for mean observed values of the other variables)

|                     | $T_1$ | $T_2$ | $T_3$ | $T_o$ |
|---------------------|-------|-------|-------|-------|
| Surgeons            | 64.8  | 67.1  | 70.0  | 66.1  |
| Surgical assistants | 66.7  | 67.4  | 70.5  | 67.5  |
| Scrubbed nurses     | 66.7  | 67.1  | 70.0  | 67.5  |
| Anaesthetists       | 68.8  | 71.8  | 71.6  | 69.9  |

$T_1$ ,  $T_2$ ,  $T_3$  are the scale values of the interview response for comfort of head, trunk and feet respectively.  $T_o$ , the general comfort response,  $= 1/3 (T_1 + T_2 + T_3)$ .

The values given have been calculated from the regression equations given in Table 5. 1. 5, and represent the ambient temperatures at which the highest proportion of each category stated that they were comfortable.

Table 5. 1. 8. Response to some environmental circumstances

| <u>Change</u>                                    | <u>Change in ambient temperature,<br/>°F., producing same effect on:</u> |                      |          |
|--------------------------------------------------|--------------------------------------------------------------------------|----------------------|----------|
|                                                  | <u>T<sub>1</sub></u>                                                     | <u>T<sub>2</sub></u> | <u>P</u> |
| From 'relaxed' to 'tense atmosphere'             | 1.8                                                                      | 2.0                  | 5.4      |
| From minor to major operation                    | -                                                                        | -                    | 2.2      |
| From 'no mistakes' to 'two mistakes'             | - 1.5                                                                    | -                    | -        |
| Increase equal to 2 $\times$ S.D. in:            |                                                                          |                      |          |
| Mean variation of air velocity<br>( + 4.52 fpm.) | 0.9                                                                      | -                    | -        |
| Entries and exits to theatre<br>( + 134/hr)      | -                                                                        | -                    | 1.8      |
| Movements within theatre ( + 52/hr.)             | -                                                                        | -                    | - 2.4    |
| Maximum noise level ( + 7.4 phons)               | -                                                                        | -                    | - 2.0    |

Table 5. 1. 9. Coefficients of the regression equations used in the calculation of predicted votes and Index Temperatures.

| <u>Variable</u>                                | <u>Response</u> |                |                |                |        |
|------------------------------------------------|-----------------|----------------|----------------|----------------|--------|
|                                                | T <sub>1</sub>  | T <sub>2</sub> | T <sub>3</sub> | T <sub>0</sub> | P      |
| Ambient Temperature, °F.                       | 0.120           | 0.126          | 0.091          | 0.113          | 0.033  |
| Vapour pressure, mm.Hg.                        | 0.065           | 0.071          | 0.048          | 0.059          | 0.035  |
| Radiation, °F.                                 | 0.014           | -0.058         | 0.052          | 0.053          | -      |
| Air Movement, (fpm.) <sup>1</sup> <sub>2</sub> | -               | -0.055         | -0.030         | -0.046         | -      |
| Status = 1 for Surgeon                         | -               | -              | -              | -              | 0.417  |
| Assistant                                      | -               | -              | -              | -              | 0.237  |
| Anaesthetist                                   | -0.366          | -0.506         | -              | -0.344         | -      |
| Sex = 1 for female                             | -               | -              | -              | -              | -0.124 |
| Constant                                       | -5.669          | -6.112         | -3.669         | -5.136         | -2.251 |
| Multiple correlation coefficient, R            | 0.516           | 0.533          | 0.394          | 0.568          | 0.452  |
| <hr/>                                          |                 |                |                |                |        |
| cf. Multiple R for Thermal variables only      | 0.504           | 0.503          | 0.394          | 0.548          | 0.331  |
| for all variables                              | 0.520           | 0.541          | 0.423          | 0.576          | 0.490  |
| <hr/>                                          |                 |                |                |                |        |

Table 5. 1. 10 Equations used to generate other Thermal Indices

| <u>Variable</u>                        | <u>Equation</u>               |                        |                              |
|----------------------------------------|-------------------------------|------------------------|------------------------------|
|                                        | I                             | II                     | III                          |
|                                        | <u>Equivalent Temperature</u> | <u>Singapore Index</u> | <u>Effective Temperature</u> |
| Ambient temperature, T. <sup>°F.</sup> | 1.00                          | 0.574                  | 0.52                         |
| Vapour pressure, mm.Hg.                | -                             | 0.468                  | -                            |
| Relative humidity, H, %                | -                             | -                      | -0.19                        |
| Cross product TxH.                     | -                             | -                      | 0.0036                       |
| Air movement, (V fpm.) <sup>1/2</sup>  | -1.474                        | -0.231                 | -1.69                        |
| Cross product TxV <sup>1/2</sup>       | 0.0147                        | -                      | 0.019                        |
| (Mean radiant Temperature, TMR)-T      | 0.478                         | -                      | -                            |
| Constant                               | -                             | 21.23                  | 27.8                         |

{ Equations I and III may be written in the following form: }

{ I Equivalent Temperature =  $0.522.T + 0.478.TMR - 0.01474 \sqrt{V} (100-T)$  }

III Effective Temperature =  $0.52.T + H(0.0036.T - 0.19) + \sqrt{V} (1.69 - 0.019.T) + 27.8$  }

#### Equation IV

$$\text{Effective Temperature} = \frac{(60 + 0.5 \sqrt{V})(T - 42 - 0.8 \sqrt{V})}{(T - T_W + 65 - 0.7 \sqrt{V})} + 45.4$$

(T - T<sub>W</sub>), the wet bulb depression of an Assman thermometer, is given approximately by (T - T<sub>W</sub>) = (1 - H/100)(0.36.T - 2.6) if only T, H. are available.

Equation IV was derived geometrically from the Effective Temperature nomogram (Normal scale), and applies only to the ranges 60 < T < 80°, 30 < H < 70%, 10 < V < 100 fpm, with an accuracy of ± 0.5°F.

Equation III was derived by multiple regression analysis, using the data of the survey, and estimates Effective Temperature (as derived by Equation IV) with a standard deviation of ± 0.18°F.

Table 5. 2. 1. Regression equations for S-vote.Calculated for the total experimental population (N = 2566)

| <u>Variable</u>           | <u>Equation I<br/>(Thermal variables<br/>only)</u> |            | <u>Equation II<br/>(All variables)</u> |            |
|---------------------------|----------------------------------------------------|------------|----------------------------------------|------------|
|                           | <u>Coefficient</u>                                 | <u>RSQ</u> | <u>Coefficient</u>                     | <u>RSQ</u> |
| Temperature, °F.          | 0.061                                              | 0.154      | 0.058                                  | 0.154      |
| Vapour Pressure, mm.Hg.   | 0.040                                              | 0.174      | 0.040                                  | 0.174      |
| Radiation, °F. above D.B. | 0.018                                              | 0.179      | -                                      | -          |
| Anaesthetist              | -                                                  |            | -0.167                                 | 0.187      |
| Sex, female               | -                                                  |            | 0.121                                  | 0.193      |
| Stay, hours               | -                                                  |            | 0.024                                  | 0.195      |
| Constant                  | -1.579                                             |            | -1.319                                 |            |
| Multiple R.               | 0.423                                              |            | 0.442                                  |            |

Note: 'RSQ' columns tabulate the proportion of the total variance attributable to the regression at each step in the sequential procedure.

Table 5. 2. 2. Correlation coefficients with S-vote.

Calculated for the total experimental population (N = 2566) for readings at head height.

| <u>Variable</u>             | <u>Correlation Coefficient</u> |
|-----------------------------|--------------------------------|
| Effective Temperature       | 0.403                          |
| D.B. Temperature            | 0.392                          |
| Equivalent Temperature      | 0.391                          |
| Mean Radiant Temperature    | 0.354                          |
| Vapour Pressure             | 0.243                          |
| (Relative Humidity          | 0.008. NS)                     |
| (Air velocity) <sup>2</sup> | -0.101                         |
| (Radiation Excess           | 0.022. NS)                     |

Note: Correlation coefficients greater than 0.051 are significant at the 0.01 level for N = 2566



Table 5. 3. 1. Regression equation for W-vote.

| <u>Variable</u>                     | <u>Coefficient</u> | <u>RSQ</u> |
|-------------------------------------|--------------------|------------|
| Temperature, °F.                    | - 0.056            | 0.127      |
| Vapour Pressure, mm.Hg.             | - 0.041            | 0.146      |
| Anaesthetist                        | 0.214              | 0.161      |
| Autumn                              | 0.094              | 0.165      |
| (Air velocity, fpm.) <sup>1/2</sup> | 0.035              | 0.168      |
| Constant                            | 6.863              | -          |
| <hr/>                               |                    |            |
| Multiple Correlation                | 0.409              |            |
| <hr/>                               |                    |            |

Note: Based on 2566 cases. 'RSQ' column tabulates the proportion of the total variance attributable to the regression at each step in the sequential procedure.

Table 5. 4. 1. Regression equation for H-vote.

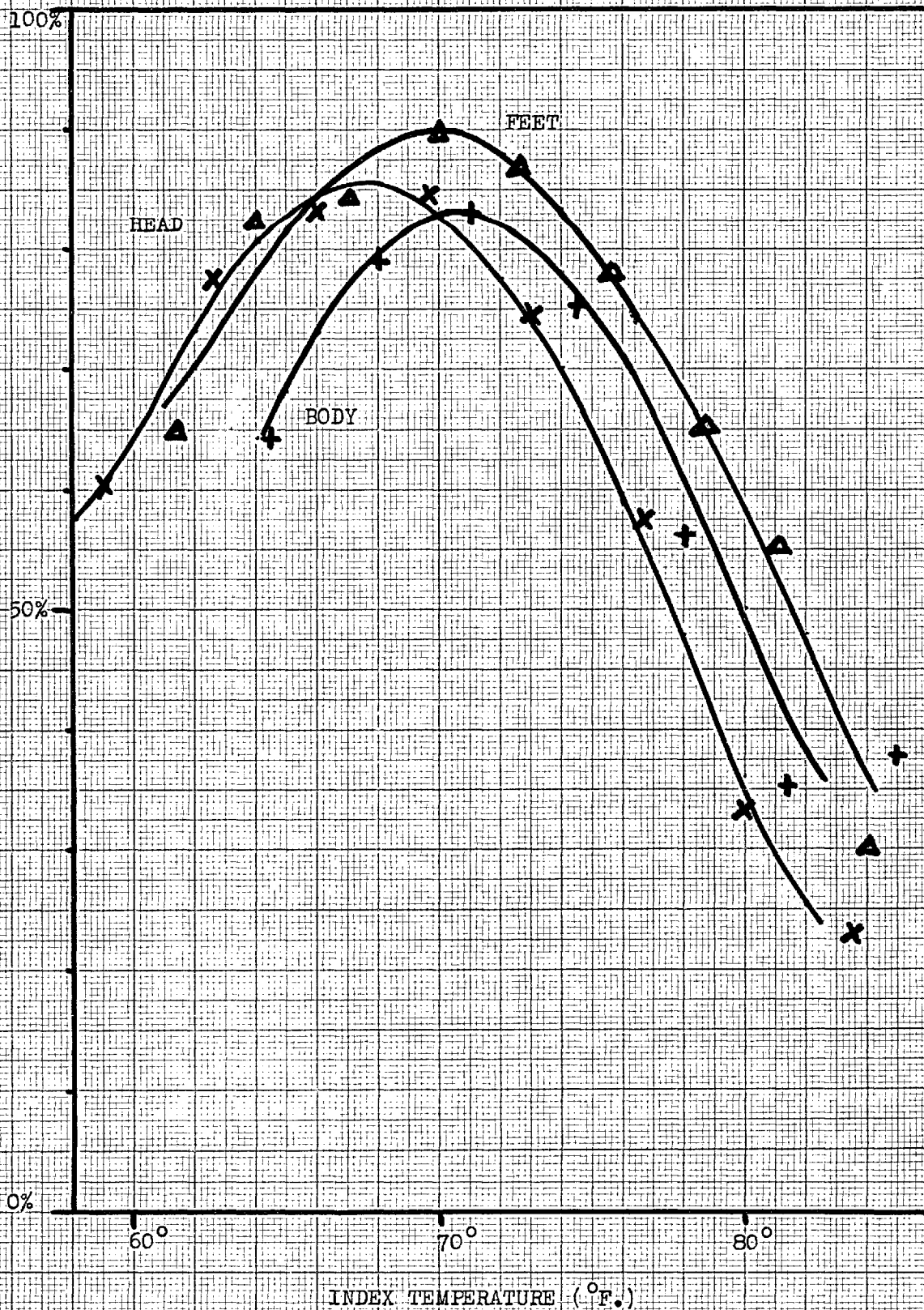
| <u>Variable</u>                        | <u>Coefficient</u> | <u>RSQ</u> |
|----------------------------------------|--------------------|------------|
| Temperature, °F.                       | 0.031              | 0.106      |
| Vapour Pressure, mm.Hg.                | 0.033              | 0.132      |
| Surgeon                                | 0.178              | 0.143      |
| Spring                                 | 0.096              | 0.151      |
| Age (years over 25)                    | -0.005             | 0.159      |
| Constant                               | -2.270             | -          |
| <hr/>                                  |                    |            |
| Multiple Correlation Coefficient 0.398 |                    |            |
| <hr/>                                  |                    |            |

Note: Based on 2566 cases.

'RSQ' column tabulates the proportion of the total variance attributable to the regression at each step in the sequential procedure.

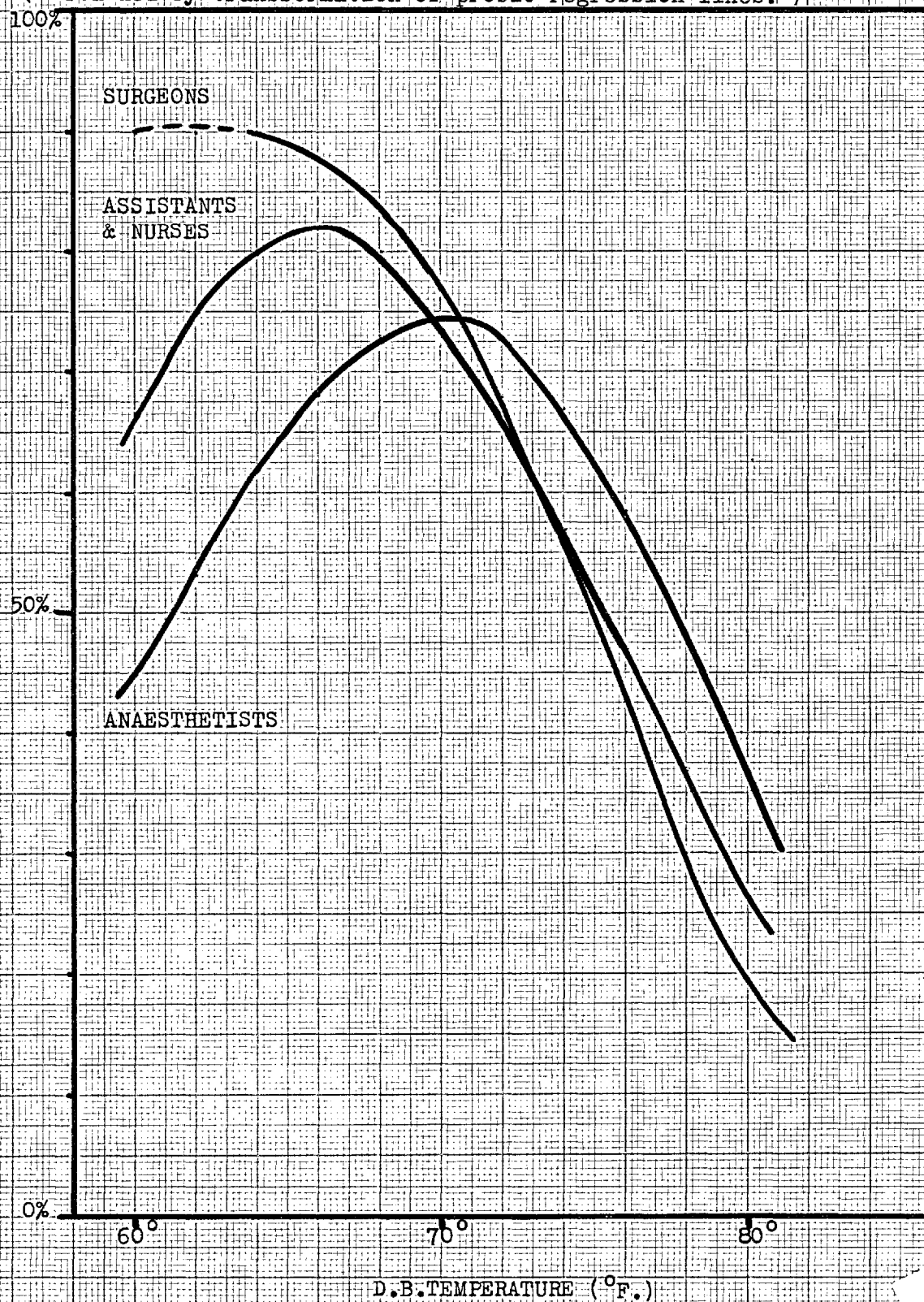
GRAPH 5.1.1. % COMFORTABLE (3 ZONES) v. INDEX TEMPERATURE.

(Index Temperature equations are given in Table 5.1.9.)



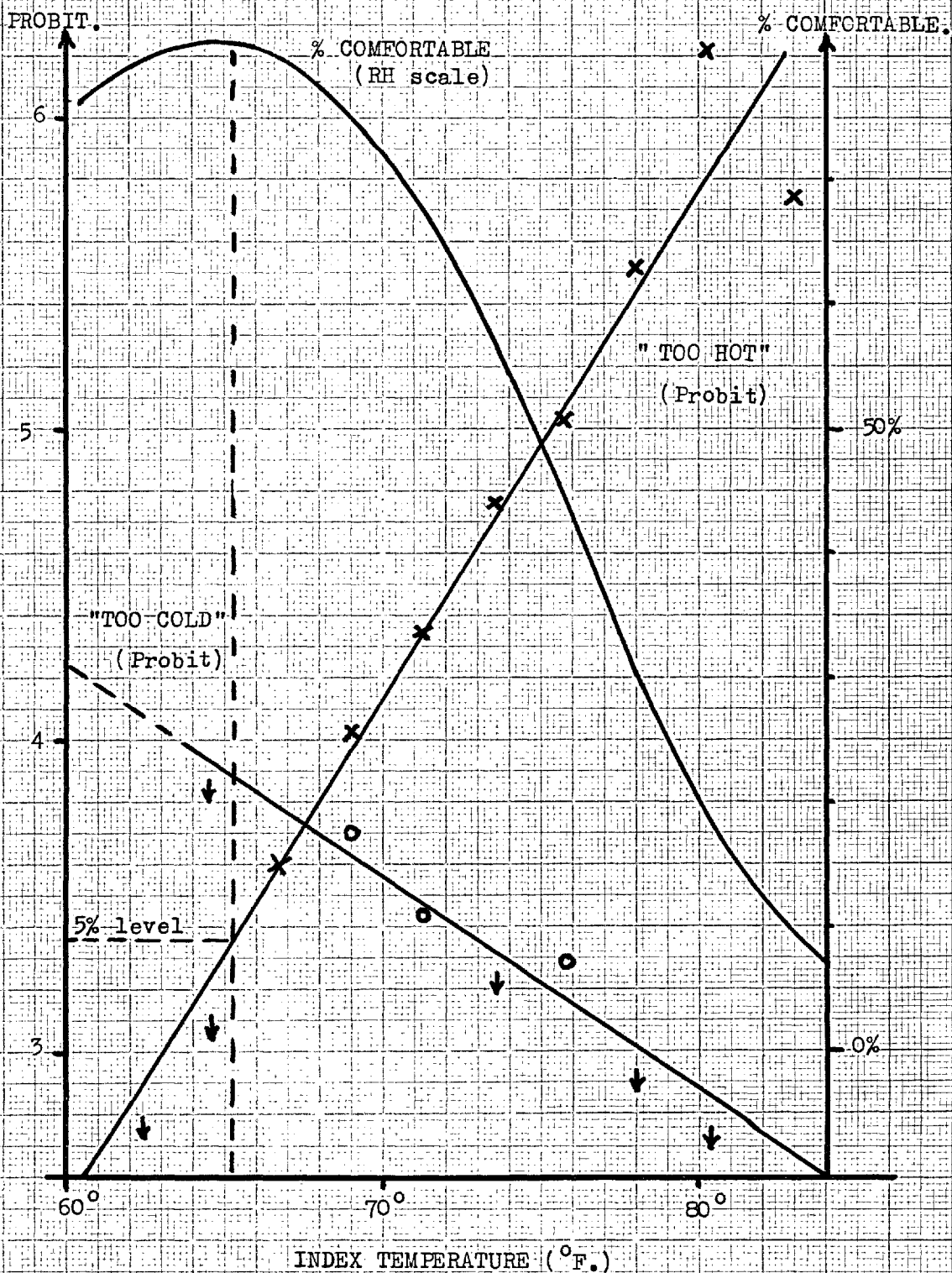
GRAPH 5.1.2. % COMFORTABLE (3 GROUPS) v. D.B. TEMPERATURE.

( Obtained by transformation of probit regression lines. )



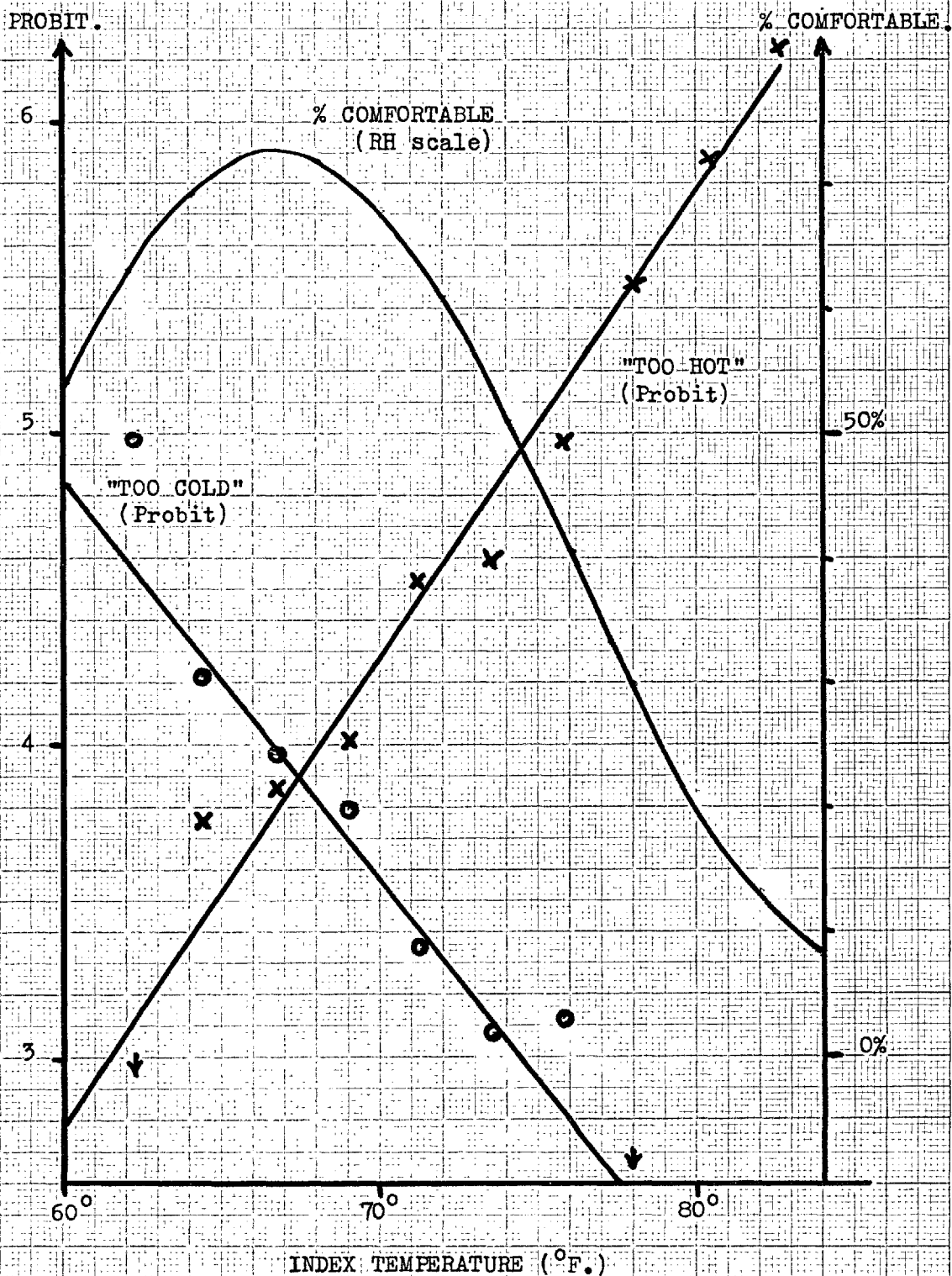
GRAPH 5.1.3. SURGEONS: THERMAL COMFORT v. INDEX TEMPERATURE.

$T_1$ ,  $T_2$ , &  $T_3$  responses were considered simultaneously for this purpose. Index temperature is that for  $T_0$  in Table 5.1.9.



GRAPH 5.1.4. ASSISTANTS & NURSES: THERMAL COMFORT v. INDEX TEMP.

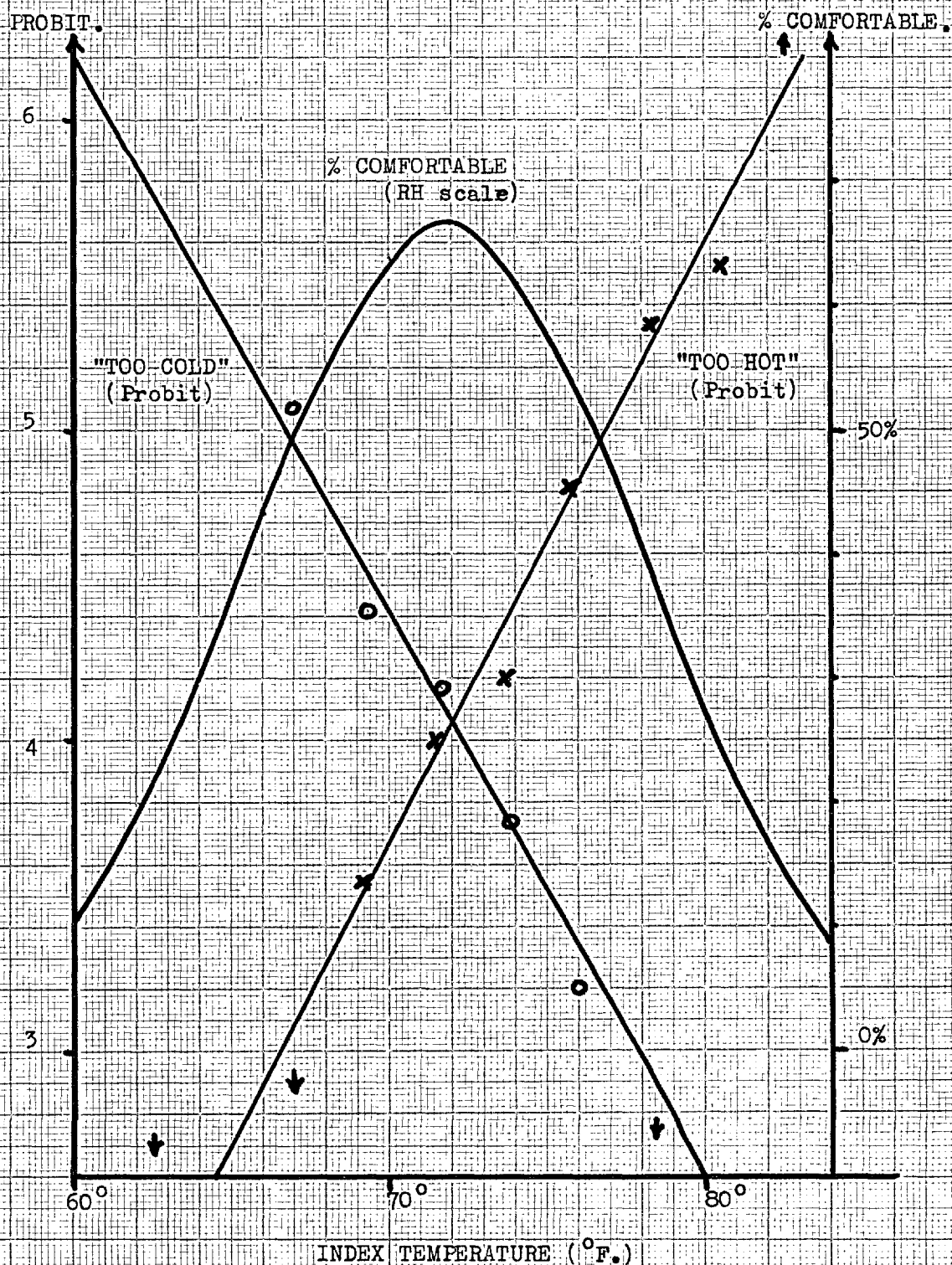
$T_1$ ,  $T_2$ , &  $T_3$  responses were considered simultaneously for this purpose. Index temperature is that for  $T_0$  in Table 5.1.9.



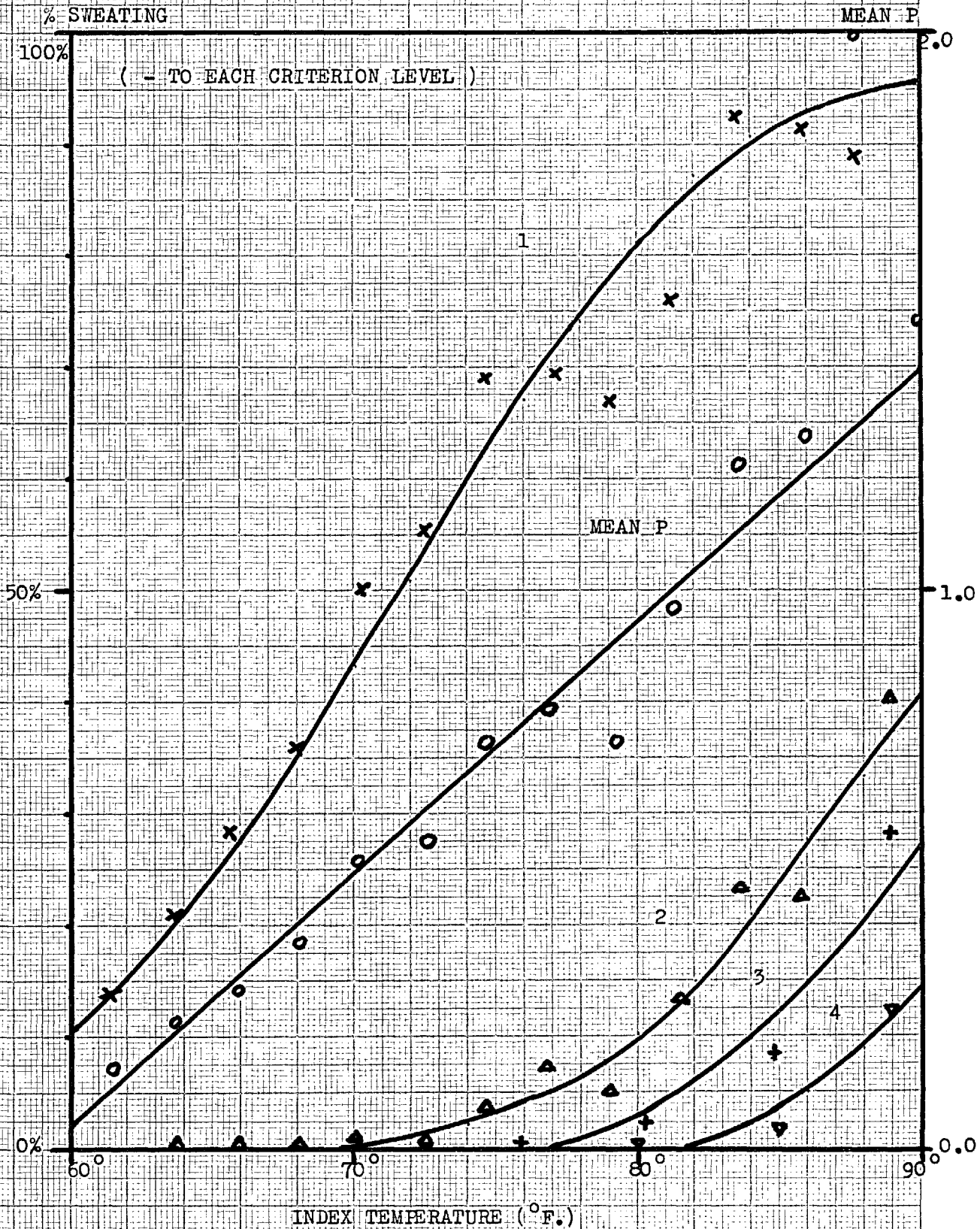


GRAPH 5.1.5. ANAESTHETISTS: THERMAL COMFORT v. INDEX TEMPERATURE.

$T_1$ ,  $T_2$ , &  $T_3$  responses were considered simultaneously for this purpose. Index temperature is that for  $T_0$  in Table 5.1.9.



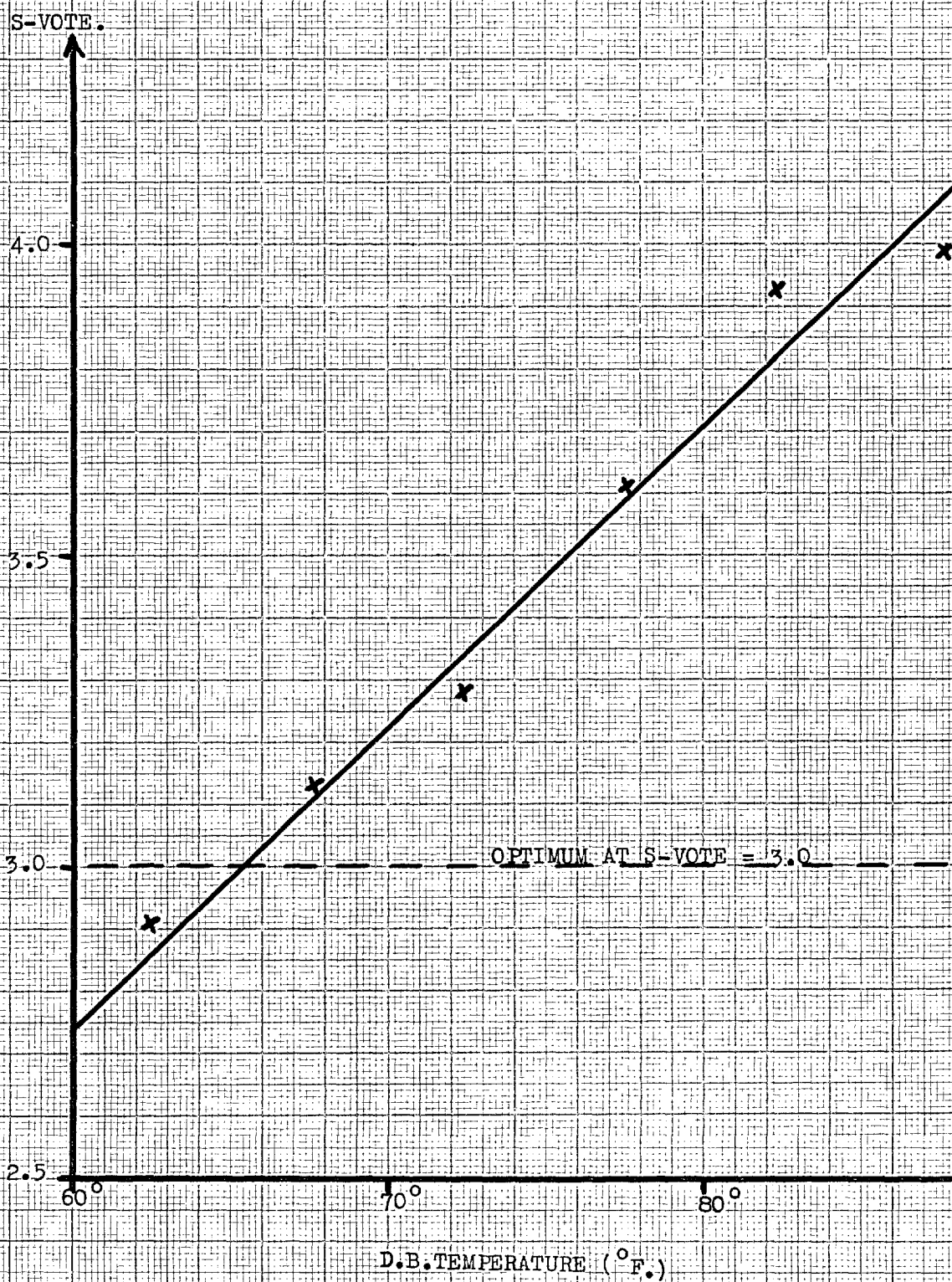
GRAPH 5.1.6. OBSERVED SWEATING (ALL STAFF) v. INDEX TEMPERATURE.





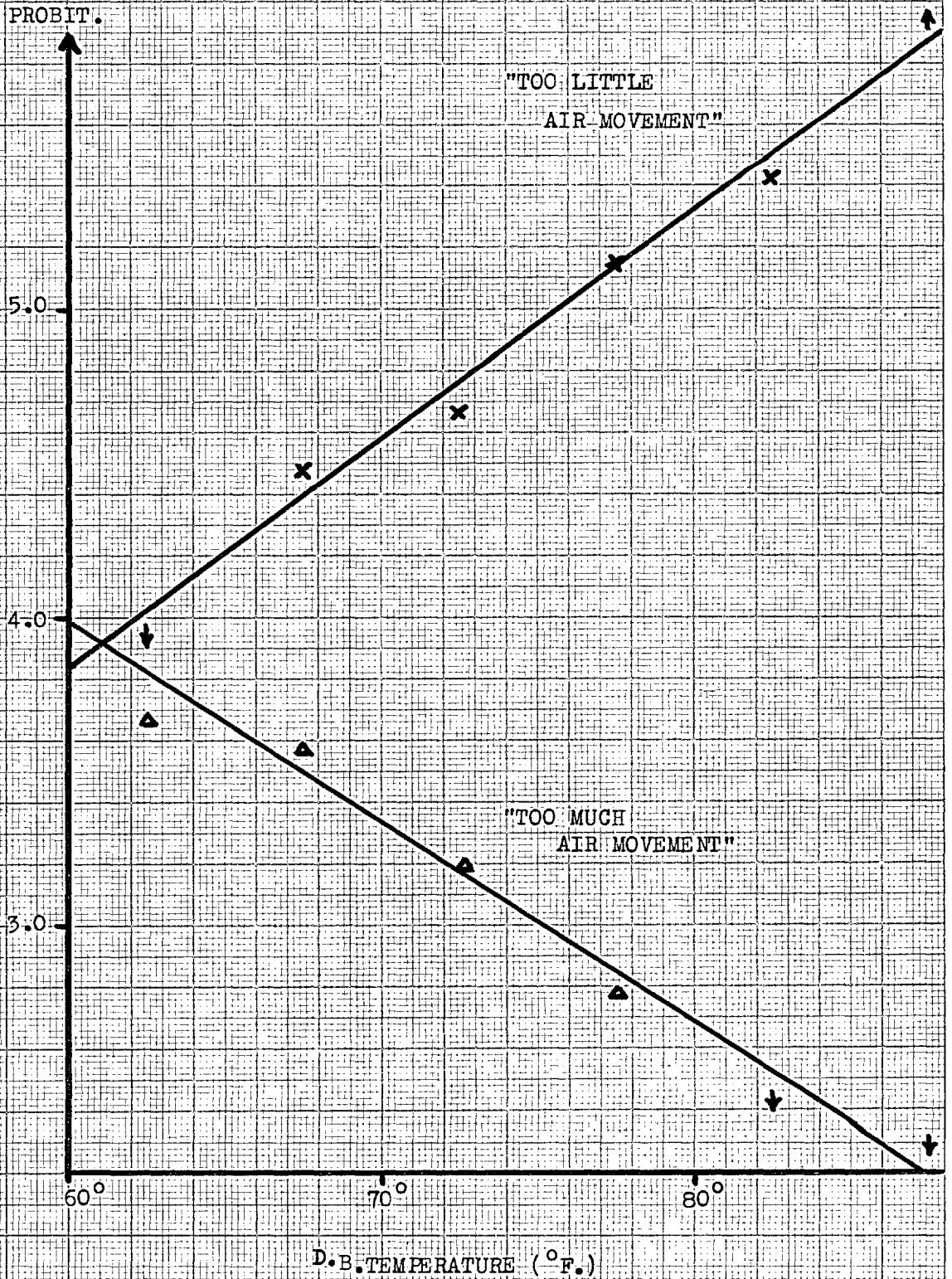
GRAPH 5.2.1. S-VOTE v. D.B. TEMPERATURE.

(Surgeons and assistants only.)



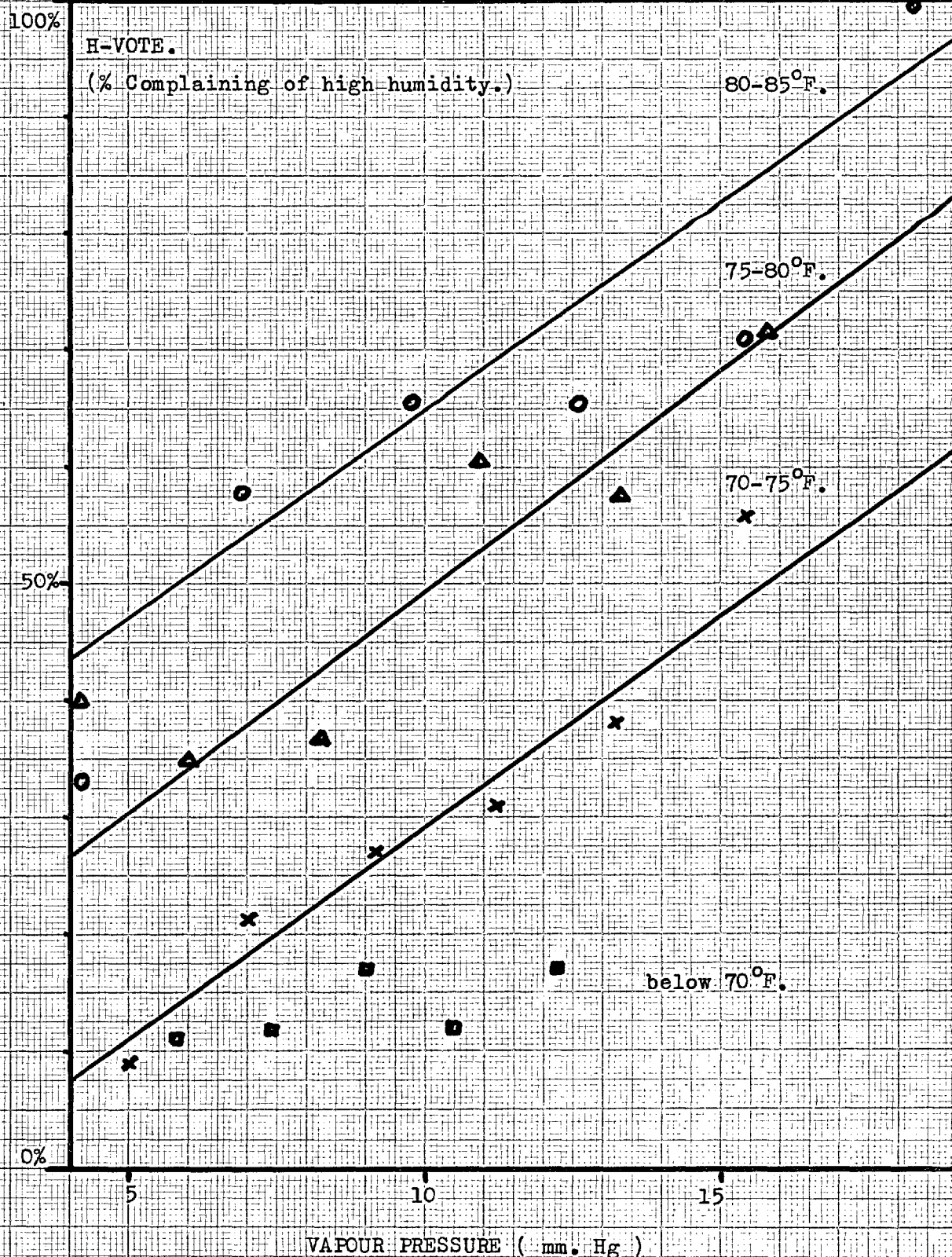
GRAPH 5.3.1. COMPLAINTS OF AIR MOVEMENT v. D.B. TEMPERATURE.

(Assistants only.)



GRAPH 5.4.1. H-VOTE v. VAPOUR PRESSURE, IN TEMPERATURE BLOCKS.

(Surgeons, assistants &amp; anaesthetists only.)



SECTION 6.

ANALYSIS OF INCOMPLETE DATA.

## 6. 1. Subsidiary response: the perception of noise

### 1. Introduction.

Surgeons frequently complain of the noise in operating theatres, particularly when the critical stage of an operation has been reached. Very little has been done to reduce noise levels. In the interests of hygiene the walls and floor must be of hard, easily cleaned material. In the interests of free movement within a suite, there are often no doors between the various areas. Sinks and bowls are often of stainless steel. Section 6. 2. will show that unexpectedly large numbers of people move through operating theatres during operations. The resulting noise climate is reverberant and highly variable, containing high frequency transients from impact sources. Broadbent (1957) has shown that high frequency noise is more distracting than low, and Woodhead (1959) has shown that a brief loud noise leads to a period of distraction from concentrated tasks involving decision-making. Sanders (1961) found that varied, unpredictable noise affected performance on concentrated tasks more than did monotonous noise. It is therefore not surprising that complaints of noise are common in operating theatres where the sound pressure levels may in fact be very low by industrial standards. However, there remains the possibility that such complaints are merely a generalised response to stress, and would be unaffected by reduction of the noise level. The present section deals with an investigation of this point.

### 2. Method.

A question on noise was included in the sequence of questions described in Section 3. Subjects were asked if they considered the

theatre had been too noisy during the immediately preceding period, and their answers were recorded as 'yes' or 'no'.

An estimate of the noise climate was made using a noise meter incorporated in the assembly of other environmental instruments designed by Dr. O.M. Lidwell and constructed at the Central Public Health Laboratory. The noise meter provided a record in the form of points on a paper chart, printed each five seconds. The chart reading in microamperes was logarithmically related to the sound pressure level over the data range, as shown in Graph 6-1-1. Arbitrary noise scale units were used for reading; the chart, the values 1-5 corresponding to 5, 10, 20, 40 and 80 microamperes respectively. These are related to sound pressure level in dB re 0.0002 Dynes/cm.<sup>2</sup> at 1500 Hz. in Graph 6-1-1. The range was therefore 50-67 dB. The frequency response of the instrument was arranged to be approximately the same as that of the ear, and the values therefore approximate to phons for general noise.

Records of the noise climate were taken during operations, with a desk microphone on a table at the periphery of the theatre. Because the acoustics of hard-walled rooms are reverberant, the exact position of the microphone was not critical and the readings are relevant to the experience of the anaesthetist and table staff. Records were taken for as long as possible, often for an hour or more, and thus provided representative samples of the noise in the periods studied. No records were taken between operations, as the noise level was always considerably higher, and questions on noise did not relate to these 'changeover' periods. Occasionally it was not possible to

obtain records, perhaps because operations were too short or ended unexpectedly soon. In these cases, no assumptions were made about the 'typical' noise climate of a theatre. In fact, noise levels seemed to be related much more closely to the preference of the consultant surgeon than to the characteristics of the theatre itself. Replies relating to periods for which no record was available were discarded, and the analysis of the noise response, or 'N-vote', has therefore been placed in the 'Incomplete data' section of this thesis.

Records were quantified in two ways. Firstly, a 'basic noise level' was found; this was usually very clearly a level to which quiet periods tended asymptotically, and beneath which no readings were obtained. The noise scale unit immediately below was written down; for example, if the base noise level was that corresponding to 15 microamperes, the figure was '2'. The information contained in this form can be expressed as 'the noise level was at all times above level 2 (54 dB.)'.

Secondly, the level exceeded for 20% of the time was found, and again written down as the next lowest noise scale unit. An '80% level' of '4' means therefore that the noise level exceeded level 4 (c.62.5 dB) for at least 20% of the time, but exceeded level 5 (c.67 dB) for less than 20% of the time. It is recognised that this is a fairly crude method, but the noise levels were so varied that a more thorough numerical approach would not have been justified.

### 3. Results.

Over four hundred noise records were obtained, and 2,222 related

replies. The noise levels were distributed approximately normally; the mean base level was 51.5 dB. with a standard deviation of 4.7 dB; the mean 80% level was 60 dB, with a standard deviation of 3.7 dB. The mean response was 0.252, i.e. 25.2% of those interviewed considered the theatre had been too noisy. The standard deviation is not an appropriate measure of dispersion for a quantal response. However, the mean N-votes for surgeons, assistants, nurses and anaesthetists all lay between 25% and 26%, a very markedly uniform response, perhaps unexpected in view of the different functions performed by each staff category. For all subsequent analysis, the data from all staff categories has been pooled.

Graph 6-1-2 shows the relation between the probit of the proportion complaining of excessive noise and the two criterion noise levels. The regression lines shown were derived by an iterative approximation to the maximum likelihood solution as given by Finney (1947). The difference in slope between the lines does not approach significance. There is no heterogeneity significant at the 0.02 level for either line, and the response is thus seen to be related to the stimulus level in an orderly way. The 80% level should be below 42 dB in order to ensure that no more than 5% of theatre occupants complain of noise. If it rises above 73 dB, 50% of theatre occupants will complain.

Table 6-1-1 shows a reduced correlation matrix for a number of variables with both noise levels and N-vote. Coefficients exceeding 0.055 are significant at the 0.01 level. The variation of the 80% level accounted for only 2% of the variation of the N-vote, and the



base noise level had even less effect. Thermal stress, as measured by the Index temperature for head height response, did not significantly influence the N-vote, even though the measured noise levels were positively correlated with the thermal stress. This association is probably due to the fact that older theatres tended to be both hotter and more noisy.

The 80% noise level was lower in difficult operations and when the 'tension' was high, though in neither case was the base noise level affected. The occurrence of mistakes in procedure tended to be associated with an increased 80% noise level, and when the tempo was fast both base noise level and 80% noise level were increased. None of these variables had an effect on the N-vote, and their effect on the measured noise levels, though significant and interesting, was small.

When a surgical complication had occurred, there were more complaints of noise, though the noise levels were not significantly increased. This is the only case of a variable other than noise leading to complaints of noise, and the effect is extremely small. Neither did the other responses made by subjects appear to affect the N-vote, as they would be expected to do if complaints of noise were fundamentally a symptom of generalised discomfort. The correlation coefficients of the N-vote with responses relating to stuffiness, thermal comfort at three levels, the sensation of air movement and the observed forehead sweating, did not approach significance. Complaints of excessive humidity were correlated ( $r = 0.074$ ) with complaints

of noise, and this is significant. However, only 0.5% of the variation can be accounted for in this way, and the effect is thus marginal.

When the method of sequential regression analysis was applied to the noise data, very little new information was obtained. The deviation of the observed forehead sweating,  $P$ , from the predicted sweating,  $P(P)$ , as calculated by Equation 5 in Table 5-1-9, was made the dependent variable in a sequential multiple regression analysis. The 80% noise level could be shown to affect this measure ( $F(1,2219) = 8.2$ ) but only to account for 0.4% of the variation. This result is referred to in Section 5.1. and appears in Table 5.1.8. Observed sweat rates were lower when 80% noise levels were higher ( $+7.4 \text{ dB} = -2 \text{ F.}^\circ$ ). The reason for this was probably that the stress sweating was reduced when tension was low and talking and laughter, almost always the source of high level noise in theatres, were consequently more frequent. The effect of noise level on deviations from the predicted thermal votes could not be shown to be significant.

The method of multivariate analysis did not reduce to insignificance the effect of surgical complications on the perception of noise, nor did it bring to light any further variables having a significant effect. In accordance with the simple correlations, 80% noise level entered first with the N-vote as the dependent variable. Complaints of noise are therefore probably related to the upper levels reached rather than to the minima or base levels of noise.

#### 4. Discussion.

Complaints of noise seem to be causally related to measured

noise levels alone, with the sole and reasonable exception of slightly increased sensitivity to noise when the surgical situation becomes more critical. The absence of heterogeneity in the probit regression indicates that there is a normal distribution of response, but the low correlation coefficients obtained show that there is considerable variation in the subjective criteria of noise annoyance. Different categories of theatre staff do not appear to have different noise expectancies, though Langdon (1965) found this to be the case for different categories of office worker. Differences between sexes were non-existent, and the remaining 98% of the variation must be ascribed to other inter and intra-individual differences that were not measured in this survey. The dependence of measured noise levels on the somewhat esoteric aspects of the surgical situation assessed by the observer is of interest chiefly as cross validation.

## 5. Summary.

Complaints of noise were related to actual noise levels and did not seem to be symptoms of generalised discomfort.

## 6. 7. Staff movement and occupancy.

### 1. Introduction.

As part of another study, on a number of occasions a careful count was made of the number of people in the theatre, the number of entries and exits, and the amount of movement within the theatre. Complaints of undue movement in theatres are common, and it is of interest to know what factors govern the occurrence of such complaints. The present sub-section deals with an investigation of these factors.

## 2. Method.

Records of all staff movements in, into and out of the theatre were kept by the nurse for periods of about an hour during roughly half the sessions studied. For this purpose, she used a double-entry table to record the starting and finishing point of each discrete movement, as described in Section 3. This enabled detailed traffic-flow plans to be made, but for the present purpose the data was reduced to two figures, representing movements per hour within the theatre, and entries and exits per hour. A third figure gave the number of people involved in the movement; however, as the high entry and exit rates show, the actual number in the theatre was constantly changing. No records were taken between operations, when movement rates were necessarily considerably higher.

Subjects were asked whether they considered there had been too much movement in the theatre, and whether they considered there had been too many people in the theatre. The answers to these questions were recorded as 'yes' or 'no' (1 or 0) and form the M- and O- votes respectively. More than 1200 sets of replies were obtained that referred to periods in which movement records had been taken. The 'Z-card' method referred to in Section 4 was used to deal with this incomplete data, whose results therefore form a sub-section of Section 6.

## 3. Results.

Entries and exits varied between 1 and 450 per hour with a mean of 122. Movements within the theatre varied between 1 and 100 per hour with a mean of 45. Occupancy varied between 3 and 19 with a

mean of about 10. This figure represents the number of different people present at some time during the operations studied, not counting the author or observer. The mean number of people continuously present would be considerably less than this.

The M-vote results for each status category are shown in Table 6. 2. 1. In all, 28% of those questioned complained of excessive movement during operations. Scrub-nurses and anaesthetists complained more than surgeons and their assistants, and the differences between status categories are significant ( $P < 0.02$ ) using the chi-square test for independence (Fisher 1958). Table 6.2.2. shows the O-vote results in similar form. In all 26% of those questioned complained of overcrowding during operations. Scrub-nurses complained more than anaesthetists, anaesthetists complained more than surgical assistants, and surgeons complained least of all. Again, the differences between status categories are significant. ( $P < 0.01$ ).

Graph 6. 2. 1. shows the increase in complaints of excessive movement with increasing entries and exits per hour, for all status categories. As the probit transformation has been used, a linear regression is expected. Between 15 and 20% complained below 60 entries and exits per hour; not more than 40% complained even at 300 entries and exits per hour. The correlation coefficient of 0.092, though significant at the 0.01 level, means that variations in actual levels of movement accounted for less than 1% of the total variation of the M-vote.

Graph 6. 2. 2. shows the dependence of the O-vote on the numbers

of people observed in the theatre during the session, for all status categories. Complaints increased from 9% with 5 people in the theatre, to 24% with 10 people and to 47% with 15 people. The correlation coefficient of 0.229 is highly significant and implies that variations in the number of people in the theatre accounted for about 5% of the total variation of the O-vote.

Table 6. 2. 3. shows the correlation matrix obtained for this data. It is worth noting that the movement within the theatre had no significant effect on the M-vote, and was negatively correlated with the noise levels measured in the theatre. This indicates that movement within the theatre was not distracting and did not increase noise levels. The number of people in the theatre had no effect on the noise levels. The inference is thus that high noise levels are probably due to talking rather than to movement and activity within the theatre. Entries and exits to the theatre led to complaints and increased the measured noise levels.

In an attempt to identify other causes of complaints of excessive movement, a sequential multiple regression analysis was performed with the M-vote as dependent variable. Table 6. 2. 4. shows the regression coefficients obtained, all of them significantly greater than zero at the 0.05 level. More complaints were made in difficult operations and when the team were working quickly; high temperatures and air velocities were also associated with increased complaints of movement in theatres. Thus there was an element of speed stress and of thermal stress in this response, accounting for about 1.5% of the total variation.

The effect of movement on thermal responses was also investigated, using deviation from the predicted response as the dependant variable in sequential multiple regression analyses, as set out in Section 4. The equations of Table 5. 1. 9. were used to generate the predicted  $T_1$  and  $P$  responses. No effect of movement on  $T_1$  (thermal sensation at head height) could be demonstrated, but Table 6. 2. 5. shows the regression coefficients obtained with  $(P - P(P))$  as dependant variable. Movement variables were forced into the equation before the other variables could enter. All the coefficients are significantly different from zero at the 0.05 level. Forehead sweating was less for high levels of movement within the theatre, more for large numbers of entries and exits. Tension and the difficulty of operations had independently significant effects, so the apparent effects of movement are not due to correlation with these factors. If forehead sweating is a symptom of stress, as suggested in Section 5.1, the inference must be that entries and exits tend to increase stress, arguably by their distracting nature, while free movement of staff within the theatre tends to decrease stress. A comparison of the magnitude of these effects with the effect of air temperature is made in Table 5. 1. 8.

#### 4. Discussion.

Complaints of 'too much movement' in theatres clearly refer to entries and exits rather than to movements within the theatre. The numbers of entries and exits recorded are indeed very high. On more than half the sessions studied, the entries and exits corresponded to

one person entering and leaving again each minute throughout the session. It should be remembered that recording ceased when the operation ended; these high rates of entry and exit occurred with an open wound. In view of the bacterial risks known to be associated with movement of staff in the theatre, some radical measures seem called for to reduce the traffic during operations. The numbers of people entering the theatre during operations were also high; this is undesirable for the same reason, and could well be reduced.

There is evidence to suggest that complaints of movement and of overcrowding can be symptoms of stress rather than responses to the actual levels of movement and occupancy, but no measurable factors were identified that could account for more than a small fraction of the variation in these responses between people and between occasions. In general, surgeons and their assistants tended to complain less than scrub-nurses and anaesthetists.

## 5. Summary.

Complaints of movement and of overcrowding were related to the measured levels of staff movement and occupancy. Entries and exits were shown to lead to more distraction than movements made within the theatre. Some evidence was provided for the view that complaints are related to stress as well as to actual levels of movement and occupancy.

## 6. 3. Variation of air velocity.

### 1. Introduction.

Bedford and Warner (1939) showed that the 'variability' of air velocity was an important factor in causing sensations of freshness in summer. A common complaint in theatres is of lack of freshness, or



stuffiness, in spite of high rates of air change. It would be of interest to know if these complaints were due to insufficient variability of the air velocity.

## 2. Method.

The method of measuring air velocity described in Section 3 resulted in the longest records of air velocity being obtained at head height at the table, since the radiometer took at least two or three minutes to reach equilibrium under the lamp. During these periods, the air velocity was sampled at four second intervals, twice in twenty seconds. Records having at least six values of air velocity recorded in sequence were selected, and those showing a systematic trend were discarded. About 500 sets of readings satisfied the conditions, and over 1600 sets of responses could be related to them, none from anaesthetists. Preliminary examination showed that the distribution of air velocity readings about their mean when measured at such short intervals was not even approximately normal, in many cases being clearly bimodal. The standard deviation did not therefore seem an appropriate measure of 'variability'; Bedford and Warner had used the mean variation, and this practice was followed. Deviations from the mean, regardless of sign, were measured, and their average taken as an estimate of the mean variation. This quantity has the merit that it is linearly related to the difference between the two most common values in a bimodal distribution; it is arguably this difference that is detected as 'variability' in a turbulent air stream.

The mean variation in feet per minute, was recorded for 1600 cases,

and transferred to the Z-card as described in Section 4. An attempt was then made to relate the mean variation to other variables and to subjective responses, within the reduced sample.

### 3. Results.

The average value of this measure of variability was 4.3 feet per minute, about 20% of the mean air velocity. Table 6. 3. 1. gives the correlation matrix obtained. Following Bedford and Warner, the mean variation of air velocity was calculated alternatively as a fraction of the mean air velocity during that run of measurements. This additional variable appears also in the matrix. It does not appear to be correlated significantly with sensations of stuffiness, thermal comfort at head height, or the observed forehead sweating, whereas the mean variation of air velocity itself shows significant negative correlation with all three. However, this could be explained either by the significant positive correlation of the measure with air velocity itself, or by the significant negative correlation of the measure with temperature. In fact, when temperature, vapour pressure and the air velocity are held constant, the partial correlation of the mean variation of air velocity with sensations of stuffiness is reduced from  $-0.061$  to  $-0.016$ , which is not significant. The partial correlation with observed forehead sweating is similarly reduced to non-significance. Only in the case of the thermal sensation at head height, for which the influence of air velocity has been shown in Section 5.1. to be quite negligible, does the partial correlation coefficient of mean variation of air velocity, with temperature and vapour pressure held constant, remain significant with a value of

-0.051. Table 6. 3. 3. shows the regression equation obtained. All the coefficients are significant at the 0.05 level. Variation of air velocity accounted for less than 0.2% of the total variance. As shown in Table 5. 1. 8., a doubling of the mean variation would have less effect than a drop of 1.F.<sup>o</sup> in air temperature.

#### 4. Discussion.

The measured variability corresponds to that of a 'badly ventilated room' in the data of Bedford and Warner; they were unable to show an effect of variability of air velocity in winter, when windows were commonly closed. It is thus not surprising that the occupants of operating theatres, with very much less skin exposed, are only very slightly affected by the variability of the air velocity. The measured variability of 4 feet per minute is well below the threshold of perception calculated by Turner (1955) as a result of laboratory experiments on a single subject, which was  $\pm 10$  feet per minute at 40 feet per minute. Perception of changes of air velocity within periods of less than a minute is a reasonable pre-requisite for sensations of freshness to occur, and would explain the present negative findings. However, a significant effect was demonstrated for thermal sensation at head height. A possible reason is that the increased variability of air velocity caused by turbulence is sufficient to disperse at least partially the 'streaming' layer of convected, slow-moving warm air close to the skin. This could probably occur under conditions that did not permit direct perception of changes of air velocity.

## 5. Summary.

The variability of the air velocity as measured by the mean variation accounted for more of the variation in subjective response than did the same quantity expressed as a fraction of the air velocity itself. Apparently significant negative correlations with the sensation of stuffiness and with the observed forehead sweating were reduced to non-significant partial correlations when temperature, vapour pressure and air velocity were held constant. A very small effect on thermal sensation at head height could be demonstrated, and was in the expected direction.

## 6. 4. The effect of temperature variations outside the theatre.

### 1. Introduction.

Although people working in operating theatres do so for several hours at once, and therefore have ample time to adjust physiologically to the thermal conditions encountered outside the theatre might have some effect on their reactions. For example, a warm day outside might lead people to judge theatre temperatures cool by comparison, or conversely might lead them to expect warmer theatre conditions and bias their judgement of the actual theatre temperature in this direction. If this effect were of any magnitude, its direction would be of considerable interest in the question of whether to provide cooling plant for operating theatres. Again, changes occasioned by 'warm spells' of several week's duration are of interest. Seasonal changes, taking place in the course of several months, have been examined in Section 5. 1. and found to exist. The present sub-section examines

the effects of shorter duration variations in external temperature.

## 2. Method.

At some time during each session studied, the temperature of the rest area in the theatre suite was measured. If surgeons rested between operations in one room, and nurses in another, as was sometimes the case, the temperature of each room was recorded and related to the appropriate personal records. A measure of the outside temperature prior to each session was obtained. In the case of morning or all-day sessions, this was usually taken from Meteorological Office readings for 09.00 on that day, while for afternoon sessions, a reading was taken from a window of the suite at the start of the session. Thus the records of outside temperature represent for each person the temperature experienced immediately before entering the theatre suite to change.

In order to identify temperature swings of longer duration, meteorological records were used to calculate for each session the mean 09.00 temperature over the preceding eighteen days.

Complete records of these three variables were provided for 2327 cases. Their analysis was necessarily carried out by the Z-card method, but in all other respects is similar to that of Section 5.1. in that multiple regression analysis was used to relate theatre conditions and external conditions simultaneously to the thermal responses of subjects.

## 3. Results.

The dependent variables used in the multiple regression analyses were  $T_1$ , the thermal sensation at head height,  $P$ , the observed

forehead sweating, and S, the sensation of stuffiness. Sections 5. 1. and 5. 2. deal with the main factors affecting these responses. Table 6. 4. 1. sets out the results of the present analyses, in which external temperatures were as free to enter the equation in the sequential procedure as were theatre variables. All the coefficients shown exceed twice their standard deviation. Comparison may be made with the corresponding equations obtained from the full data pack for theatre variables only; these are set out in Tables 5. 1. 3. and 5. 2. 1. Again air velocity cannot be shown to have a significant effect, but theatre air temperature, vapour pressure and the radiant excess temperature all enter before the external temperatures. The outside temperature can be seen to affect all three responses and the mean temperature to affect the two verbal responses, while the resting temperature had no significant effect at all. The addition of the external temperatures to the equations accounted for between 0.002 and 0.005 of the total sum of squares. The effects are thus marginal, but they are significantly different from zero at the 0.05 level.

Table 6. 4. 1. sets out the means and standard deviations of the external temperatures. Changes equal to twice the standard deviation are likely to occur quite frequently. In order to illustrate the magnitude of the effects, the change in theatre temperature necessary to produce the same effect as a change of two standard deviations in the external temperature can be calculated from the relative size of the regression coefficients. Thus a change from 42° to 64°F. in outside temperature would produce the same effects on T<sub>1</sub>, P and S as

would increasing the theatre temperature by  $2.0^{\circ}$ ,  $1.8^{\circ}$  and  $1.9^{\circ}\text{F}$ . respectively. A change from  $40^{\circ}$  to  $58^{\circ}\text{F}$ . in the mean temperature for the preceding eighteen days would produce the same effects on T1 and S as would decreasing the theatre temperature by  $1.0^{\circ}$  and  $1.6^{\circ}$  respectively.

#### 4. Discussion.

Comparison of the theatre temperature with that experienced only minutes earlier while resting between operations evidently had no effect on subjective responses or forehead sweating.

The outside temperature experienced a matter of hours earlier tended to influence both subjective response and observed forehead sweating. Higher outside temperatures led to more complaints of heat and stuffiness in the theatre, and to increased forehead sweating.

Changes in the outside temperature lasting several weeks did not affect forehead sweating, but did affect subjective responses. Higher mean temperatures outside the theatre led to decreased complaints of heat and stuffiness, possibly due to habituation. It is interesting that when the time scale is again extended, to take account of the temperature variations over several months that are associated with the seasons of the year, the effect is reversed. (Section 5. 1. showed that complaints of heat were more frequent and forehead sweating more profuse in summer even when the actual theatre temperature was held constant.) However, these effects of external temperature were always small and of somewhat doubtful significance.

## 5. Summary.

Temperature variations outside the theatre were shown to have only marginal effects on subjective responses and forehead sweating. However, marginally significant effects were shown to exist, their direction dependent upon the time scale of the temperature variations outside the theatre.

## 6. 5. The effect of clothing.

### 1. Introduction.

The clothing worn by the members of a surgical team is highly standardised. Cotton shirt, trousers and gown for men, cotton dress and gown for women are always supplied, and nowadays are nearly always worn. Nevertheless, some variation is possible in that an apron may be worn as well, anaesthetists may leave off their gown (or wear two), and extra items of clothing may be worn beneath the standard theatre clothing. The present sub-section reports an attempt to discover whether variations in clothing had any measurable influence on the reactions of operating theatre staff to their environment.

### 2. Method.

The clothing worn by each person questioned in the survey was determined by observation and by interview, and written down. At a later stage this was reduced simply to a figure for the number of layers of clothing worn and a figure taking the value 0 or 1 according to whether an apron was worn. This decoding was done by computer program, and the two measures included on the Z-card, which is why these results appear in Section 6. A number of sequential multiple



regression analyses were performed with response measures as the dependant variables and the two clothing measures as independent variables, free to enter the equations in the usual way.

### 3. Results.

The mean number of layers of clothing was 2.3, and an apron was worn by 11% of the sample questioned. That women tended to wear more clothing and anaesthetists less clothing was shown by the correlation coefficients of 0.599 and - 0.244 respectively. Both were obtained from 2553 pairs, and are highly significant.

In studying thermal sensation and observed forehead sweating, deviation from the predicted value was made the dependent variable. No significant effects could be shown. However, the following equation was obtained for the S-vote, the sensation of stuffiness, as discussed in Section 5. 2.:

$$\text{S-vote} = 0.052.N - 0.119.A + 0.068 T_I - 1.730$$

where  $N$  = No. of layers of clothing.

$A$  = 1 if apron worn, otherwise 0.

$T_I$  = Index Temperature at head height, as defined in Section 5. 1. and calculated from the equation in Table 5. 1. 9.

The multiple correlation coefficient was 0.428, but the clothing variables accounted for only 0.63% of the variance. All three regression coefficients are highly significantly different from zero, exceeding three times their standard error. Each layer of clothing was thus equal to an increase of 0.75°F. in terms of its

effect on the S-vote, whereas wearing an apron was associated with a reduced sensation of stuffiness equal to that produced by a drop of 1.75°F. in Index Temperature.

In Section 8 the results of similar analyses of the objectively measured responses are given. It is shown that clothing affected the upper-arm sweat rate, but not the forehead sweat-rate or the measured skin temperature.

#### 4. Discussion.

It is perhaps surprising that clothing can be shown to have so little effect on thermal sensations. However, clothing differences can be seen as a means to decrease inter-individual variation in thermal preference. Those habitually cold would wear more clothing, and vice versa. If carried out successfully, this policy would result in variations of clothing cancelling out individual differences; neither would have any apparent effect on thermal sensation. An approximation to this situation apparently exists, taking together the results of this section and those of Section 7, where inter-individual differences are shown to be small in comparison with differences between occasions. However, two identifiable classes of individual are clearly failing to clothe themselves adequately; women do wear more clothes than men, but feel slightly cooler, as shown in Section 5. 1. Anaesthetists wear less clothing than other staff categories and feel very much cooler. The implication is clear.

#### 5. Summary.

The effects of variation in clothing are shown to be extremely small. It is suggested that clothing variations are being used

near-optimally to compensate for individual differences, with the notable exception of anaesthetists, who wear less clothing and feel much cooler.

Table 6. 1. 1. Correlation coefficients with noise levels and N-vote.

| <u>Variable</u>   | <u>Base noise level</u> | <u>80% noise level</u> | <u>N-vote</u> |
|-------------------|-------------------------|------------------------|---------------|
| Index Temperature | 0.234                   | 0.223                  | NS            |
| Difficulty        | NS                      | -0.078                 | NS            |
| Mistakes          | NS                      | 0.056                  | NS            |
| Complications     | NS                      | NS                     | 0.065         |
| Tension           | NS                      | -0.133                 | NS            |
| Tempo             | 0.109                   | 0.141                  | NS            |
| <hr/>             |                         |                        |               |
| Base noise level  | 1.0                     | 0.661                  | 0.114         |
| 80% noise level   | 0.661                   | 1.0                    | 0.141         |

Note: All coefficients are based on 2221 pairs;  
values greater than 0.055 are thus significant  
at the 0.01 level.

Table 6. 2. 1. M-vote and status: Chi-square for Independence.

| <u>Observed (Expected) Frequencies</u> |                        |                  |                    |                     |               |
|----------------------------------------|------------------------|------------------|--------------------|---------------------|---------------|
|                                        | <u>Status category</u> |                  |                    |                     |               |
|                                        | <u>Surgeon</u>         | <u>Assistant</u> | <u>Scrub-Nurse</u> | <u>Anaesthetist</u> | <u>Totals</u> |
| 0                                      | 446                    | 490              | 504                | 432                 | 1872          |
| M-vote                                 | (427)                  | (471)            | (524)              | (448)               |               |
| 1                                      | 149                    | 166              | 226                | 192                 | 773           |
|                                        | (168)                  | (185)            | (206)              | (176)               |               |
| <hr/>                                  |                        |                  |                    |                     |               |
| TOTALS                                 | 595                    | 656              | 730                | 624                 | 2605          |
| <hr/>                                  |                        |                  |                    |                     |               |
| MEAN M-VOTE                            | 0.251                  | 0.253            | 0.310              | 0.308               | 0.282         |

$$\chi^2_{(3)} = 10.43 \quad (0.01 < P < 0.02)$$

Table 6. 2. 2. O-vote and status: Chi-square for Independence.

| <u>Observed (Expected) Frequencies</u> |                |                  |                    |                     |               |      |
|----------------------------------------|----------------|------------------|--------------------|---------------------|---------------|------|
| <u>Status Category</u>                 |                |                  |                    |                     |               |      |
|                                        | <u>Surgeon</u> | <u>Assistant</u> | <u>Scrub-Nurse</u> | <u>Anaesthetist</u> | <u>Totals</u> |      |
| O-Vote                                 | 0              | 459              | 485                | 501                 | 463           | 1908 |
|                                        |                | (436)            | (476)              | (536)               | (460)         |      |
|                                        | 1              | 127              | 156                | 220                 | 155           | 658  |
|                                        |                | (150)            | (165)              | (185)               | (158)         |      |
| <hr/>                                  |                |                  |                    |                     |               |      |
| TOTALS                                 | 586            | 641              | 721                | 618                 | 2566          |      |
| <hr/>                                  |                |                  |                    |                     |               |      |
| MEAN O-VOLE                            | 0.217          | 0.244            | 0.305              | 0.251               | 0.257         |      |
| <hr/>                                  |                |                  |                    |                     |               |      |

$$\chi^2_{(3)} = 14.37 \quad (P < 0.01)$$

Table 6. 2. 3. Correlation Matrix for Movement and Occupancy data.

Based on at least 1100 pairs (at least 2200 pairs when underlined), the coefficients are significant at the 0.01 level, except for those in brackets, which are significant at the 0.05 level.

|                   | <u>Entries and Exits</u> | <u>Movement Within</u> | <u>No. in Theatre</u> | <u>M-vote</u> | <u>O-vote</u> |
|-------------------|--------------------------|------------------------|-----------------------|---------------|---------------|
| Entries and Exits | 1                        |                        |                       |               |               |
| Movement within   | 0.377                    | 1                      |                       |               |               |
| No. in theatre    | 0.187                    | 0.153                  | 1                     |               |               |
| M-vote            | 0.092                    | NS                     | 0.200                 | 1             |               |
| O-vote            | NS                       | 0.082                  | 0.229                 | 0.517         | 1             |
| Base noise level  | NS                       | -0.144                 | NS                    | (0.054)       | (0.052)       |
| 80% noise level   | 0.189                    | -0.157                 | NS                    | 0.077         | 0.063         |
| N-vote            | 0.084                    | NS                     | 0.119                 | 0.314         | 0.283         |

Table 6. 2. 4. Regression equation for the M-vote

| <u>Variable</u>                                              | <u>Coefficient</u> | <u>Regression sum<br/>of squares</u> |
|--------------------------------------------------------------|--------------------|--------------------------------------|
| Entries and Exits (per hour)                                 | 0.00066            | 0.0085                               |
| Surgical assistant (0 or 1)                                  | -0.085             | 0.0144                               |
| Difficulty (0, 1 or 2)                                       | 0.043              | 0.0192                               |
| Tempo (0, 1 or 2)                                            | 0.048              | 0.0225                               |
| Temperature (°F)                                             | 0.008              | 0.0249                               |
| Air Velocity((feet per minute) <sup>1</sup> / <sub>2</sub> ) | 0.026              | 0.0294                               |
| Constant                                                     | -0.641             |                                      |
| <hr/>                                                        |                    |                                      |
| Multiple Correlation Coefficient                             | 0.171              |                                      |

$$F(6, 1197) = 6.042$$

All regression coefficients are significant at the 0.05 level.



Table 6. 2. 5. Regression Equation for observed sweating.

Dependent variable:  $(P - P(P))$ , the deviation of observed sweating from calculated sweating - see Section 5. 1.

| <u>Variable</u>                  | <u>Coefficient</u> | <u>Regression sum of squares</u> |
|----------------------------------|--------------------|----------------------------------|
| Entries and Exits (per hour)     | -0.0015            | 0.0020                           |
| Movements within (per hour)      | 0.0005             | 0.0040                           |
| Tension (0, 1, 2)                | 0.10               | 0.0104                           |
| Difficulty (0, 1, 2)             | 0.05               | 0.0149                           |
| Constant                         | -0.1555            |                                  |
| <hr/>                            |                    |                                  |
| Multiple Correlation Coefficient | 0.122              |                                  |
| <hr/>                            |                    |                                  |

$$F(4, 1199) = 4.538$$

All coefficients are significant at the 0.05 level.

( This result is also shown in Table 5. 1. 8.)

Table 6. 3. 2. Regression equation for thermal sensation at head height.

Dependant variable:  $T_1$ -vote

| <u>Variable</u>                        | <u>Coefficient</u> | <u>Regression sum of squares</u> |
|----------------------------------------|--------------------|----------------------------------|
| Temperature, °F.                       | 0.116              | 0.2178                           |
| Vapour pressure, mm.Hg.                | 0.083              | 0.2475                           |
| Mean variation, air velocity,<br>fpm.  | -0.023             | 0.2494                           |
| Constant                               | -5.398             |                                  |
| <hr/>                                  |                    |                                  |
| Multiple Correlation Coefficient 0.499 |                    |                                  |
| <hr/>                                  |                    |                                  |

$$F ( 3, 1615 ) = 178.9$$

Table 6. 3. 1. Correlation Matrix for Variation of Air velocity.

Based on 1619 pairs, correlation coefficients greater than 0.065 are significant at the 0.01 level. Those greater than 0.050 are significant at the 0.05 level.

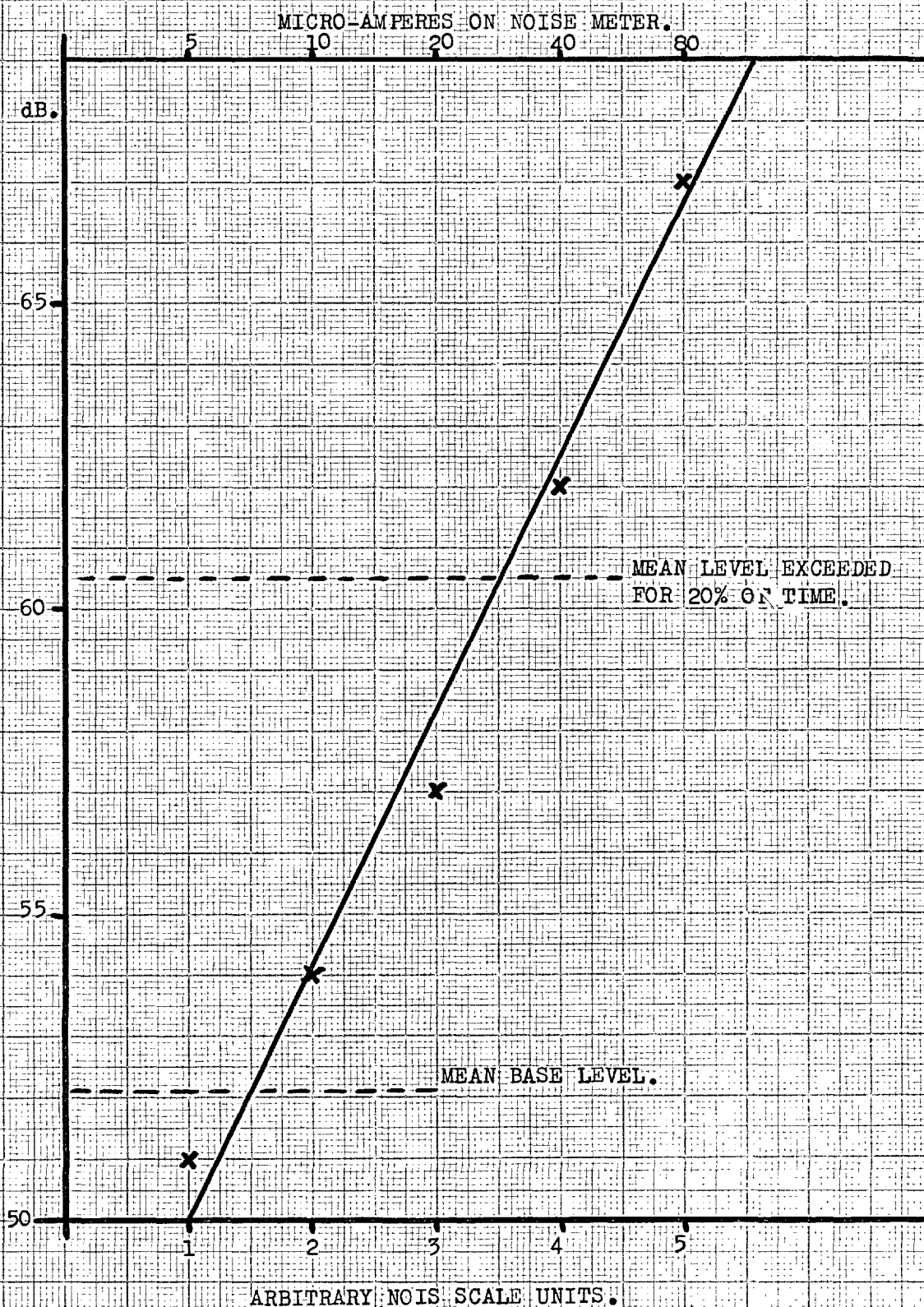
|                                             | <u>T</u> | <u>V.P.</u> | <u><math>\sqrt{V}</math></u> | <u>Var(v)</u> | <u>Var(v)/v</u> | <u>S</u> | <u>T<sub>1</sub></u> | <u>P</u> |
|---------------------------------------------|----------|-------------|------------------------------|---------------|-----------------|----------|----------------------|----------|
| Temperature T                               | 1        |             |                              |               |                 |          |                      |          |
| Vapour Pressure<br>V.P.                     | 0.256    | 1           |                              |               |                 |          |                      |          |
| (Air velocity) <sup>1/2</sup><br>$\sqrt{V}$ | -0.210   | -0.260      | 1                            |               |                 |          |                      |          |
| Mean variation,<br>Var (v)                  | -0.106   | 0.219       | 0.517                        | 1             |                 |          |                      |          |
| Var (v)/v                                   | 0.112    | NS          | -0.373                       | 0.503         | 1               |          |                      |          |
| S-vote                                      | 0.374    | 0.216       | -0.073                       | (-0.061)      | NS              | 1        |                      |          |
| T <sub>1</sub> -vote                        | 0.467    | 0.286       | -0.141                       | -0.127        | NS              | 0.600    | 1                    |          |
| P - (observed<br>sweating)                  | 0.243    | 0.200       | -0.073                       | (-0.061)      | NS              | 0.239    | 0.352                | 1        |

Table 6. 4. 1. The effect of temperature variations outside the theatre.

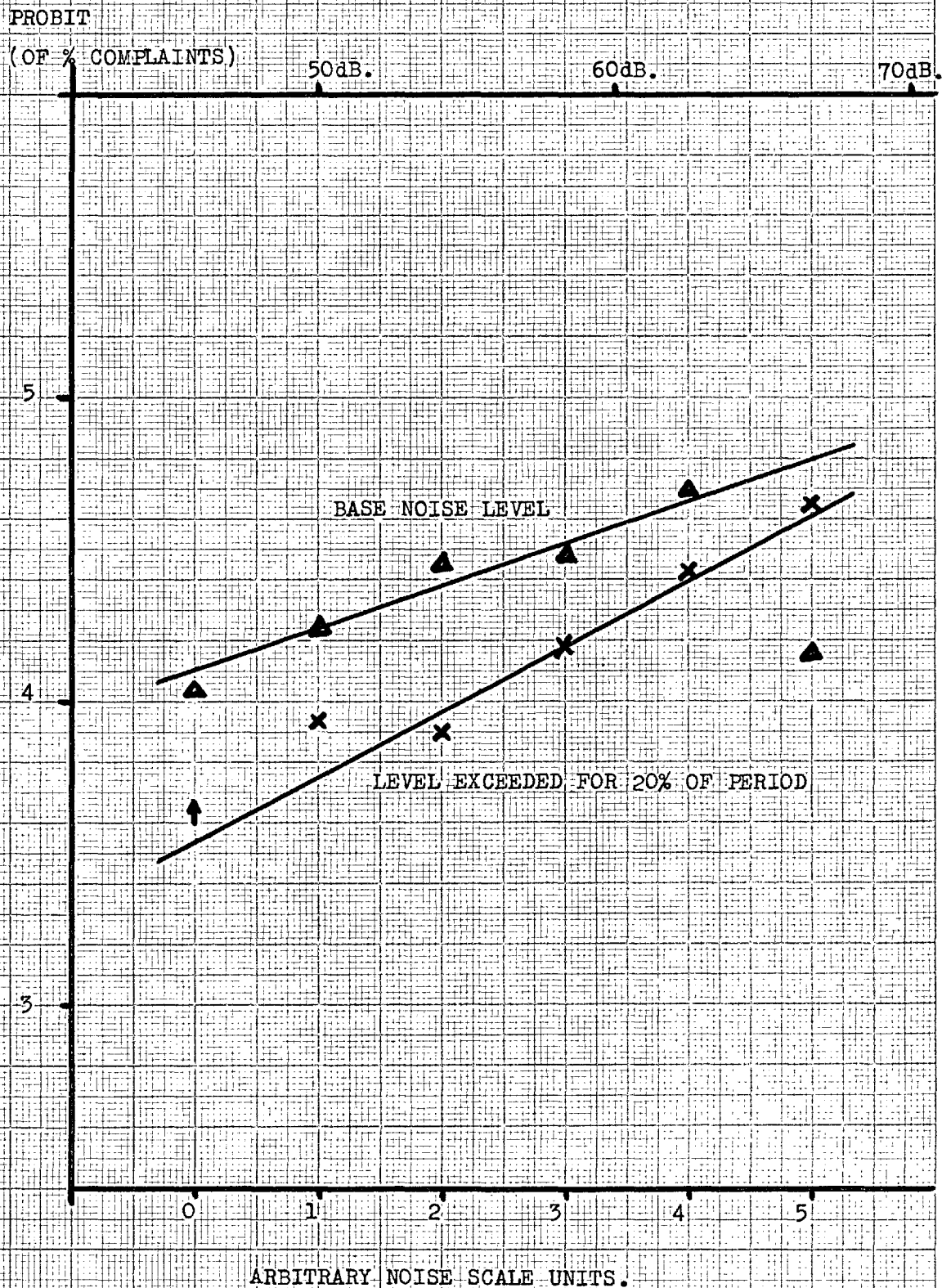
Data from a sub-sample of 2327 cases.

| <u>Variable</u>                        | <u>Mean</u> | <u>S.D.</u> | <u>Coefficient of regression equations</u> |          |          |
|----------------------------------------|-------------|-------------|--------------------------------------------|----------|----------|
|                                        |             |             | <u>T<sub>1</sub></u>                       | <u>P</u> | <u>S</u> |
| T (Head) °F.                           | 73.0        | 4.1         | 0.122                                      | 0.037    | 0.057    |
| V.P. mm.Hg.                            | 10.2        | 2.3         | 0.060                                      | 0.028    | 0.037    |
| Rad. Excess °F.                        | 5.9         | 3.7         | 0.038                                      | 0.024    | 0.012    |
| T (Outside) °F.                        | 52.6        | 11.0        | 0.011                                      | 0.003    | 0.005    |
| T (Mean) °F.                           | 48.6        | 8.9         | -0.007                                     | -        | -0.005   |
| T (Rest) °F.                           | 71.4        | 3.5         | -                                          | -        | -        |
| Constant in regression equation        |             |             | -6.293                                     | -2.687   | -1.295   |
| Multiple Correlation Coefficient       |             |             | 0.516                                      | 0.331    | 0.420    |
| Proportion of variance: due regression |             |             | 0.266                                      | 0.109    | 0.176    |
| due external conditions                |             |             | 0.005                                      | 0.002    | 0.003    |

GRAPH 6.1.1. RELATION OF NOISE SCALE UNITS TO dB. SOUND PRESSURE.  
(re 0.0002 dynes/cm<sup>2</sup> at 1500 Hz.)



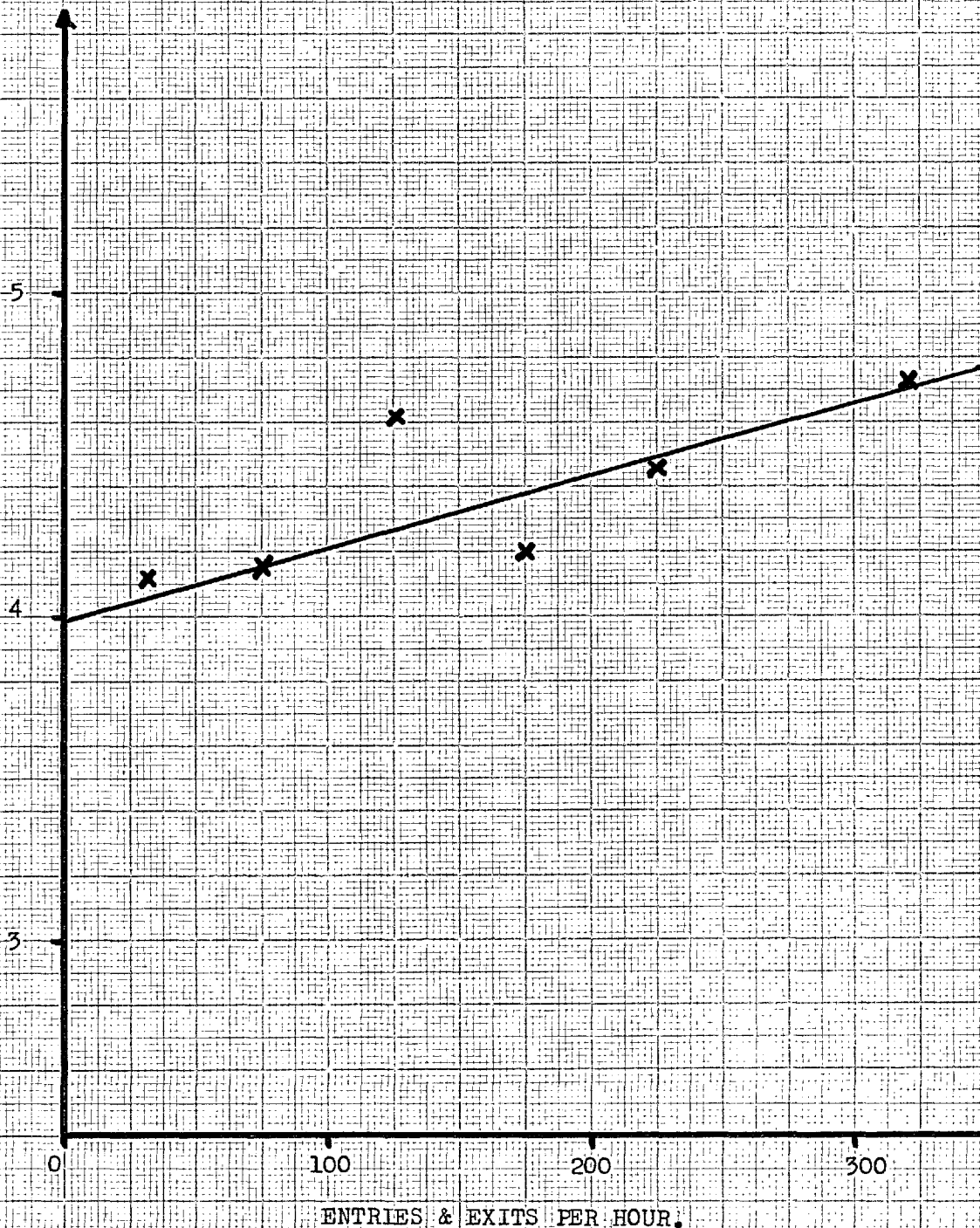
GRAPH 6.1.2. PROBIT OF NOISE VOTE v. NOISE LEVELS.

(Regression lines are calculated and refer to all staff.)

GRAPH 6.2.1. M-VOTE v. ENTRIES & EXITS PER HOUR.

(Based on 1204 replies from all staff categories.)

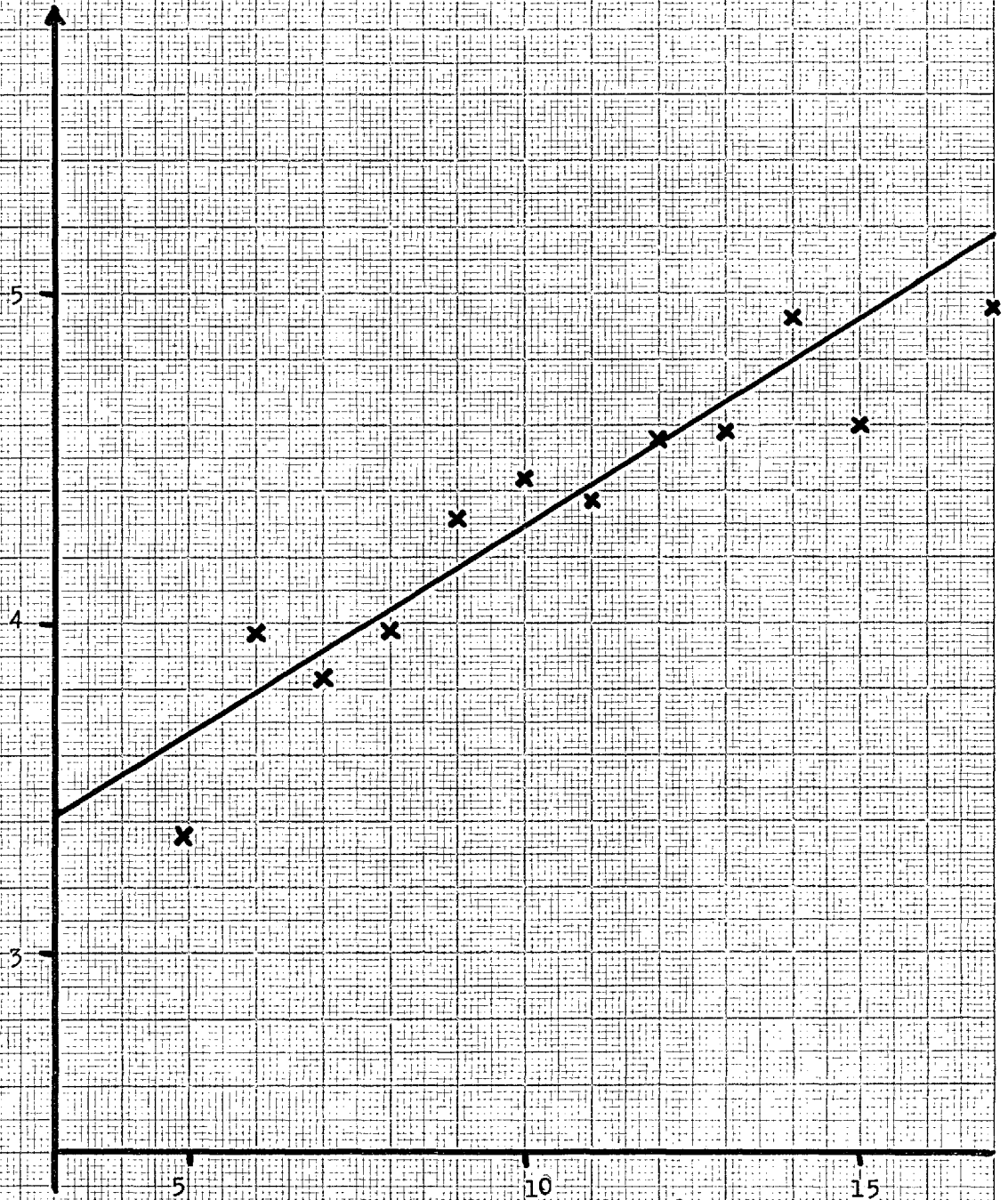
PROBIT ( OF % COMPLAINTS OF "TOO MUCH MOVEMENT" )



GRAPH 6.2.2. O-VOTE v. No. PEOPLE IN THEATRE.

(Based on 1210 replies from all staff categories.)

PROBIT ( OF % COMPLAINTS OF OVERCROWDING )



NUMBER OF PEOPLE IN THEATRE ( EVEN IF ONLY BRIEFLY )



SECTION 7.

INDIVIDUAL DIFFERENCES

## 1. Introduction.

In the foregoing sections of this thesis, the basic unit has been the response obtained from a particular person on a particular occasion. No attempt has been made to relate to each other the responses obtained at a particular hospital, or during a particular session, though in the latter case they have all been related to the same session details. Similarly, no attempt has been made to relate to each other all the responses obtained from a particular person on different occasions, though they have naturally been related to the same personal details. Reasons for this approach have been given in Section 3. The resulting regression equations have not accounted for more than 33% of the variance, even when all the measured variables were considered.

It seemed possible that the residual variation might contain a component attributable to consistent inter-individual differences, governed by factors not susceptible to the available methods of measurement. Sex, age, race and build have all been shown to have significant effects, though small in magnitude. More subtle physiological or even psychological differences could conceivably lead to consistently biased responses. If these were of appreciable magnitude, they could render the calculated variability unduly pessimistic when applied to successive occasions for the same people. It was therefore decided to examine the consistency of individuals' responses.

## 2. Method.

The practice of questioning subjects at roughly two-hour intervals,

together with the two repeat visits to each operating suite, resulted in 632 of the total of 1094 subjects being questioned more than once. From the 267 subjects questioned twice to the five who were questioned ten times, they gave in all 2092 units for analysis. In order to eliminate the variations due to thermal factors, the predicted response for thermal comfort at head height,  $T_1$ , was generated for each unit, using the equation shown in Table 5. 1. 9. This equation was used in the calculation of predicted response in Section 6. It involves temperature, vapour pressure and radiant excess temperature measurements, and contains an adjustment to the constant for anaesthetists. The multiple correlation coefficient on the full body of data, from which it was derived, was 0.516.

For each unit, the deviation of the actual  $T_1$  response from the predicted response was obtained. For each person, the mean of this quantity was derived, and also the sum of squares of deviations about the mean. This procedure amounts to a partition of the deviation about the regression into components due to what might be called personal bias and to residual variation respectively. For all 2092 units, the total sum of squares of deviations about the various personal means was obtained, together with the total sum of squares of the actual  $T_1$  responses and the total sum of squares due to the regression. These calculations make possible the partition of variance.

Personal details such as sex, age, race, build and height were correlated with the figure for mean personal bias for each person in an attempt to discover the origin of such bias if it should prove significant. Similarly, personal details were correlated with the

calculated variance about each personal mean, based on differing degrees of freedom.

### 3. Results.

The partition of variance obtained by the above methods is shown in Table 7.1. The regression is of course highly significant, as has been shown in Section 5. 1. The F-test for personal bias, or individual differences, is made against the residual, and is significant beyond the 0.001 level. However, the root mean square between individuals is only 1.32 times the residual root mean square, and the proportion of variance absorbed by the regression for repeated observations on the same individual only rises from 27% to 38% ( $714/(714 + 1148)$ ), corresponding to a correlation coefficient of 0.62.

Table 7. 2. shows the correlation coefficients obtained, together with their level of significance. The remainder were not significant.

### 4. Discussion.

Reference to Table 5. 1. 5. shows that multiple regression analysis involving all measured variables identified only thermal variables, age and status as having significant effects on the T<sub>1</sub>-vote. No more than 27% of the variance could be attributed to the regression. Individual differences other than those measured thus appear to account for a further 11% of the variance, leaving 62% of the variance attributable to residual variation between occasions. Thus even repeated experiment on the same individuals would not greatly increase the reliability of the predicted responses. The choice of a person-occasion as the basic unit for the main analysis is thus

justified. The results can be taken to apply to any randomly selected team, with the proviso that in certain cases the variability between occasions will be marginally less than the variability between persons.

Davis et al. (1965) have reported correlation coefficients of 0.9 and above for repeated measurements on single individuals, but the thermal conditions and especially the activity of their subjects were very highly standardised. A great deal of the variation between occasions in the present survey can surely be attributed to differences between the work performed on different occasions. Although attempts were made to measure these differences in terms of the nominal difficulty of operations, the tempo of work and the tension in the theatre, the complications encountered and the mistakes made (see Table 5. 1. 8.), such variables are very difficult to quantify and only marginally significant results were obtained. The true situation is one of complex interaction between personal abilities, experience and attitudes on the one hand, and degrees of technical difficulty and of risk too subtle to measure on the other.

The marginally significant correlation coefficients obtained in Table 7. 2. show that taller people tended to complain less of heat than shorter people. This effect is probably included in the effect of build in Table 5. 1. 5, but could not be shown to be significant there. They show also that older people were more consistent in their responses, and scrub-nurses were less consistent. These findings are in accord with subjective impressions at the time.

##### 5. Summary.

Individual differences have been shown to have a significant effect on thermal response at head height. However, in the theatre situation, variation between people was very much less than the variation between occasions for the same person. This result is contrary to some recently reported findings for sedentary office work.

Table 7. 1. The significance of individual differences.Dependant variable:  $T_1$ , thermal response at head height

| <u>Source of Variation</u>                | <u>Sum of Squares</u> | <u>Degrees of Freedom</u> | <u>Mean Square</u> | <u>F</u> |
|-------------------------------------------|-----------------------|---------------------------|--------------------|----------|
| Regression                                | 714                   | 4                         | 178.5              | 184.7    |
| Deviation about Regression                | 2018                  | 2087                      | 0.97               |          |
| <u>Components of the above deviation:</u> |                       |                           |                    |          |
| Between persons                           | 870                   | 631                       | 1.38               | 1.75     |
| Residual                                  | 1148                  | 1456                      | 0.79               |          |
| Total                                     | 2732                  | 2091                      | -                  |          |

Note:  $F(631, 1456) = 1.23$  at the 0.001 levelTable 7. 2. Correlations with personal bias and variability

Based on 632 pairs

| <u>Variable 1</u> | <u>Variable 2</u>                                  | <u>Correlation Coefficient</u> | <u>P</u> |
|-------------------|----------------------------------------------------|--------------------------------|----------|
| Height            | Mean personal deviation from predicted $T_1$ -vote | - 0.091                        | < 0.05   |
| Age               | Variance about above mean                          | - 0.103                        | < 0.01   |
| Scrub-nurse       | Variance about above mean                          | 0.094                          | < 0.05   |

SECTION 8.

OBJECTIVE MEASUREMENTS OF RESPONSE.



## 1. Introduction.

The results reported in this thesis rely extensively on subjective estimates by the subject of his own sensations, and on subjective estimates by the observer of forehead sweating. In order to support the validity of these estimates, a limited number of objective measurements of response were desirable. These had to remain subsidiary to the main investigation, and to be carried out within the existing framework of data collection. As this was one of brief encounters with large numbers of subjects, it was not ideal for the collection of objective physiological data. However, the reasons given in Section 3 were sufficient to justify the method adopted.

A number of physiological measures were considered for a limited investigation to be carried out concurrently with the main survey of thermal sensation, among them pulse rate, body temperature, total fluid loss, skin temperature and local sweat rate. As detailed in Section 1, the work of Robinson, Turrell and Gerking (1945) indicated that the pulse rate and body temperature of subjects would not increase significantly until the air temperature reached 82°F, regardless of the relative humidity. The figures in Table 5. 1. 1. indicate that this temperature was reached on less than 1% of occasions in the present survey. In addition, continuous recording would have been necessary to achieve a sufficient sensitivity of measurement, and it was considered that this would involve an unacceptable interference with the freedom of movement of surgeons in the present survey. Similarly, the measurement of total fluid loss was considered impracticable in

the present survey. It would have involved transporting a heavy, sensitive weighing machine, whose accuracy would suffer as a result, and the process of being weighed naked before and after an operation would have been unacceptable to most surgeons performing routine work in their own hospitals. Measurement of skin temperature and local sweat rate presented fewer practical difficulties. Houghten and Cook (1939) found that the observed forehead sweating was a sensitive index of thermal conditions in an operating theatre; preliminary results from the present survey supported the inference that quantitative measurement of forehead sweat rates would be worthwhile. Kuno (1934) showed that although both forehead and trunk sweating were influenced by thermal stress, the forehead sweat rate responded much more to emotional stimuli. A comparison of the two was considered desirable in the present case.

Skin temperature has been shown by many workers to be a sensitive index of thermal conditions, though Bedford (1964) showed that it was no more closely related to thermal sensation than was air temperature. It was decided to obtain measures of the skin temperature and local sweat rate of surgeons and their assistants during the final year of data collection.

## 2. Method.

In order to obtain a meaningful measure of the skin temperature produced by thermal conditions during an operation, it was necessary to take a reading immediately the operation finished and before the subject left the theatre. Only the skin of the forehead and the back of the neck is exposed by surgical clothing, and the forehead was found to be nearly always damp with sweat. Thus the dry skin available for

measurement of skin temperature for the present purpose was effectively that between the collar of the gown and the hair line. An alternative would have been to fix sensing elements to the skin beneath the clothes, and bring out leads to permit immediate measurement. This was considered to involve unacceptable interference with the surgeons' routine before an operation, when time is usually rather short. Using a thermistor-in-glass probe and a battery-powered bridge circuit for measurement of the resistance, the dial calibrated directly in Fahrenheit degrees, it was found to be possible to obtain a reliable reading of skin temperature on the back of the neck in under ten seconds. The tip of the probe was stroked slowly over the skin surface, using insufficient pressure to indent the skin or to cause any heating of the tip by friction. The instrument is manufactured commercially as the 'Dependatherm' clinical thermometer. The version used had two ranges, covering temperatures from 70-110°F.

Measurements of local sweat rate on the forehead and on a control site beneath the clothes were required. For the latter, the inside of the upper arm was chosen as being representative of trunk sweat rates and readily accessible; the shirts worn in operating theatres have short sleeves, and the measuring device could be fixed just prior to an operation, before the sterile gown was put on, and removed immediately after an operation, when the gown was removed. A suggestion by Professor Weiner led to the development of lightweight absorptive pads about 2.5 cm. in diameter. A disk of filter paper 18 mm. in diameter was held lightly against the skin surface

by means of a foam rubber disc only slightly larger, secured by a thin elastic strap round the upper arm or round the head. The assembly was held together by means of a central metal rivet, drawn slightly into the foam rubber in order to allow the filter paper to press against the skin. A small central area of skin about 4 mm. in diameter (3% of the total area) was thus not in contact with the filter paper; the effective area in contact was then 3.75 cm.<sup>2</sup> An assembly is shown in Fig. 8. 1. These, less the elastic strap, were prepared and placed in moisture-tight weighing bottles, numbered and weighed to the nearest tenth of a milligram. They were transported in a sealed plastic box, and returned to it after use. They were re-weighed on the same balance at the conclusion of a visit, usually about four days after the initial weighing. The weighing bottles in a box were treated as a batch and the accuracy of measurement was controlled by re-weighing also the unused bottles. Only changes in weight significantly different at the 0.05 level from the mean change in weight of the unused bottles in the batch were recorded as being other than zero. This led to changes of up to 5 mg. being rejected on occasion. Discs were exposed for widely different lengths of time, from half an hour to two hours or more, depending on the operations performed. Only surgeons and their assistants took part as subjects, and in the 108 measurements of forehead sweat rate obtained, only three of them were from women. It was not always possible to obtain the readings, due to pressure of work or to operations that were too short. Rather fewer readings of arm sweat rate were obtained, as the discs could become

dislodged by the clothing, or the opportunity to fix the disc before the subject had put on his gown could be missed. Forehead discs could be fitted to a fully gowned and gloved subject without breach of sterile procedure. There were no cases of these discs become dislodged during an operation and surgeons did not find them uncomfortable to wear.

Skin temperature measurements were not made if the subject had left the theatre, as skin temperature can respond very quickly to changes of ambient temperature, and a further source of variation could have been introduced. For this reason, only 74 measurements of skin temperature were obtained.

### 3. Results.

Special summary cards were prepared for each person-occasion, bearing the three readings obtained by the above methods and all relevant data as for the subjective responses. In order to cope with missing data, the cards were arranged into sub-samples which could be grouped to give input packs with no missing data for each of the three independent variables. A different multiple regression program, BMD.03.R., was used, enabling the selection of sub-samples to be made as appropriate. Table 8. 1. shows some of the correlation coefficients obtained in the preliminary stages of the regression calculations. They are significantly different from zero at the 0.01 level unless in parentheses, when they are significant at the 0.05 level. Tests of significance were made using the exact formula given by Fisher (1958), and students' t distribution.

It can be seen that skin temperature was much more closely related to thermal conditions and to thermal sensation than were sweat rates.

Observed forehead sweating was less well correlated with measured forehead sweating than one might have expected. Reasons for this are given in the discussion. The direction of the status effect was such that assistants tended to have lower arm sweat rates than did surgeons. However, as in the main analysis, all the independent variables were highly inter-correlated, and multiple regression analysis is required.

Tables 8. 2. - 8. 4. give the results of the three analyses. All regression coefficients listed are significantly different from zero at the 0.05 level. The level of significance of the regression sum of squares is given in the last line of each table. Column 1 gives the nature of the variable and the units of measurement; Column 2 gives the mean value obtained in the sample; Column 3 gives the partial correlation coefficient of each variable with the dependant variable, all other independent variables in the equation being held constant; Column 4 gives the regression coefficients in the derived equation; Column 5 gives the proportion of variance attributable to the regression at each step in the sequential procedure. Although in the program used the variables were added to the equation in the order specified by the user, inspection of the partial correlation coefficients indicates that this was not markedly different from the logical order used in the main analysis, in which at each step the variable added was the one making the greatest reduction in the residual sum of squares.

Table 8. 2. shows that an increase in Effective Temperature of about  $4\frac{1}{2}^{\circ}\text{F.}$  was necessary to produce the same forehead sweat rate in

assistants as in surgeons. The multiple correlation coefficient was 0.331. Table 8. 3. shows that the difference in arm sweat rate between surgeons and assistants was equivalent to a change of about  $7.4^{\circ}\text{F}$ . Effective Temperature, and that successive layers of clothing compensated for decreases in Effective Temperature of about  $6^{\circ}\text{F}$ . The multiple correlation coefficient was 0.461.

Table 8.4. shows that age, not status, was associated with differences in skin temperature. The partial correlation coefficient of status and skin temperature with age held constant was not significant, whereas with status held constant the effect of age was significant. An age increase of nine years appears to be associated with a decrease of  $0.45^{\circ}\text{F}$ . in skin temperature; the same change could be caused by a decrease of  $1^{\circ}\text{F}$ . in Effective Temperature. At a given Effective Temperature, skin temperatures were between 2 and  $3^{\circ}\text{F}$ . higher in the spring and summer months. Mistakes in procedure, as defined in Section 3, were associated with a significant decrease in skin temperature, equivalent to a decrease of about  $3^{\circ}\text{F}$ . in ambient Effective Temperature. The multiple correlation coefficient was 0.782.

#### 4. Discussion.

It is disappointing that no more than 11% of the variance of forehead sweat rate could be attributed to the regression. However, the fact that this measure was unaffected by clothing and that the mean was twenty times as great as the mean arm sweat rate indicates that forehead sweating was mediated to a much greater extent by emotional

stimuli. Variation of Effective Temperature accounted for about 7 $\frac{1}{2}$ % of the variance of both measures of sweat rate. As suggested in Section 7 in connection with differences in thermal sensation between individuals and between occasions, the greater part of the variation must be caused by interactions between personal abilities and experience on the one hand and levels of technical difficulty and of risk on the other. The fact that surgeons tended to sweat more than their assistants is an indication that the cause was related to responsibility for the operation, but no attempt could be made to measure personal abilities and experience, and only tentative attempts to measure levels of difficulty.

The correlation coefficient between measured and observed forehead sweating was 0.479. The actual forehead sweat rate undoubtedly varies throughout an exposure, particularly if, as seems to be the case, it is mediated by emotional stimuli as well as thermal. The measured sweat rate is a time-average of this variation, whereas the observed sweating is a spot check, usually at the end of an operation. Furthermore, the sweat absorbed on a disc and measured is the total sweat produced and is unaffected by the rate of evaporation, whereas the observed sweating is a measure of the sweat remaining unevaporated on the skin surface. In view of these differences the agreement is satisfactory.

The mean sweat rates on both forehead and arm are rather low. Even though sweating is most profuse on the forehead, the mean forehead sweat rate is only about 25% of the physiological limit of 15.5 mgm/cm<sup>2</sup>/hr.



given by Lfstedt (1966) as an average over the whole body surface area.

The skin temperature measured on the back of the neck seems to be a useful index of thermal conditions. Effective Temperature alone accounted for 30.7% of the variance, corresponding to a correlation coefficient of 0.55. In all, 61% of the variation of skin temperature was attributable to the measured factors, approaching the values found by Ward (1930) for observations on single individuals. Evidently unmeasured emotional factors influence skin temperature very much less than they influence rates of sweating. The mean skin temperature of 88.6°F. for a mean Effective Temperature of 69.3°F. (corresponding to a mean air temperature of about 73°F.) agrees exactly with the mean skin temperature on the hand, 88.5°F., found by Bedford (1964) at this air temperature. Furthermore, the regression coefficient between air temperature and hand skin temperature found by this author was 0.46, in almost exact agreement with the present finding of 0.45 for the back of the neck. The skin temperature on the forehead and on the foot were found to vary quite differently with air temperature in Bedford's survey of about 2000 clothed persons.

Bedford found a correlation coefficient of 0.36 between hand skin temperature and thermal sensation. The present finding of 0.483 for the correlation between back of the neck skin temperature and thermal sensation at head height is a considerable improvement, significant beyond the 0.001 level. The improvement may be due in part to the more standardised clothing worn in operating theatres, and partly to the difference between

thermal response at head height and the overall response used by Bedford. Reference to Table 5. 1. 3. shows that the back of the neck skin temperature was a slightly but not significantly better predictor of thermal sensation than was air temperature alone, but was slightly and significantly worse than was the regression in all thermal variables. Thus, as Bedford concluded, the thermal sensation of an individual can be better estimated from a knowledge of the warmth of the room than from his skin temperature.

The effects on skin temperature of season of the year and of the occurrence of mistakes exactly parallel the effects of these factors on thermal sensation, set out in Tables 5. 1. 5. and 5. 1. 8., supporting the validity of these findings. At a given air temperature, subjects felt hotter in spring and summer, and their skin temperature was in fact higher. When mistakes occurred, subjects felt colder and their skin temperature was lower. This is a striking demonstration of the relevance of subjective reports of sensation to real physiological changes, but no explanation of the mechanism causing these particular changes can be given from the results of the present investigation.

## 5. Summary.

In a limited investigation carried out concurrently with the main survey of thermal sensation, quantitative measurements were made of forehead sweat rate, upper arm sweat rate and of the skin temperature on the back of the neck. These measures of response were found to parallel those of thermal sensation. It was shown that sweating in operating theatres is almost entirely confined to the forehead and is

mediated by emotional rather than thermal stimuli. Skin temperature on the back of the neck was shown to vary as the hand skin temperature in another survey, and to be as closely related to thermal sensation as is the air temperature.

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Fig. 8.1.    The sweat disc assembly described in the text.



Table 8. 1. Correlation Coefficients.

| <u>Variable</u>                   | <u>Response</u>                |                                 |                                    |
|-----------------------------------|--------------------------------|---------------------------------|------------------------------------|
|                                   | <u>Forehead<br/>Sweat Rate</u> | <u>Upper Arm<br/>Sweat Rate</u> | <u>Back of Neck<br/>Skin Temp.</u> |
| Effective Temperature<br>(Head)   | 0.273                          | (0.278)                         | 0.554                              |
| Index Temperature (Head)          | 0.268                          | (0.278)                         | 0.549                              |
| Air Temperature (Head)            | (0.242)                        | (0.234)                         | 0.552                              |
| Thermal { Head, $T_1$             | (0.219)                        | NS                              | 0.483                              |
| Sensation { Body, $T_2$           | (0.224)                        | NS                              | 0.402                              |
| Sensation of Stiffness, S.        | NS                             | NS                              | (0.245)                            |
| Sensation of Humidity, H.         | NS                             | NS                              | 0.418                              |
| Observed Forehead Sweating,<br>P. | 0.479                          | (0.234)                         | NS                                 |
| Status (Surgeon/Assistant)        | NS                             | (-0.232)                        | NS                                 |
| Layers of Clothing                | NS                             | 0.313                           | NS                                 |
| <hr/>                             |                                |                                 |                                    |
| Number of pairs                   | 108                            | 79                              | 74                                 |
| <hr/>                             |                                |                                 |                                    |

Correlation coefficients shown are significant at the 0.01 (0.05) level.

Table 8. 2. Regression equation for Forehead Sweat Rate

| <u>Variable</u>                                    | <u>Sample<br/>Mean</u> | <u>Partial Corr.<br/>Coefficient</u> | <u>Regression<br/>Coefficient</u> | <u>RSQ at<br/>each<br/>step</u> |
|----------------------------------------------------|------------------------|--------------------------------------|-----------------------------------|---------------------------------|
| Forehead Sweat Rate, mg./cm <sup>2</sup> /<br>hour | 3.94                   | -                                    | -                                 | -                               |
| Effective Temperature, °F.,<br>(Head)              | 69.0                   | 0.298                                | 0.7                               | 0.074                           |
| Status (0 or 1)                                    | 0.45                   | -0.194                               | -3.1                              | 0.109                           |
| Constant in regression equation                    |                        |                                      | -43.5                             |                                 |
| Multiple Correlation Coefficient                   |                        |                                      | 0.331                             |                                 |
| F ( 2,105 )                                        |                        |                                      | 6.44                              |                                 |
| Level of Significance                              |                        |                                      | 0.01                              |                                 |

Table 8. 3. Regression Equation for Upper Arm Sweat Rate.

| <u>Variable</u>                               | <u>Sample<br/>Mean</u> | <u>Partial Corr.<br/>Coefficient</u> | <u>Regression<br/>Coefficient</u> | <u>RSQ at<br/>each<br/>step</u> |
|-----------------------------------------------|------------------------|--------------------------------------|-----------------------------------|---------------------------------|
| Arm Sweat Rate, mg./cm <sup>2</sup> /<br>hour | 0.20                   | -                                    | -                                 | -                               |
| Effective Temperature, °F.<br>(Head)          | 68.7                   | 0.259                                | 0.042                             | 0.078                           |
| Status (0 or 1)                               | 0.44                   | -0.299                               | -0.310                            | 0.158                           |
| Layers of clothing                            | 2.35                   | 0.255                                | 0.253                             | 0.213                           |
| Constant in Regression equation               |                        |                                      | -3.140                            |                                 |
| Multiple Correlation Coefficient              |                        |                                      | 0.461                             |                                 |
| F ( 3, 75 )                                   |                        |                                      | 6.75                              |                                 |
| Level of significance                         |                        |                                      | 0.001                             |                                 |

Table 8.4. Regression Equation for Back of Neck skin temperature.

| <u>Variable</u>                     | <u>Sample Mean</u> | <u>Partial Corr. Coefficient</u> | <u>Regression Coefficient</u> | <u>RSQ at each step</u> |
|-------------------------------------|--------------------|----------------------------------|-------------------------------|-------------------------|
| Skin temperature, °F.               | 88.6               | -                                | -                             | -                       |
| Effective Temperature,<br>°F (Head) | 69.3               | 0.672                            | 0.45                          | 0.307                   |
| Spring (0 or 1)                     | 0.11               | 0.522                            | 3.11                          | 0.441                   |
| Summer (0 or 1)                     | 0.19               | 0.449                            | 2.01                          | 0.533                   |
| Mistake (0 or 1)                    | 0.09               | -0.254                           | -1.45                         | 0.579                   |
| Age (years above 25)                | 16                 | -0.272                           | -0.05                         | 0.610                   |
| Constant in Regression equation     |                    |                                  | 57.38                         |                         |
| Multiple Correlation Coefficient    |                    |                                  | 0.782                         |                         |
| F ( 5, 68 )                         |                    |                                  | 21.35                         |                         |
| Level of significance               |                    |                                  | 0.001                         |                         |

SECTION 9.MEASUREMENT OF MANUAL SKILL.



## 1. Introduction

Other sections of this thesis have shown that conditions in operating theatres frequently cause complaints, and can also cause measurable changes in the sweat rates and skin temperatures of those working in them. It would be of great interest to know if performance is also affected, since this is arguably a more important criterion. However, there are grave difficulties in the way of any investigation of surgical performance, firstly in identifying the parameters of such a complex skill, and secondly in measuring them. The organisation of knowledge and experience in formulating the innumerable judgements and decisions of surgery probably constitutes the greater part of a surgeon's skill, and accounts for most of the mental load. A recent review by Wing (1965) shows that no effect of thermal stress on mental performance has ever been shown below 31°C. Effective Temperature, for a four-hour exposure. This level of thermal stress, corresponding to over 95°F. ambient temperature with 60% relative humidity, was not approached in the present survey, but the tasks reviewed by Wing were all very much less complex and difficult than surgery, and it is still possible that lower levels of thermal stress could affect adversely this aspect of the surgical task. However, it was not considered possible to measure mental load in the present survey. In the interests of the patient, secondary task techniques were ruled out, and almost any conceivable technique would also have interfered unacceptably with the primary task of surgery.

A high degree of perceptual-motor skill is also demanded by the

surgical task. It was considered that the physical fatigue of operating might cause this aspect of surgical skill to deteriorate, and that thermal stress might cause the deterioration to be more marked. Since it was not possible to measure perceptual-motor skill during actual operations, it was decided to obtain measures before and after operations. For the reasons set out in Section 1, a pursuit meter task was chosen. The present section sets out the results obtained by this method.

This part of the investigation was subsidiary to the survey of thermal sensation, and was carried out within the framework of brief visits to operating suites. For this reason, it was not always possible to test the same subject on successive days, or to control the thermal conditions. The investigation can only be considered a pilot study, but the results are of some interest.

## 2. Method.

The apparatus was constructed by Dr. O.M. Lidwell. The design was based on the pursuit meter used by Pepler (1952, 1960), with a number of modifications to simulate more closely the task of surgery, an improvement in the method of producing a variable track, and a more flexible method of scoring performance. Fig. 9. 1. shows a general view of the apparatus. The target was a diffuse shadow about 5 cm. long and 2 cm. wide, with a bright line in the centre about 2 mm. wide; it was projected from below onto ground glass, and moved on an arc about 20 cm. long with a radius of 30 cm. The ground glass was evenly illuminated from below with a rather dim red light and was surrounded by a screen as shown. The immediate surround was green. With the apparatus

on a table, subjects stood while attempting to follow the target with a pointer similar to a scalpel, mounted on an arm of 30 cm. radius like the target. The 'blade' could be held within 2 mm. of the ground glass surface to reduce parallax.

The target moved with a velocity averaging about 40 cm./sec., and reversed its direction on average about twice per second. This irregular oscillation was produced by two cams of irregular shape, both linked mechanically to the arm bearing the target, but rotating at slightly different speeds. The resulting movement repeated only after 29 minutes and could not be learnt by the subjects, since their trials were only of two minutes duration.

A brush contact on the target arm moved over a sectored contact plate linked to the arm bearing the following pointer and controlled by the subject. When the following pointer was over the target, electrical contact was made with the centre sector. There were three other sectors on each side, linked in pairs so that a given discrepancy on either side of the target closed the same electrical circuit. These four circuits were linked via a multicore cable to the control unit mounted in the carrying case. A synchronous motor locked onto the mains electric supply frequency drove a commutator generating short pulses at 100 m.sec. intervals, and four relay counters connected to the sector plate circuits thus registered the time for which an error of alignment was maintained. A time delay switch enabled the counting unit to be run for a preset time during a continuous trial.

During each visit to an operating suite, the apparatus was set up

on a trolley or a table close to the theatre, where it usually attracted considerable interest from the surgical team. Surgeons and their assistants who agreed to take part in trials (there was no case of a refusal to do so) were asked to keep the pointer continuously on the target for two minutes. After about ten seconds of practice, the counting unit was run for 50 seconds, the counters read and reset, and the counting unit run again for a further 50 seconds. This took about two minutes in all.

It was intended to collect data from subjects in two groups, group one meeting the trial for the first time before operating and again after operating, group two meeting the trial for the first time after operating and again the next day before operating. With the further conditions that the operations should be quite long ones, and that a range of temperature conditions should be studied, only nine subjects in each group were tested in the course of about six months. A further ten performed the first trial as group two, but did not perform the second trial.

### 3. Results.

A number of measures of performance were tested; the time spent on target, a weighted error score, and the occurrence of large errors. Since they all showed the same trends, it was decided to use time on target, the most unambiguous measure. This was expressed as a fraction of the sample period, which though nominally 50 seconds, in fact varied slightly about this figure. A more accurate measure of the sample period was provided by the total score on all four counters, in units of 100 msec. The time-fraction on target varied between 0.35 and 0.65;

the difficulty of the task had been arranged to ensure that performance would remain in this central range in order to maximise the sensitivity of the measure, after Poulton (1965).

Graph 9. 1. shows the group mean scores for each successive semi-trial, each group consisting of nine subjects. Performance on semi-trials 1 and 3 appears to be constant within each group, but the scores for semi-trials 2 and 4 appear to be sensitive to conditions; subjects in both groups performed better after operating than before. In order to test the significance of this rather unexpected result, Table 9. 1. sets out a non-parametric test of the difference for each individual subject. The level of measurement is assumed to be 'ordered metric' (Siegel 1956) for a Wilcoxon matched-pairs signed-ranks test, but no assumption about the underlying distribution of values is necessary. The probability of the result obtained, under the Null Hypothesis of no difference before and after operating, is 0.0236 for a two-tail test, so the existence and direction of the effect is confirmed at this level of significance.

A further group of ten subjects tested after operating gave group mean scores for semi-trials 1 and 2 that were very close to those of group 2, showing the same tendency to improve within the two-minute trial.

Air temperatures during the operations considered ranged from  $62^{\circ}$  -  $84^{\circ}$  F., with a mean of  $73^{\circ}$  f. Two subjects from group one had experienced temperatures over  $80^{\circ}$ , and four had experienced temperatures below  $72^{\circ}$ . The same was true of group two. An attempt was made to show an effect of temperature between the 'hot' group of four subjects and the 'cold' group of eight subjects; the

trend was again unexpected, in that within-trial improvement tended to be greater after a 'hot' session and before a 'cool' one. This tendency was not significant ( $P = 0.071$  as calculated by Fishers exact probability test, Siegel 1956). The mean exposure time was over  $2\frac{1}{2}$  hours.

#### 4. Discussion.

Welford, Brown and Gabb (1950) have reported a persistent effect of initial condition in a field experiment, and this effect is well illustrated by the results of semi-trials 1 and 3. Teichner and Wehrkamp (1954) obtained negatively accelerated learning curves for their pursuit rotor task, using time on target as the score. Neither group 1 nor group 2 show a tendency to approximate to this result. Evidently the anticipation of a major operation was sufficient to cause a marked decrement both in trial performance and in within-trial learning. Possibly to head the list of operations for the day is not as desirable as it is commonly supposed to be. At least under the conditions studied, surgeons appeared to improve their manual performance after taking part in an operation.

An alternative explanation that must be mentioned is that the anticipation of a major operation might have decreased the motivation of subjects to co-operate in irrelevant scientific research. The extremely short trial period required and the author's subjective impressions at the time of subjects' willingness to co-operate, tend strongly to rule out this explanation, but it remains a possibility. It is difficult to think of a field study that does not suffer from

this or some related disadvantage.

5. Summary.

In a short experiment the manual skill of surgeons and their assistants was measured on a modified pursuit meter. Half of them first performed the test before operating and subsequently after operating, the remainder in the reverse order. Performance was shown to be significantly better after operating than before operating. No effect of thermal stress could be shown.

Table 9. 1. Pursuit meter scores before and after an operating session.Wilcoxon matched-pairs signed-ranks test for significance

| <u>Subject On-target time-fraction</u> |                  |                  |          |                |                       |
|----------------------------------------|------------------|------------------|----------|----------------|-----------------------|
|                                        | <u>Before</u>    | <u>After</u>     | <u>d</u> | <u>Rank of</u> | <u>Rank with less</u> |
|                                        | <u>Operating</u> | <u>Operating</u> |          | <u>d</u>       | <u>frequent sign</u>  |
| 1                                      | 440              | 517              | -77      | -17            |                       |
| 2                                      | 398              | 438              | -40      | -12            |                       |
| 3                                      | 402              | 472              | -70      | -16            |                       |
| 4                                      | 446              | 501              | -55      | -15            |                       |
| 5                                      | 444              | 442              | 2        | 1              | 1                     |
| 6                                      | 300              | 332              | -32      | -11            |                       |
| 7                                      | 451              | 400              | 51       | 14             | 14                    |
| 8                                      | 522              | 528              | -6       | -2.5           |                       |
| 9                                      | 528              | 556              | -28      | -9             |                       |
| 10                                     | 518              | 506              | 12       | 4.5            | 4.5                   |
| 11                                     | 582              | 595              | -13      | -6             |                       |
| 12                                     | 386              | 417              | -31      | -10            |                       |
| 13                                     | 298              | 541              | -243     | -18            |                       |
| 14                                     | 321              | 363              | -42      | -13            |                       |
| 15                                     | 635              | 623              | 12       | 4.5            | 4.5                   |
| 16                                     | 490              | 471              | 19       | 7              | 7                     |
| 17                                     | 415              | 409              | 6        | 2.5            | 2.5                   |
| 18                                     | 445              | 469              | -24      | -8             |                       |
|                                        |                  |                  |          | <u>T =</u>     | <u>33.5</u>           |

The probability of this result under the Null Hypothesis is given by

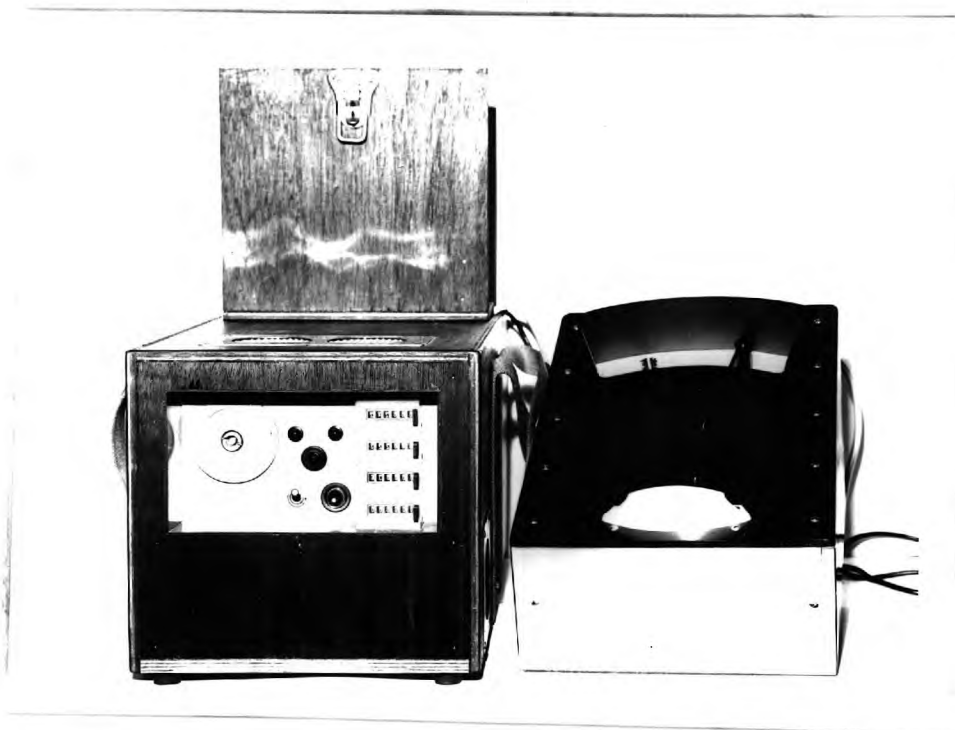
$$\underline{P = 0.0236} \text{ for a two-tail test.}$$

Subjects thus performed significantly better after operating than before operating.

Note: Subjects 1-9 were tested in the order before-after, subjects 10-18 in the reverse order. The scores are for the final 50 secs. of a continuous two-minute trial. The decimal point has been omitted for clarity.

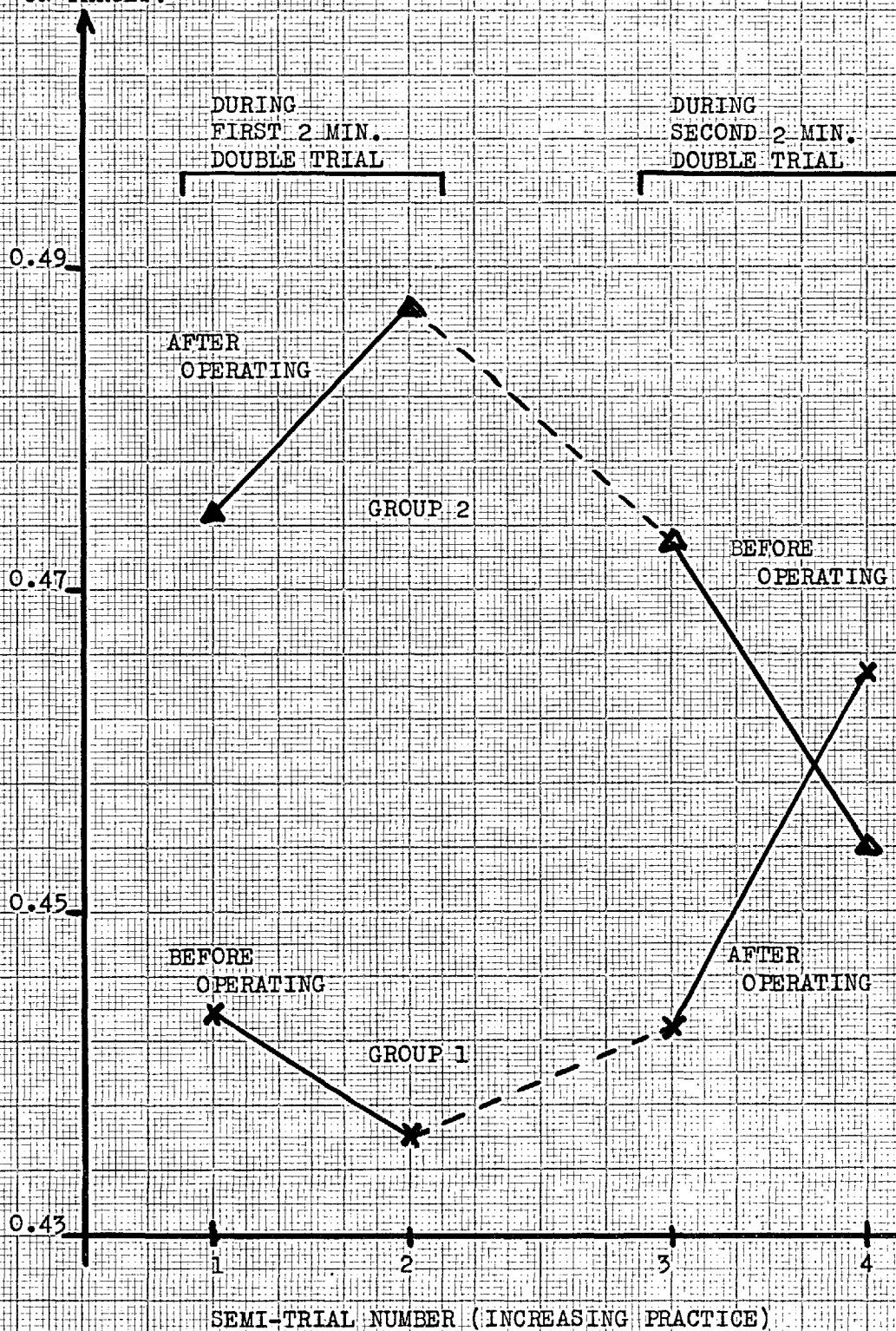


Fig. 9.1. View of pursuit meter assembly.



GRAPH 9.1. PURSUIT METER SCORES FOR SUCCESSIVE 50 SEC. TRIALS.

MEAN  
TIME-FRACTION  
ON TARGET.



SECTION 10.

PREFERENCE FOR DAYLIGHT.

## 1. Introduction.

A strong case can be made for dispensing with windows in operating theatres now that operating lamps can be relied upon to give adequate illumination of the surgical task. The result would be to increase the flexibility of layout in operating suites, and to reduce the dependence of the thermal environment in operating theatres upon the external weather conditions. Since the chief reason for retaining windows is the strong stated preference of surgeons and operating theatre staff, it would be of interest to know whether a change of attitude occurs when windowless theatres have been experienced. This section reports the result of an investigation of this point.

## 2. Method.

A number of modern operating theatres without windows were included in the present survey. Occupants interviewed for the thermal survey were also asked whether they preferred daylight in operating theatres, and their answers were recorded as 'yes', 'indifferent' or 'prefer no daylight'. The same question was asked of a somewhat smaller control group in conventional operating theatres with windows. Almost all of the control group had had no experience of working in theatres without windows, whereas almost all of the former group had had experience of working both with and without daylight in operating theatres.

Readings of lighting levels were taken in all the theatres, using an ordinary incident light meter in a horizontal plane at table height. 'Task' illumination was measured in the spot of the operating lamp, with all lights as for an operation; 'local' illumination in the same place, but with the operating lamp switched off. 'Background'

illumination was measured at the periphery of the room, in the best lit place, and 'daylight' illumination in the same place with all lamps off. These readings were intended only as a rough guide as to whether other aspects of the theatre lighting were having an influence on the preference for daylight.

### 3. Results.

Table 10. 1. shows the correlation matrix for all four lighting levels and the D-vote (preference for daylight), reduced for this purpose to 'Prefer daylight' or not. Because of missing data, the numbers on which the correlation coefficients are based are slightly less than the smaller number of observations involved. Correlation coefficients given are significant at the 0.01 level, except for those in parentheses, which are significant at the 0.05 level.

The high correlation between background and daylight levels indicates the high proportion of operating theatres that are predominantly daylight, while the very small correlation coefficients between task illumination and other measures indicate that task illumination is now practically independent of the general illumination of the theatre. Preference for daylight can be seen to be independent of task and local illumination, while variations in background and daylight levels of illumination account for less than 0.8% of the variation in preference. Clearly the operative factor in any change of attitude to daylight is not the resulting level of illumination, but rather some subjective assessment of satisfactoriness. A common reason, given especially by anaesthetists, is that colour judgements of skin tone are more difficult to make in theatres without daylight.

Table 10. 2. sets out the responses obtained from each of four status categories (surgeons, assistants, scrub-nurses and anaesthetists) when working in theatres that either had some daylight or no daylight at all. The data is in the form of frequency tables, each with one dimension for working illumination and the other for stated preference. Both dimensions are measured only at a nominal level, thus avoiding all assumptions about the properties of either scale; the only requirement is that the categories are discriminable (Siegel 1956). In order to test for the existence of an effect of working illumination on stated preference, the appropriate test is then the nonparametric chi-square test for independence (Fisher 1958). Expected frequencies are calculated from the marginal totals and tabulated in parentheses, giving six components of chi-square on two degrees of freedom. Values of chi-square on two degrees of freedom that are greater than 13.8 are significant at the 0.001 level.

Significant results were obtained for surgeons, scrub-nurses and anaesthetists; examination shows that the change of preference associated with working in the absence of daylight is in each case towards acceptance. However, as many as 50% still stated a preference for daylight.

Table 10.3 sets out the same results in a different form in order to examine the differences between the lighting preferences of the four status categories. Frequency tables are given for each condition of working illumination, the two dimensions of each table being in this case status category and stated preference. Expected frequencies calculated from the marginal totals are again tabulated in parentheses;

in this case there are twelve components of chi-square on six degrees of freedom. Values of chi-square on six degrees of freedom that are greater than 22.5 are significant at the 0.001 level. Differences of stated preference obtained from those working with some daylight are not significant at the 0.05 level. Differences of stated preference obtained from those working with no daylight are highly significant, beyond the 0.001 level; examination shows that surgeons and scrub-nurses tended to accept the absence of daylight more than did assistants and anaesthetists.

A further calculation, not set out in tabular form, showed that the differences between the stated preference of surgeons and anaesthetists working without daylight gave a value of chi-square on two degrees of freedom that was significant at the 0.005 level ( $\chi^2(2) = 11.4$ ), whereas the differences for those working with some daylight were not significant even at the 0.10 level ( $\chi^2(2) = 3.3$  NS.) Thus the significant value of chi-square obtained from Table 10.3.B. is not solely dependent on the difference of assistants from the rest.

In all, though 75% of the group working with some daylight stated that they preferred daylight in operating theatres, only 45% of those working without daylight stated that they would have preferred to work with some daylight.

#### 4. Discussion.

The objection can be raised that the windowless theatres examined were mostly modern ones, and that this could have led to acceptance on other grounds. However, subjects were specifically asked about their

attitude to daylight, and any biasing factors present would be operative also in the real situation of adjusting to a new windowless theatre. There seems little doubt that a measure of acceptance had been achieved. The reservations of assistants, and particularly of anaesthetists are serious, and require serious consideration in the planning of future theatres. The considerable advances being made in the colour quality of available lamps may go some way to removing them, but this is beyond the scope of the present investigation.

#### 5. Summary.

The experience of working in windowless operating theatres has been shown to alter significantly the attitudes of surgeons, scrub-nurses and anaesthetists; from overwhelming preference for daylight in operating theatres they moved to a position where at least half of those questioned expressed no such preference. Assistants did not change their attitude, and anaesthetists were significantly less reconciled to the absence of daylight than were surgeons.



Table 10. 1. Correlation Matrix for lighting levels and D-vote.

|            | <u>Task</u> | <u>Local</u> | <u>Background</u> | <u>Daylight</u> | <u>D-vote</u> | <u>Numbers</u> |
|------------|-------------|--------------|-------------------|-----------------|---------------|----------------|
| Task       | 1           |              |                   |                 |               | 2532           |
| Local      | 0.069       | 1            |                   |                 |               | 2512           |
| Background | 0.068       | 0.652        | 1                 |                 |               | 2489           |
| Daylight   | (0.045)     | 0.637        | 0.983             | 1               |               | 2489           |
| D-vote     | NS          | NS           | (0.087)           | (0.081)         | 1             | 512            |

Note: These values are significant at the 0.01 (0.05) level. For explanation of terms see text.

Table 10. 2. Lighting preference in relation to working illumination.

Observed (Expected) Frequency for each status category

A. Surgeons.

|             |             | <u>Working Illumination</u> |                      |               |
|-------------|-------------|-----------------------------|----------------------|---------------|
|             |             | <u>No Daylight</u>          | <u>Some Daylight</u> | <u>Totals</u> |
| Stated      | Daylight    | 29 (39.2)                   | 30 (19.8)            | 59            |
| Preference: | Indifferent | 36 (30.5)                   | 10 (15.5)            | 46            |
|             | No Daylight | 22 (17.3)                   | 4 ( 8.7)             | 26            |
| Totals      |             | 87                          | 44                   | 131           |

$$\chi^2_{(2)} = 14.6 \text{ ( } P < 0.001 \text{ )}$$

B. Assistants.

|             |             | <u>Working Illumination</u> |                      |               |
|-------------|-------------|-----------------------------|----------------------|---------------|
|             |             | <u>No Daylight</u>          | <u>Some Daylight</u> | <u>Totals</u> |
| Stated      | Daylight    | 50 (53.9)                   | 29 (25.1)            | 79            |
| Preference: | Indifferent | 43 (38.3)                   | 13 (17.7)            | 56            |
|             | No Daylight | 6 ( 6.8)                    | 4 ( 3.2)             | 10            |
| Totals      |             | 99                          | 46                   | 145           |

$$\chi^2_{(2)} = 3.1 \text{ NS ( } 0.10 < P \text{ )}$$

Table 10. 2. (Continued)C. Scrub-Nurses

|               |             | <u>Working Illumination</u> |                      |               |
|---------------|-------------|-----------------------------|----------------------|---------------|
|               |             | <u>No Daylight</u>          | <u>Some Daylight</u> | <u>Totals</u> |
| Stated        | Daylight    | 47 (56.6)                   | 23 (13.4)            | 70            |
| Preference:   | Indifferent | 29 (24.2)                   | 1 ( 5.8)             | 30            |
|               | No Daylight | 29 (24.2)                   | 1 ( 5.8)             | 30            |
| <u>Totals</u> |             | 105                         | 25                   | 130           |

$$\chi^2_{(2)} = 18.3 \quad (P < 0.001)$$

D. Anaesthetists.

|               |             | <u>Working Illumination</u> |                      |               |
|---------------|-------------|-----------------------------|----------------------|---------------|
|               |             | <u>No Daylight</u>          | <u>Some Daylight</u> | <u>Totals</u> |
| Stated        | Daylight    | 45 (54.3)                   | 31 (21.7)            | 76            |
| Preference:   | Indifferent | 38 (29.3)                   | 3 (11.7)             | 41            |
|               | No Daylight | 7 ( 6.4)                    | 2 ( 2.6)             | 9             |
| <u>Totals</u> |             | 90                          | 36                   | 126           |

$$\chi^2_{(2)} = 14.8 \quad (P < 0.001)$$

Table 10. 3. Differences in lighting preference between status categories

Observed (Expected) Frequency tables for two lighting conditions.

A. Working with some daylight.

|                    |             | <u>Status Category</u> |                   |                     |                      |               |
|--------------------|-------------|------------------------|-------------------|---------------------|----------------------|---------------|
|                    |             | <u>Surgeons</u>        | <u>Assistants</u> | <u>Scrub-Nurses</u> | <u>Anaesthetists</u> | <u>Totals</u> |
| Stated Preference: | Daylight    | 30<br>(32.9)           | 29<br>(34.4)      | 23<br>(18.7)        | 31<br>(27.0)         | 113           |
|                    | Indifferent | 10<br>(7.9)            | 13<br>(8.2)       | 1<br>(4.5)          | 3<br>(6.4)           | 27            |
|                    | No Daylight | 4<br>(3.2)             | 4<br>(3.4)        | 1<br>(1.8)          | 2<br>(2.6)           | 11            |
| Totals             |             | 44                     | 46                | 25                  | 36                   | 151           |

$$\chi^2_{(6)} = 11.4 \quad \text{NS.} \quad (0.05 < P)$$

B. Working with no daylight.

|                    |             | <u>Status Category</u> |                   |                     |                      |               |
|--------------------|-------------|------------------------|-------------------|---------------------|----------------------|---------------|
|                    |             | <u>Surgeons</u>        | <u>Assistants</u> | <u>Scrub-Nurses</u> | <u>Anaesthetists</u> | <u>Totals</u> |
| Stated Preference: | Daylight    | 29<br>(39.1)           | 50<br>(44.4)      | 47<br>(47.1)        | 45<br>(40.4)         | 171           |
|                    | Indifferent | 36<br>(33.3)           | 43<br>(37.9)      | 29<br>(40.3)        | 38<br>(34.5)         | 146           |
|                    | No Daylight | 22<br>(14.6)           | 6<br>(16.7)       | 29<br>(17.6)        | 7<br>(15.1)          | 64            |
| Totals             |             | 87                     | 99                | 105                 | 90                   | 381           |

$$\chi^2_{(2)} = 30.6 \quad (P < 0.001)$$

SECTION 11.

GENERAL SUMMARY.

The work reported in this thesis represents an attempt to study fairly comprehensively the working environment of surgeons and operating theatre staff. Although the emphasis was placed primarily upon thermal conditions and the physiological measures that were dependent upon them, a large number of other factors were considered. The work therefore fell naturally into a number of separate sections; a detailed discussion of the results and a summary of the conclusions has been given within each section. Further detailed discussion would be inappropriate. In this section a brief summary of the thesis as a whole will be given.

In tracing the origins of the study of the thermal environment, a fundamental distinction was drawn between measures of stress and measures of strain. By considering the literature, the important parameters of thermal stress were identified. Various measures of strain were discussed. It was shown that subjective reports of discomfort were no more arbitrary than any other index of strain, and that under most working conditions they could be the most sensitive and useful index. A large number of other factors likely to influence subjective reports were considered. Measures of skin temperature and of local sweat rate were proposed to support the validity of the subjective responses. A method of measuring manual performance was proposed.

In order to justify the method used to obtain subjective responses, the results of several surveys that had used similar methods were recalculated and quantitatively compared by the method of probit

analysis. It was shown that the assumptions underlying the analysis of the thermal questionnaire results were fully justified. Some general conclusions could be drawn, concerning particularly the distribution of thermal comfort responses about the optimum.

A full account of the methods used in the present survey was given. Reasons were set out for the choice of a scheme involving brief visits to many operating suites, and interviews with over a thousand subjects, rather than an intensive study of a small group of subjects. This choice is fundamental to the survey, and upon it rests the validity of any generalisation from the experimental results. Some details of the rather specialised instrumentation were given, though a fuller account has been published elsewhere. (Liddwell and Wyon 1968). The method of documentation was given in some detail; it is perhaps of some interest in that it formed the framework for the survey, and allowed a very large amount of data acquired over the two years of the survey to be processed consistently right through to the analysis by computer program.

Methods of analysis were discussed and validated by reference to preliminary sorting of the data. At this stage it was decided to use the vapour pressure of water as a variable instead of relative humidity. Some special techniques of analysis were introduced, including the deviation of predicted responses and of a mean thermal response combining questionnaire responses relevant to different areas of the body. An index of observed sweating was shown to be useful as a measure of thermal strain. Sequential multiple regression analysis

was proposed as the main statistical technique for processing the large number of inter-correlated variables.

Using thermal questionnaire results and observed sweating as dependent variables, regression equations in the main thermal parameters were derived. Though more successful than any other index of thermal stress, the equations accounted for at most 30% of the variation of response. Other factors significantly affecting these responses were identified, but no more than 33% of the variation of response could be attributed to the more extensive equations. A new method of setting out response distributions was suggested. It was shown that the air temperature in operating theatres should not rise above 64.3°F. with 50% relative humidity, air velocity of 25 feet per minute and the normal amount of thermal radiation, if no more than one surgeon in twenty is to be uncomfortably hot. This temperature would be considered too cold by the majority of anaesthetists. It was shown that disagreement between surgeons and anaesthetists as to the optimum temperature is almost universal, and it was suggested that this may be the root cause of many complaints of overheating in operating theatres. Paradoxically, complaints of excessive heat could be eliminated in many cases were the anaesthetist to wear more clothing. These and related conclusions have been published elsewhere. (Kyon, Lidwell and Williams, 1968)

Responses relating to 'stuffiness', air velocity and humidity were found to be largely mediated by the air temperature. The variation of air velocity was found to be very small in operating theatres, and to have a negligibly small effect on thermal responses. Temperature variations outside the operating theatre were found to have but small effects,



equivalent to changes of only  $1\text{F.}^{\circ}$  in air temperature within the operating theatre. Variations in clothing were found to have a very small effect. It was suggested that clothing was being used near-optimally to cancel out individual differences, which were also found to be small. Differences between occasions for the same person were shown to be almost as great as differences between persons, a finding that justifies the use of several responses from the same person within the survey.

Complaints of noise were shown to be related to actual noise in theatre, not merely to a general feeling of tension. Though the measurements were somewhat crude, it was suggested that fewer than one person in twenty would complain of noise if the noise level remained below 42 dB. for most of the time. Complaints of excessive movement in the operating theatre were shown to be due to exits and entries rather than to movement within the theatre. Unexpectedly high rates of movement in and out of the theatres were recorded, and there was some evidence to suggest that they tended to increase strain.

Quantitative measures of local sweat rate were made on a limited number of subjects. They were found to parallel the subjective reports of discomfort. Sweating was shown to be almost entirely confined to the forehead. The skin temperature on the back of the neck was found to parallel hand skin temperature in another survey, and to be as closely related to subjective response as was the air temperature.

In a pilot study of a method of measuring manual skill, in which a small sample of surgeons and their assistants took part, no effects of temperature could be shown. Performance tended to be better after operating than before.

Attitudes to windowless operating theatres were investigated. A significant change of attitude towards acceptance was demonstrated in those who were actually working in such theatres. Anaesthetists were less inclined to accept the absence of daylight.

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