SEQUENTIAL EXPERIENCES IN ARCHITECTURE : COMPUTER SIMULATION OF HUMAN RESPONSE TO THE PHYSICAL ENVIRONMENT.

G. Mckennan Dip.Arch.

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STATEMENT

The work leading to the preparation of this thesis was conducted within the School of Architecture, Plymouth Polytechnic.

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DECLARATION

No part of this thesis has been submitted for any award or degree at any other institute.

CONTENTS

ABSTRACT

The importance of the sequential experience of architecture has long been recognised by architects. Section 1 outlines some of the ways this has been done in the past and sets the present work in its architectural context.

Section 2 discusses the environmental factors and the dynamic thermal regulatory mechanisms involved in predicting people's responses to changes in the thermal environment.

Section 3 describes previous attempts at simulating the regulatory mechanisms involved, using control system equations. Fanger's model is discussed in this section to illustrate the limitations of models that ignore the body's regulatory actions.

Section 4 is new work and is a discussion of the problems associated with applying one of the models outlined in section 3 to the simulation of human motion through buildings. The modifications made to the model are described.

Section 5 is also new work. Previously, simulation of people's transient responses by models has been validated by laboratory studies (see sections 2 and 3). Section 5 describes the recording and analysis of people's transient responses from two studies within buildings. Predictions by the model are validated by this data.

Section 6 is concerned with people's responses to changes in lighting level. This section centres on studies of adaptation which indicate that a model based on the photochemistry of the eye may be appropriate for the simulation of people's responses to changes in lighting level, experienced on walking through a building. This is followed in section 7 by a description of a model of the photochemical changes of cone pigment and how this model is related to the changes of lighting level in a series of rooms.

This is continued in section 8 with a description of the method of recording people's impressions of the lighting level along a route through a building (unsteady state) and whilst viewing a small scale office (steady state). This data is analysed and a simple expression is derived for the prediction of changes in people's impressions of brightness. Predictions by the model are validated by the data.

The estimation of the average luminance of the surfaces of rooms is also validated by this data. The method of estimation is dealt with in section 9, together with a description of the simulation of the indoor thermal environment.

Section 10 concludes with an indication of the direction of future studies. The models are described by a number of FORTRAN subroutines, included in appendix C.

1. Introduction

1.1 The Past

There has always been an awareness on the part of some architects that it is through movement that we perceive works of architecture.

At the beginning of his introduction to 'An Outline of European Architecture', Pevsner applies the term architecture to buildings designed with a view to aesthetic appeal and states how aesthetic sensations may be caused.

> "Thirdly, there is the effect on our senses of the treatment of the interior, the sequence of rooms, the widening out of a nave at the crossing, the stately movement of a Baroque staircase. The first of these three ways is two-dimensional; it is the painter's way. The second is three-dimensional, and as it treats the building as a volume, as a plastic unit, it is the sculptor's way. The third is three-dimensional too, but it concerns space; it is the architect's way more than the others." (ref. 1)

Pevsner gives the sequential experience a central place in architecture. However, the history of architecture shows no coherent continuum in the development of this central theme. Often it is forgotten or becomes subservient to other themes. Occasionally it is re-invented; always its interpretation is moulded by the individual architect to fit the circumstances.

For Michelangelo, the sequential experience ideally expressed tension. The Biblioteca Laurenziana (Figs. 1.1.1

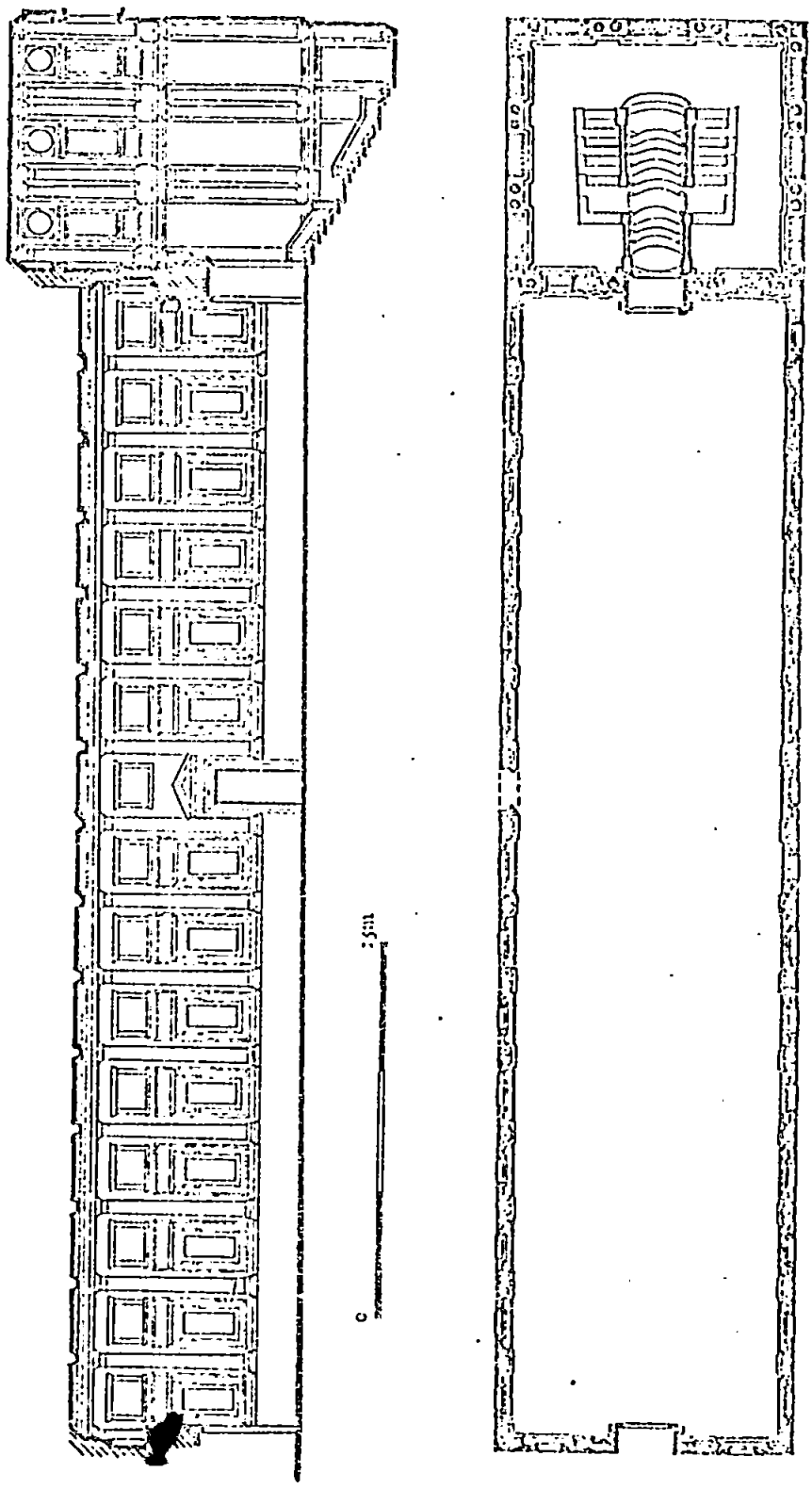


Figure 1.1.1 Plan and section of the main reading room and ricetto (Laurentian library, Michelangelo)

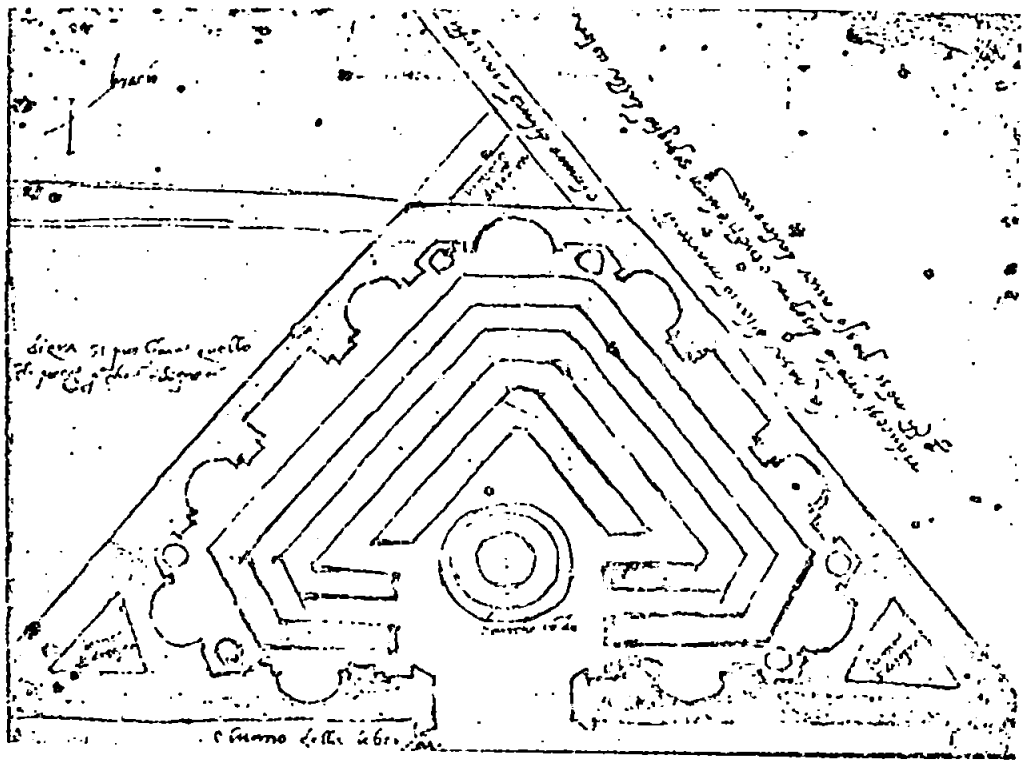


Figure 1.1.2 Plan of the unbuilt rare book study (Laurentian library, Michelangelo)

and 1.1.2) formed a succession of three spatial units; a square (the ricetto), a rectangle (the library proper) and a triangle (the unbuilt piccola libreria). The experience was to be one of conflict within the ricetto, followed by a harmonious but rhythmic calm in the library proper, concluding in peace in the presence of the rare books of the piccola libreria (ref. 2).

The building is a landmark in architectural history and has been called "the most influential building of the sixteenth century" (ref. 3). However, the sequential aspects have little antecedent or precedent except in Michelangelo's own work.

The sequential experience, which for Michelangelo expressed tension, for Palladio, was to express harmony.

> "Beauty will result from the form and correspondence of the whole, with respect to the several parts, of the parts with regard to each other, and of these again to the whole." (ref. 4)

To this end, Palladio used a systematic method of proportions (usually harmonic) which could be extended from two dimensions to three and from three into a series so that not only rooms, but whole plans could be encompassed by the system.

The Villa Rotunda (Fig. 1.1.3) is an excellent manifestation of this system. The transition of spaces through the building, which in the Laurentian library was dynamic, is here harmonious. It is interesting to see that whereas the dynamic experience of the Laurentian library is

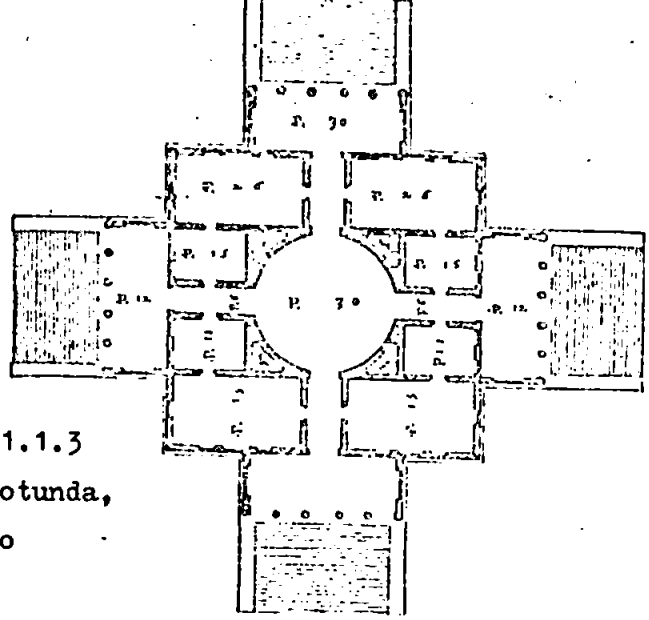


Figure 1.1.3
Villa Rotunda,
Palladio

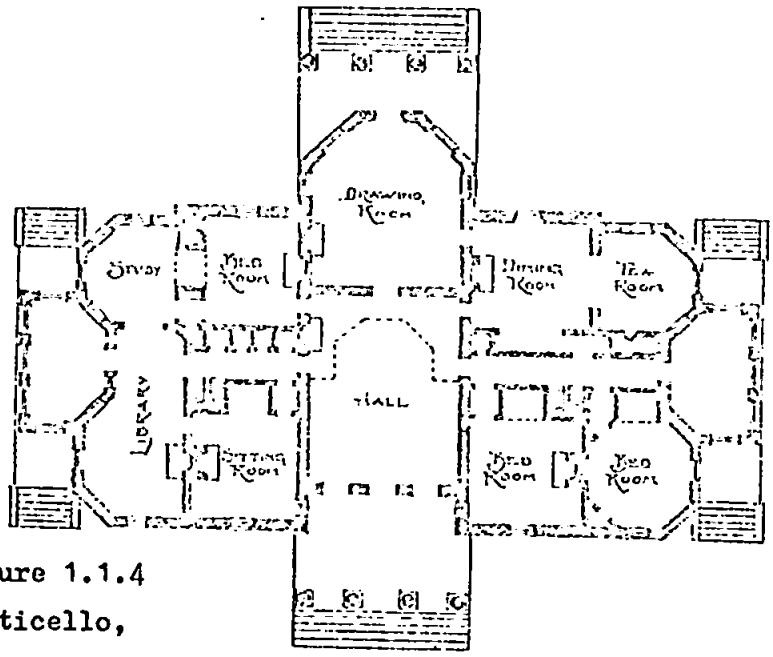


Figure 1.1.4
Monticello,
Jefferson

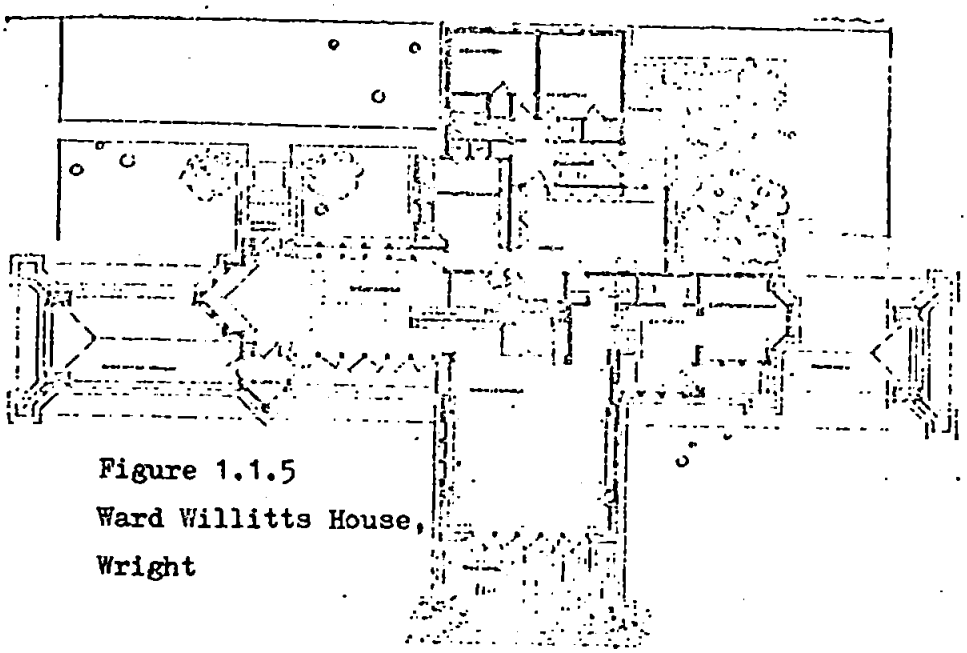


Figure 1.1.5
Ward Willitts House,
Wright

lost in plan drawings the harmonious qualities of the Villa Rotunda are not. This may be one reason why Palladio's works were more readily adapted in other periods.

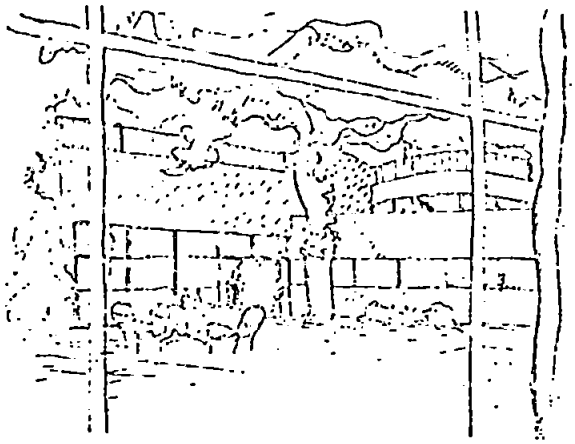
Thomas Jefferson's house at Monticello (Fig. 1.1.4) also took advantage of the difference in character of its rooms. The entrance and hall face east. From there one moves into the warmer living rooms of the house facing west. The publication of Leoni's Palladio, at the time of the design of Monticello, is said to have exerted a controlling influence.

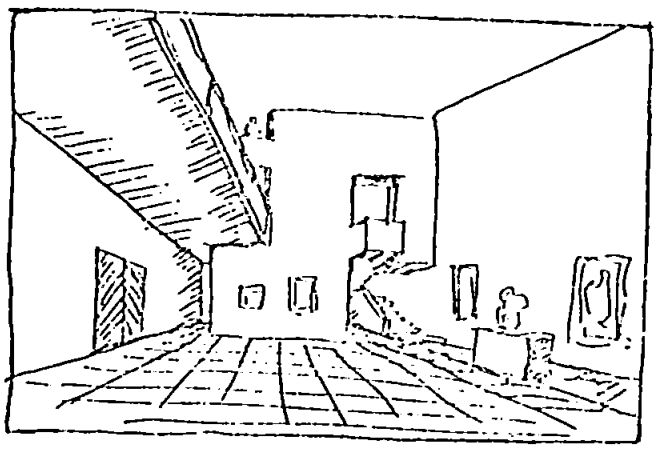
The harmonious sequence of rooms based on an axial plan as seen in Palladio and Jefferson become in Wright an "organic" sequence of spaces bounded and directed by intersecting planes (Fig. 1.1.5).

The building was to be experienced through movement and the experience was thus to be a dynamic process. This is what Wright meant by "The complete goal of the ideal of organic architecture is never reached." (ref. 5)

However, little is said of how one experiences the harmony or tension within these interiors. Le Corbusier is a little more explicit.

Le Corbusier was so attracted to the sequential experience of buildings that he invented his own term. 'La promenade architecturale' was a recurring theme in Corbusier's buildings but is most evident in the Maison La Roche. Corbusier's record of his own work shows us how he considered this aspect in design (Fig. 1.1.6).





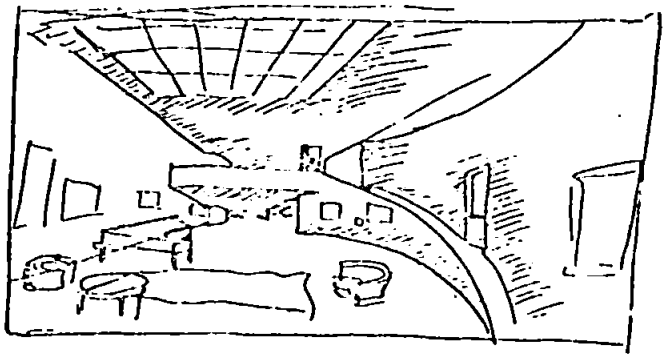


Figure 1.1.6 Perspective views of the Villa La Roche, drawings by Le Corbusier.

Much like the layout of Greek cities he had previously visited, "les perspectives se developpent avec une grande variete." (ref. 6). The promenade is treated as a series of dramatic views, leading from the hall to the gallery. One is left to presume that this route, in this direction, was all that was worthy of study.

Le Corbusier's approach is in almost direct contrast to this statement by Roger Scrutton (ref. 7).

> "Moreover it would be wrong to concentrate only on the visual aspect of the experience of architecture. We do not treat buildings simply as a series of dramatic facades. We walk through and around them, testing them, as it were through movement."

This apparent paradox can be resolved if we are prepared to accept that Corbusier understood an important aspect of experience: that <u>change</u> of stimulus is of the essence of perception and that it is where this change is abrupt that the stimulus is perceived. More is said of this in paragraph 1.3.

The phenomenon of parallax as a further explanation of how buildings may be experienced sequentially is provided by Collins. Not only are Le Corbusier's and Wright's works susceptible to this interpretation but so also is the 18th century delight in the interior use of colonades and mirrors. Wolfgang Hermann, as quoted by Collins, provides us with a concise description of this experience. "While the visitor moves forward, the cluster of columns seems to move too, opening up constantly changing views." (ref. 8)

1.2 The Present Day

It is worth noting at this point that it is not only our impressions of the great works of architecture that are gained through the sequential experience. A person's <u>everyday</u> experience of a building is often transient.

Occupants have to enter and very often pass through entrance foyers, lobbies, receptions and offices, along corridors and up and down by stairs and lifts. Even essentially sedentary occupations involve movement from space to space within a building, especially where users share resources, for example in educational buildings. Transience can, in fact, be a major aspect of the experience where the occupants move around or through as an essential part of their use of a building, for example in galleries, or, as we have seen above, where the architect takes cognizance of the sequential experience in his design.

One of the aims of a building is to provide a comfortable environment for the people within, one that is sympathetic to the activity it encloses. In protecting the occupants from the natural heat and cold, rain and winds, we presume to construct an artificial environment more comfortable than that provided by nature. The increase of industrialisation has resulted in most people spending by far the greater part of their lives in such artificial environments.

A visitor's experience of most buildings is therefore often the transient experience of a series of similar or dissimilar artificial environments.

Other historic examples of works of architecture can be found which have as a central theme the sequential experience, for example the Spanish steps in Rome, the Bazaar Kashan in Iran and many works where processional functions occur. However the previous examples are sufficient to illustrate that architects have recognised the sequential experience of buildings as a central element of the vocabulary of architecture.

This thesis will seek to show how the theme can be considered in a way consistent with, and hopefully extending, today's study of the 'environmental' aspects of buildings.

At present, little account is taken of the transient aspects of an occupant's experience in the design of the physical environment (here taken to mean the heating, lighting and acoustics) within the building.

At a particular stage in the design process each space or room is given its overall physical qualities. The shape and size having been determined, generally on the basis of the activity or number of occupants to be housed, the services are installed and finishes applied. The heating (and possibly ventilation) system is, more often than not, designed to keep the whole of the building at a constant temperature, the more sophisticated systems incorporating

thermostatic control and zoning to achieve this end, the system in each room or zone being designed to maintain the desired temperature of that room or zone. Criticisms are now beginning to be levelled against this approach (ref. 9) and research is being conducted into the effects of changing conditions (refs. 10 and 11).

Specific acoustic treatment is applied in rooms where necessary, and the acoustic environment throughout the rest of the building may be considered in a general way when choosing finishes for each room.

Lighting systems too are usually designed on a room by room basis, each one taken on its own merits and the luminaires designed to provide the desired lighting for that room. A partial answer to the question, Why?, is given in paragraph 1.5.

Each aspect is considered, in providing an environment within each room or space, while often it is the change from one to another which impinges on our consciousness. Moreover, there is evidence that the human systems of perception are adapted to detecting change of rather than absolute levels of stimulus. A note on this point follows.

1.3 Experience and Change of Stimulus

Within the real world (that excluding laboratory experiments and drug experiences) our experience of objects and their qualities is mediated by the senses.

A <u>change</u> in the sequence of stimuli from point to point or from moment to moment is of the essence of perceptual

experience. With regard to each of the senses this has been shown to be the case.

The homogeneous total field experiment demonstrates that when every ray (of light) has the same wavelength and intensity there is no perception, and this experiment implies that the organism cannot respond to ray directions as such. What the retina does respond to is a differential intensity from point to point over the retina (ref. 12).

Thermal receptors have been shown to exhibit both phasic and static responses. Below an average skin temperature of about 34°C. the stimulus for warmth has been shown to be most probably an increase in temperature of the warmth receptor above the temperature to which it is adapted. (ref. 13)

1.4 Architectural Movement Studies

The recognition of the importance of movement in architecture has generated a number of studies. These may be broadly classed as either predictive of behaviour or descriptive of experience.

Studies falling within the first category include the analysis of people's movement patterns as part of a general theory of movement systems within buildings. Burberry (ref. 14) proposes that the movement system of people exhibits similar characteristics to the movement systems of other flow media (water, air, vehicles and electricity) and, as such, is susceptible to a similar analysis.

Hallberg (ref. 15) also provides a classification of movement, regarded as a "personal characteristic". He obtained the following five dimensions as a descriptive classification of movement behaviour: stiff/laborious/heavy, tempo, jerky/floppy, amount of movement, careful/monotonous/restrained.

Also within this category is Whitehead and Elders' classic work on spatial allocation based on the association of activities and the number of 'standard journeys' between activities (ref. 16). The analysis of route patterns (ref. 17) is an extension of this approach to the study of movement.

Other studies have been concerned with more specific situations. The movement of people through air terminals has been studied (ref. 18) and simulation techniques applied to the analysis of queuing. The movement of people through museum environments has also been studied with the aid of simulation models (ref. 19) and Canter has studied the behaviour of people in fire escape situations (ref. 20).

A few studies have been concerned with the experiential aspects of movement and have been notable in producing systems of notation. The notations of Halprin (ref. 21) and Thiel (refs. 22 and 23) fall in this category. Essentially these systems allow the designer to describe either the major physical aspects of a route (Fig. 1.4.1) or the experience of a route (Fig. 1.4.2) and to write this description in a form much like a musical score.

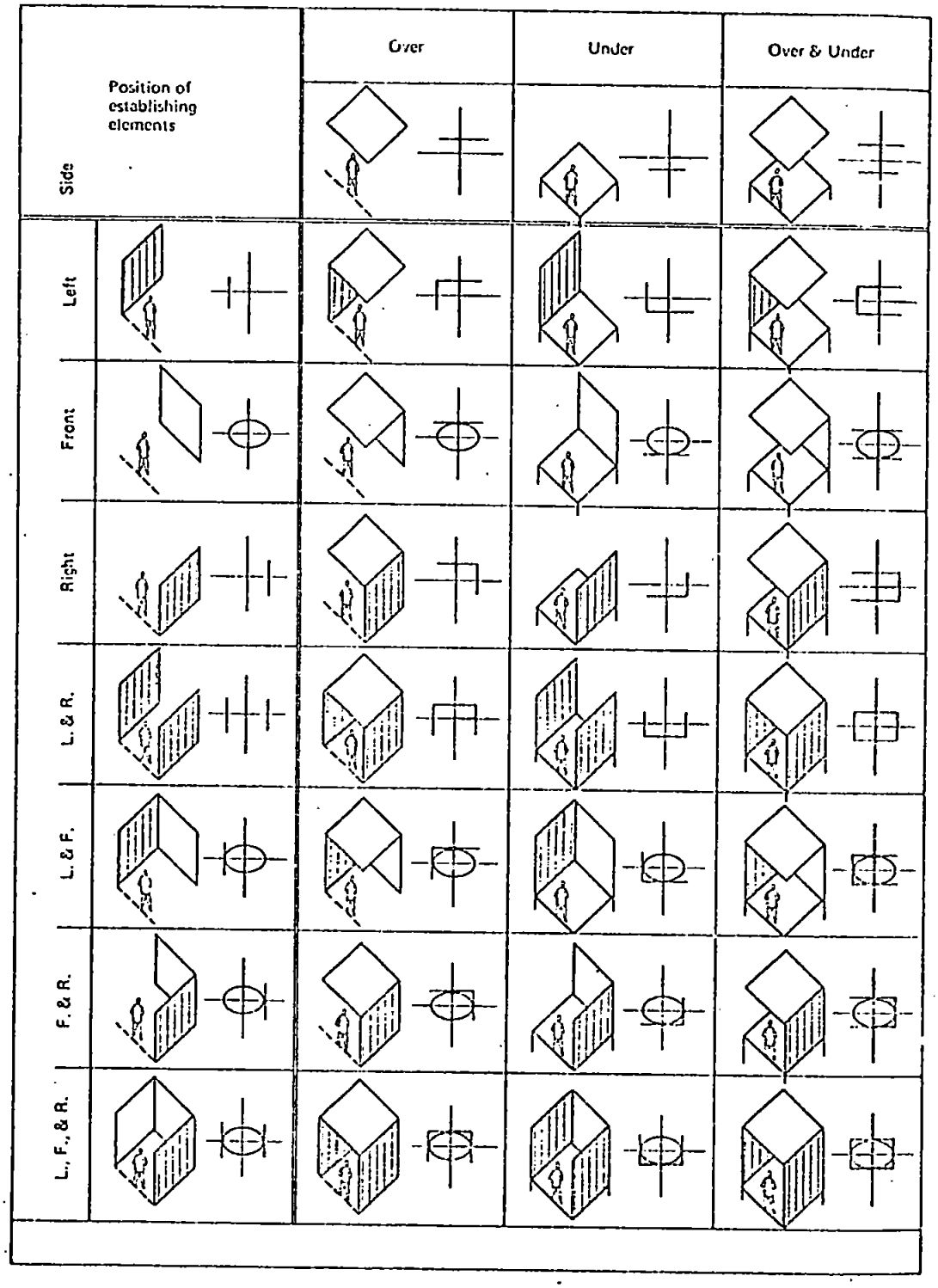


Figure 1.4.1 Space-form notation for orthogonal surfaces (Thiel).

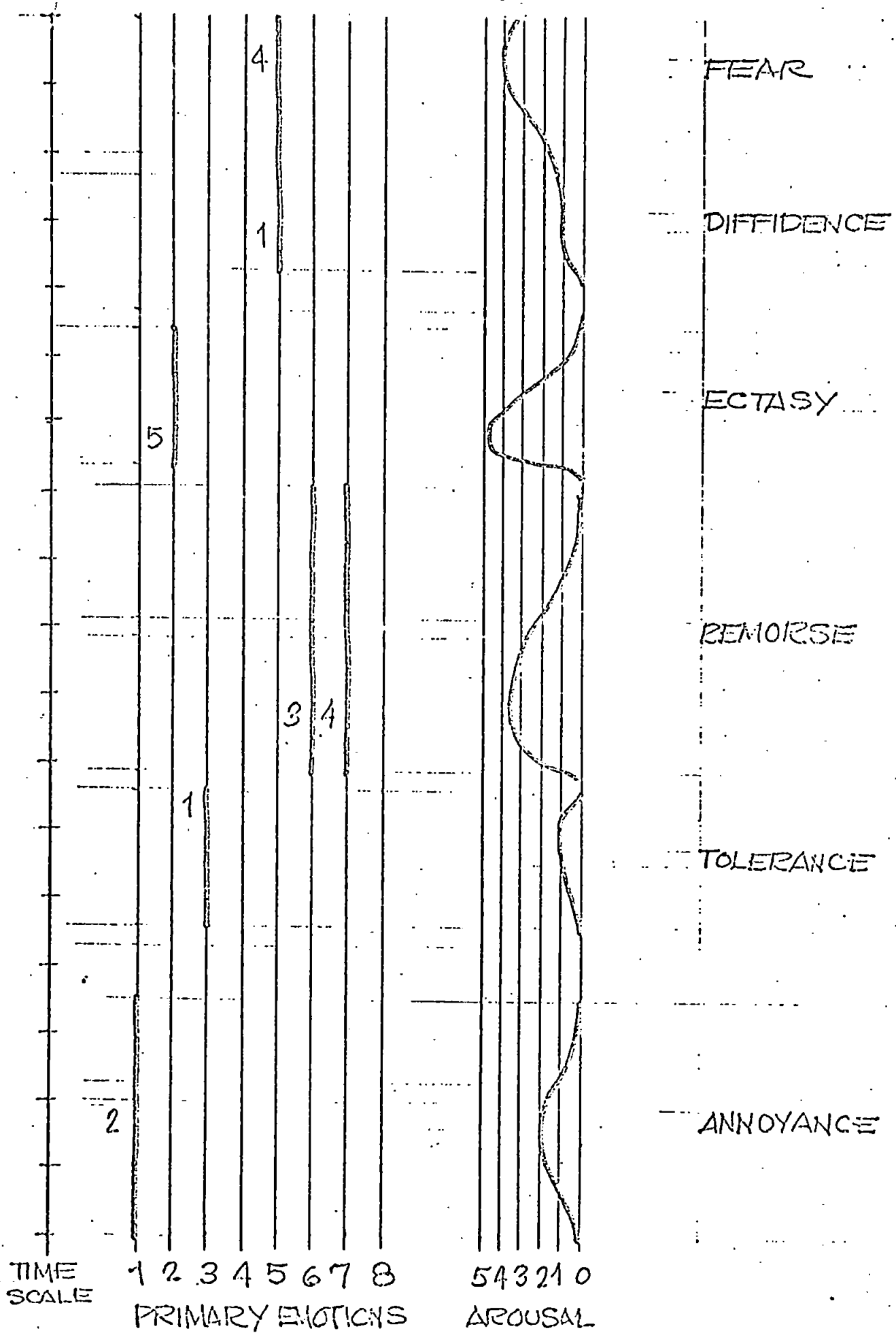


Figure 1.4.2 Experiential notation (Thiel).

No attempt has been made in these studies to correlate the description of a route with people's experience of it or the description of one's experience with a constructed route. These studies must therefore remain descriptive and not predictive.

However, the nature of the present study is both experiential and predictive.

1.5 Models

A model is a representation of certain relevant characteristics of reality. It is therefore less complex than reality, wherein lies both its strength and weakness. The fact that we do not need to represent all the facts of reality is to our advantage but the fact that we cannot means that a model is once removed from reality.

The question of why we should wish to construct models is thus answered. We construct them to investigate certain characteristics of reality without the necessity of possessing knowledge of the whole of reality.

Echenique makes a classification of models (Fig. 1.5.1) on the basis of three categories: what the model is made for, what the model is made of, and how the time factor is treated (ref. 24). Of particular interest is the last category.

A look at the use of models in architecture shows that by far the most common type of model used by architects

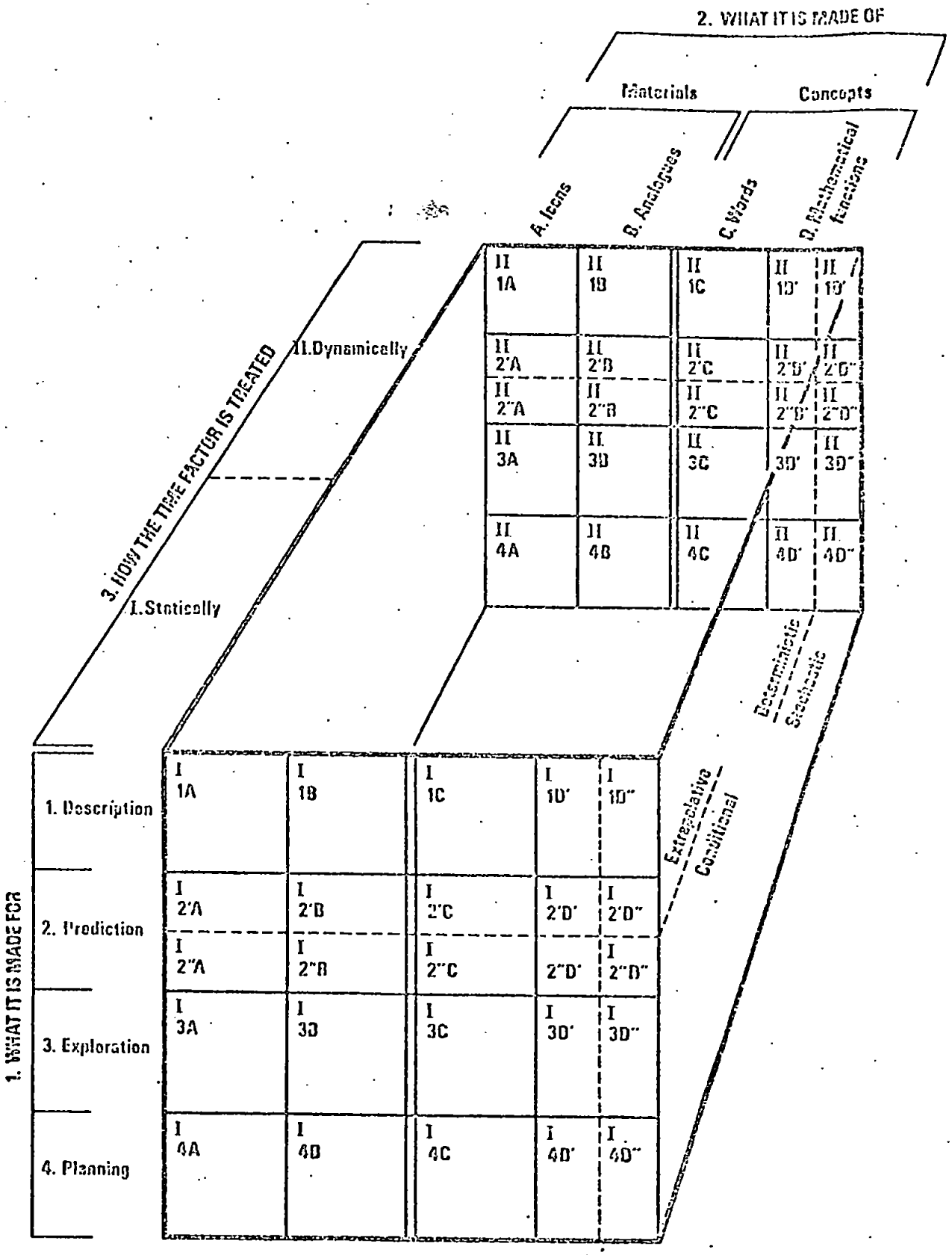


Figure 1.5.1 Three-way classification system for models (Echenique)

is the visual model. Plans, sections, elevations, isometric projections, perspectives, photographs, card models and heliodons are all of this type.

With respect to the third category of Echenique's classification these models treat the time factor statically. The answer to the question, Why?, in paragraph 1.2 is now evident. There are inherent difficulties in modelling a dynamic process, such as movement, with models that are static.

The problem of modelling a person's response to the environment, as he or she moves through a sequence of spaces, is complex and the previous failure to develop a modelling system of the dynamic process of the sequential experience may therefore be partly excused.

However, computer simulation offers a possible approach towards a solution.

1.6 Concluding Remarks

The sequential experience is seen to be an important aspect of architectural experience. Furthermore, change is central to perceptual experience itself.

Previously, the impressions gained by someone moving through a building have been considered in dramatic or nebulous ways. The heating, lighting and acoustics of a building are designed on a room by room basis, without taking account of the sequential experience, and this is in large part due to the complex problem of modelling the response of a person in this dynamic situation.

The general acceptance of the importance of movement as a determinant of architectural form has led to a number of related studies, mentioned above, none of which are, however, predictive of experience.

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2. Towards a Model of Human Thermal Response

2.1 Environmental Factors

Any comprehensive study of a person's thermal responses and thermal sensations must take into account the following four environmental factors governing the heat loss from the body.

Radiation from surrounding surfaces

Air temperature

Air humidity

Air velocity

Table 2.1.1 Environmental factors governing heat loss from the body.

Air temperature is perhaps the oldest recognised environmental factor affecting one's feeling of warmth. Figure 2.1.1 illustrates this effect of air temperature on warmth. The regression line in Fig. 2.1.1 is fitted to data from 1296 observations (ref. 1).

The cooling effects of moving air are commonly recognised and as early as 1914 the kata-thermometer was introduced as a measure of warmth. Figure 2.1.2, taken from Bedford (ref. 2), illustrates the reduction in forehead temperature due to moving air.

The effect of air humidity on the impression of warmth has been recognised and has been shown to have greater effect at higher temperatures. Figure 2.1.3 is a re-plot of data from Koch and colleagues (ref. 3) and shows the reduced air

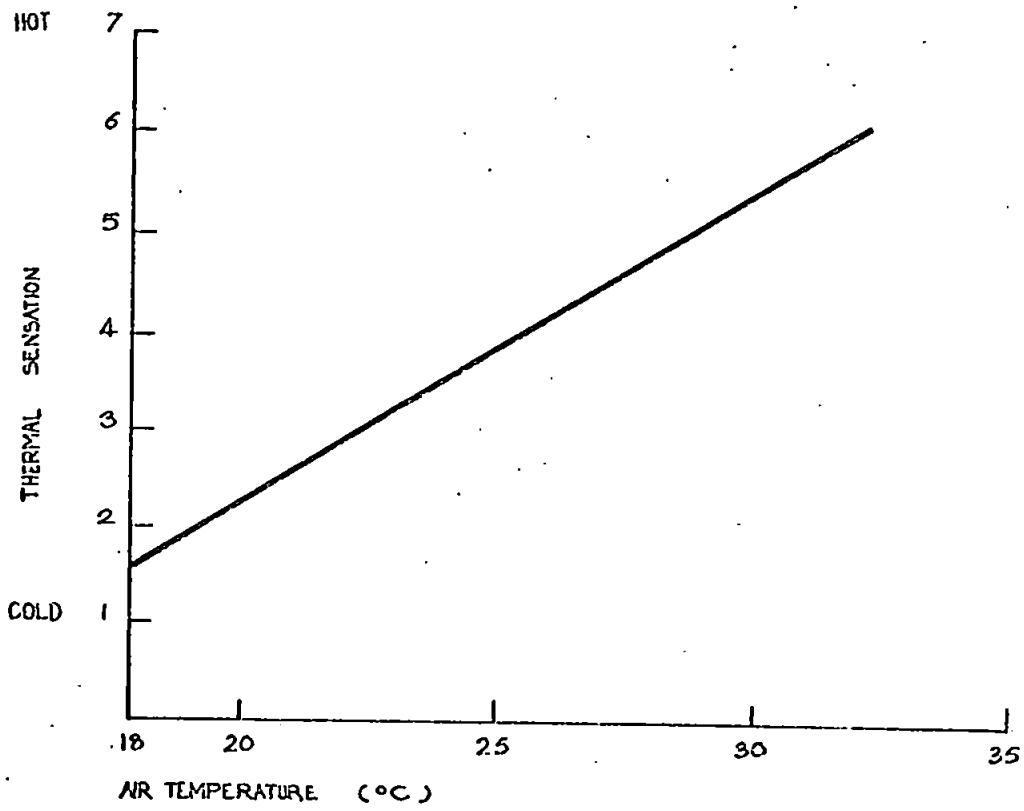

Figure 2.1.1 Plot of warmth vote against temperature

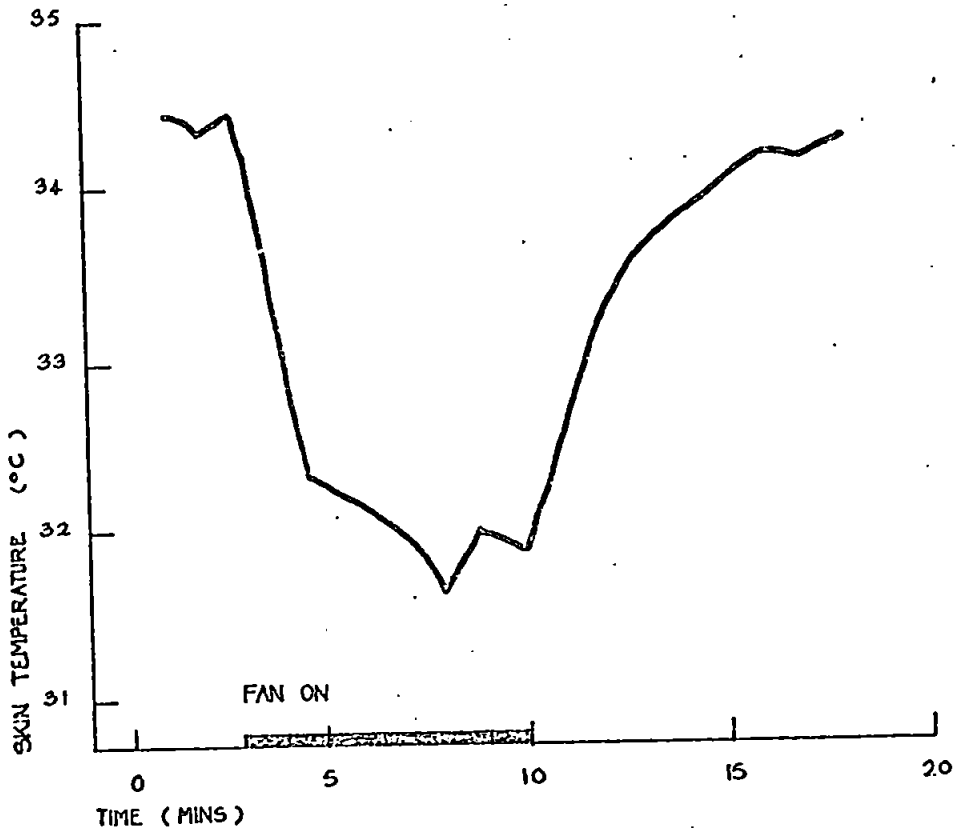

Figure 2.1.2 Forehead temperature in calm and moving air

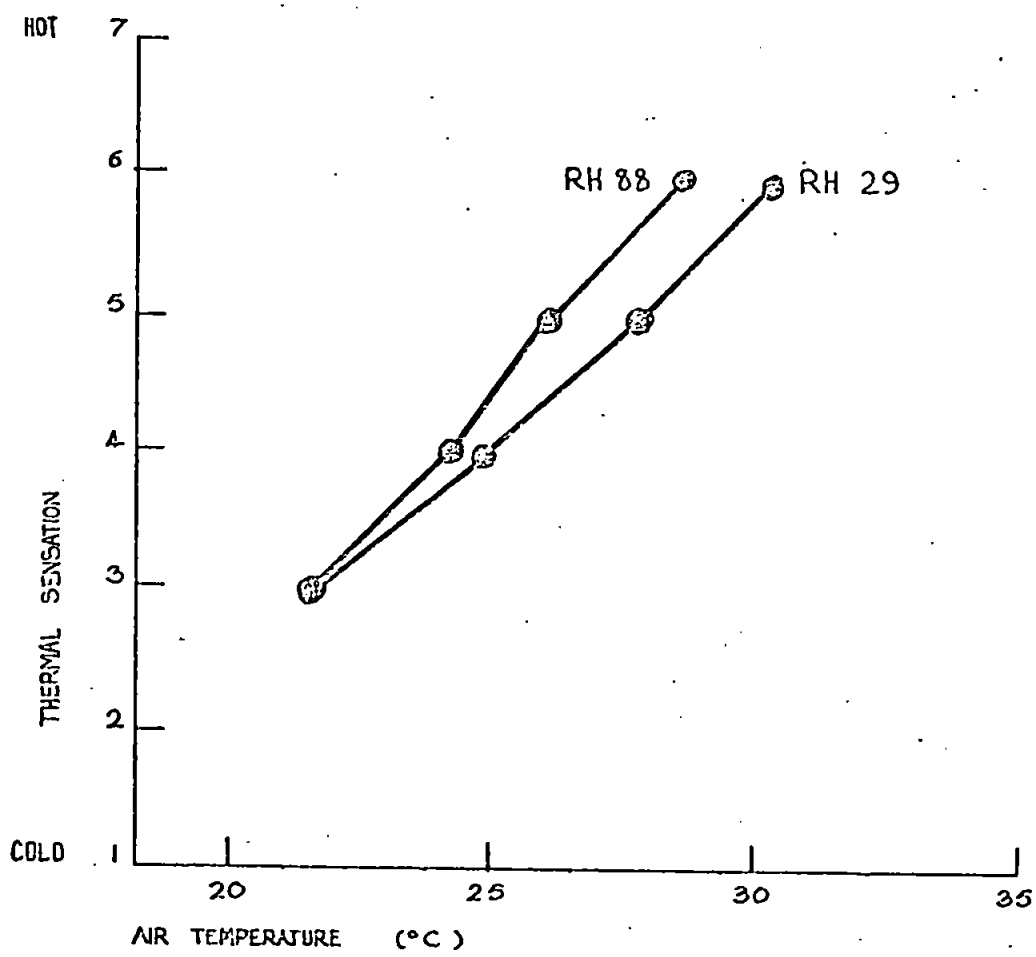

Figure 2.1.3 Effect of relative humidity on thermal sensation

temperature at which a particular thermal sensation is registered with an increase in relative humidity. This effect can be seen to increase with an increase of air temperature.

The radiant heat of surroundings has also been shown to affect comfort. In 1930, Vernon (ref. 4) introduced the globe thermometer as a means of assessing this influence. Figure 2.1.4 shows data plotted by Humphreys (ref. 5) indicating the effect of the variation of globe temperature, from the monthly mean, on the variation of the comfort vote from the monthly mean. The two outer lines are at one standard deviation on either side.

This brief outline of the environmental variables associated with the study of the thermal environment introduces a few concepts which will be further clarified.

The existence of four variables is an inconvenience if a prediction of the impression of the warmth of an environment is desired. For example, an environment with a particular air temperature and relative humidity might be considered as warm as one with a higher air temperature but lower relative humidity. This can be seen from Figure 2.1.3. The situation is complicated by the inclusion of all four environmental factors and engineers have attempted to express the combined effect of these factors by one figure or index. These will be discussed in section 2.2.

In mentioning the influence of the environmental variables, the words 'comfort', 'warmth' and 'thermal sensations' have been deliberately used. These will be

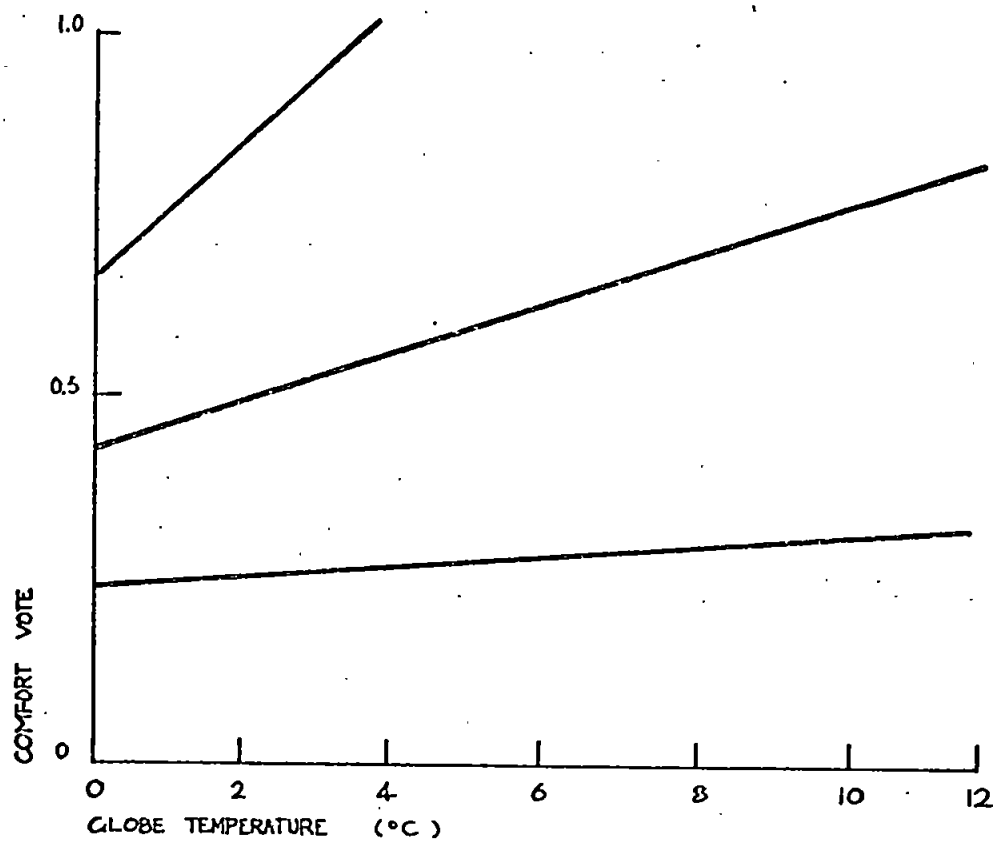

Figure 2.1.4 Variation of comfort vote with variation of globe temperature

discussed in section 2.3.

The word 'vote' has been used in connection with comfort, warmth and thermal sensations and numbers have been used in this context. This will be discussed in section 2.4.

2.2 The Search for a Single Index

In 1923 Houghten and Yagloglou conducted a climate chamber experiment (ref. 7) in which semi-nude men and men in summer clothing walked to and fro between two rooms. Air temperature and relative humidity were adjusted in both rooms, in various combinations, so that the men felt the same thermal sensation in the one room as they did in the other. Each group of equal thermal sensation votes was plotted for the various values of air temperature and relative humidity and a series of "equal comfort lines" produced. By definition, any combination of air temperature and relative humidity locating a point on a comfort line would produce the same thermal sensation as any other combination locating any other point on the same line. This experiment on three subjects formed the basis of the Effective Temperature Index.

The effect of air movement was incorporated into the index by Yagloglou and Miller (ref. 8) and in 1932 Vernon and Warner (ref. 9) incorporated the effect of radiation by replacing dry bulb temperature with readings from a globe thermometer. Vernon had already shown globe thermometer temperature to be an index of warmth (ref. 4). In 1933 Missenard introduced the Resultant Temperature which also corrected Effective Temperature for radiation.

Figure 2.2.1 shows the Corrected Effective Temperature chart as it stands today. It is implied that any combination of globe thermometer temperature, wet bulb temperature and air velocity producing a value for Corrected Effective Temperature will induce the same thermal sensation as any other combination producing the same value.

It is worth noting that it is not possible to predict thermal sensations as such with Effective Temperature (E.T.). It cannot be inferred from E.T., as it stands, that an environment with for example 32.2°C. globe temperature, 21 C. wet bulb temperature and air velocity of 3.05 m./sec. will be felt warm or hot, but only that it will register the same thermal sensation as for example 24°C. globe temperature, 24°C. wet bulb temperature and an air velocity of 0.1 m./sec.

In 1936, Dufton (ref. 5) introduced the term Equivalent Temperature based on measurements made with his eupatheoscope. The rate of heat loss from the surface of the eupatheoscope varies with the temperature and velocity of the surrounding air and with radiation from surrounding surfaces. The readings of the instrument depend on the heat input to maintain a constant temperature inside. The instrument therefore gives an indication of the combined effects of air temperature, air velocity and radiation.

The eupatheoscope is needed for the precise measurement of Equivalent Temperature but if the environmental variables are known it can be estimated.

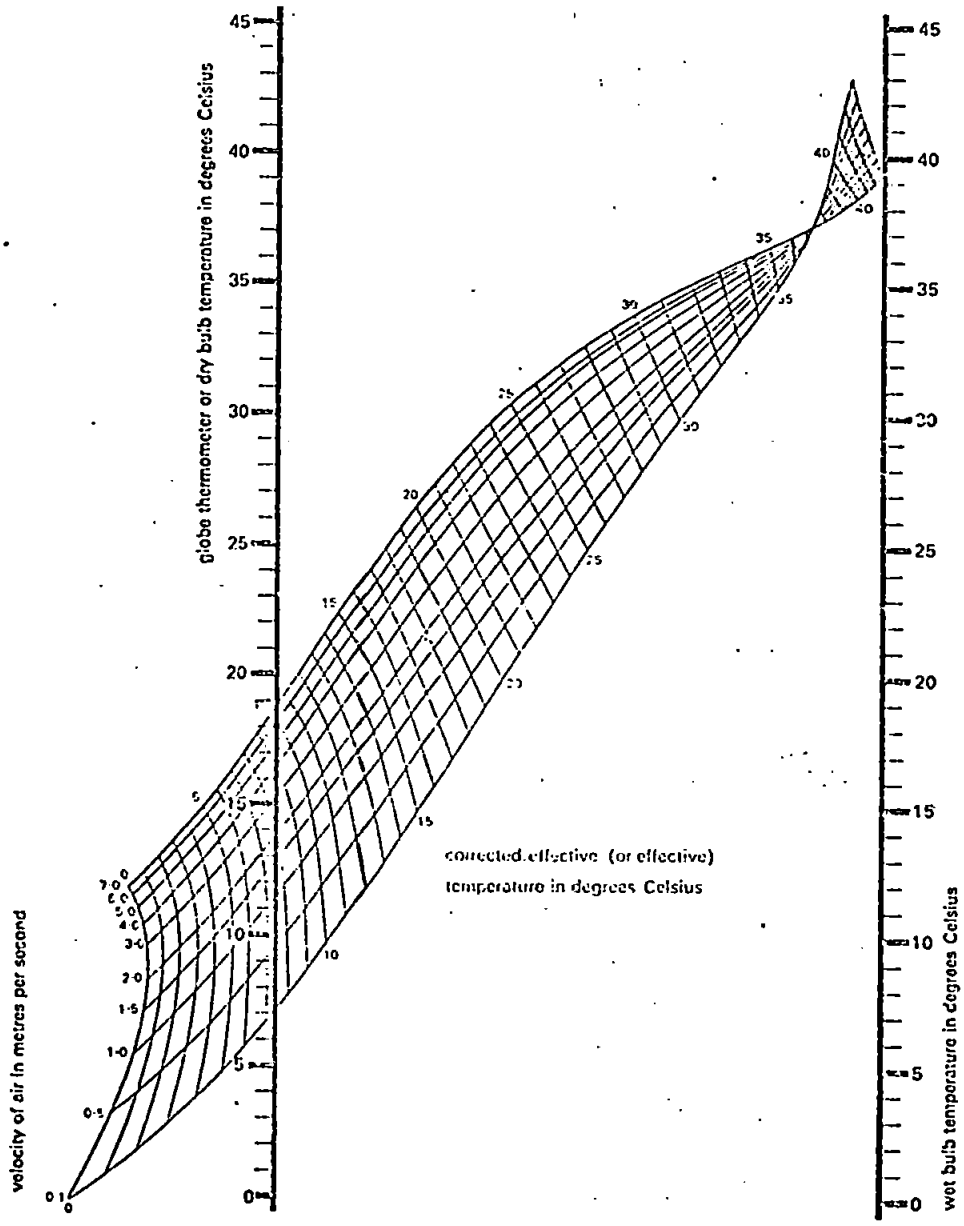

Figure 2.2.1 Corrected Effective temperature in its normal form (fully clothed in Summer clothing)

In the same year, Bedford made a very important advance (ref. 10). Houghton and Yagloglou had determined comfort in the laboratory, in which subjects had equated different thermal environments. Bedford studied the subjective assessment of comfort of a large number of people (nearly 2000 in all, mostly women) in the factory, engaged in their normal occupations. Furthermore, he recorded their impressions on a scale ranging from 'much too warm' to 'much too cool' and assigned numerical values to each category.

Unlike E.T., which gives no indication of whether any combination of variables is warmer, cooler or more preferable than any other, Bedford's method makes it possible to relate predictions of an index directly to verbal statements of warmth.

Bedford compared his data with predictions made by thermal indices. Table 2.2.1 shows his results. The closest correlation was found to be with Dufton's Equivalent Temperature, with a correlation of -0.52. From his results Bedford then prepared a provisional index of warmth, the index of Equivalent Warmth.

Sensations correlated with:	Correlation coefficient
Equivalent Temperature	- 0.52 ± 0.010
Globe thermometer temperature	- 0.51 ± 0.010
Effective Temperature	- 0.48 ± 0.010
Air temperature	- 0.48 ± 0.010
Dry Kata thermometer cooling power	0.43 ± 0.011

Table 2.2.1 Correlation between thermal sensations and environmental indices

It is interesting to see from table 2.2.1 that E.T. does not correlate as well with Bedford's data as does Equivalent Temperature. In fact it is no more a superior index than is air temperature alone, both having correlation coefficients of - 0.48.

However, Bedford's conditions were neither hot nor humid, nor was there a wide range of air movement. Furthermore the E.T. was not corrected for radiation. When this is done, the correlation coefficient is - 0.51 (ref. 11). However, Hickish confirmed Bedford's work with a study of male and female factory workers in summer (ref. 12). He found the correlation coefficient for E.T. with subjective sensations was 0.368 and for air temperature with subjective sensations 0.377. E.T. was corrected for radiation.

Many more environmental indices and instruments have been developed over the years with the aim of either predicting thermal sensations or the conditions under which

thermal stress will occur. A discussion of these is beyond the scope of the present study and can be found in the text books on the thermal environment, see for example refs. 1, 11 and 39.

2.3 Thermal Sensation, Warmth and Comfort

There is clearly a distinction between comfort and thermal sensation. Comfort is a recognizable state of feeling which is normally associated with conditions that are pleasant and compatible with health and happiness.

It is possible to conduct studies of thermal comfort without subjects stating their thermal sensations, for example the words 'comfortable', 'slightly uncomfortable', 'uncomfortable' and 'very uncomfortable' have been used (ref. 13) and it is also possible to refrain from the use of the word comfort with such words as 'very pleasant', 'pleasant', 'indifferent', 'unpleasant' and 'very unpleasant' (ref. 14).

The relationship between comfort and thermal sensation is illustrated in Figure 2.3.1, where comfort data, divided into three categories (too cool, comfortable, too warm) are plotted against air temperature (ref. 15). Increasing air temperature though causing an increase of 'too warm' votes does not necessarily entail an increase of comfort votes. Neither does a decrease of temperature which causes an increase of 'too cool' votes necessarily cause an increase of comfort votes. However, there is some temperature at which comfort votes are at a maximum, which lies about half way between the

Figure 2.3.1 The relationship between comfort, warmth and air temperature (ref. 15)

threshold temperatures eliciting the maximum numbers of 'too cool' and 'too warm' votes.

The mid point or comfortable temperature varies from study to study. However, Gagge (ref. 13) illustrates an interesting point (Fig. 2.3.2).

Three sets of data are compared and we can see that the choice of words used to describe the sensations affects the discrimination of the subject. For a given change of temperature a change of 'pleasantness' vote is more likely to occur or will be greater than a change of 'temperature sensation'. However, all three sets of data point to the same range of temperatures for neutral temperature sensation, pleasantness and comfort.

Bedford's study of warmth (ref. 10) made use of a combination of words describing thermal sensation and comfort, ranging from 'much too warm' to 'much too cool'. This feature has been criticised on the grounds that the relationship between the two is not necessarily constant (ref. 16) although a recent study has shown these categories to predict very similar comfortable temperatures to the scale of thermal sensation (ref. 17).

What is clear is that some thermal comfort workers and physiologists have used the terms loosely. Rohles and Nevins (ref. 18) used the categories in Figure 2.3.3 in their study of 'comfort'. Gagge (ref. 19) has used an extended version of this scale in a study of 'temperature sensation' (Fig. 2.3.4) and Chrenko used Bedford's

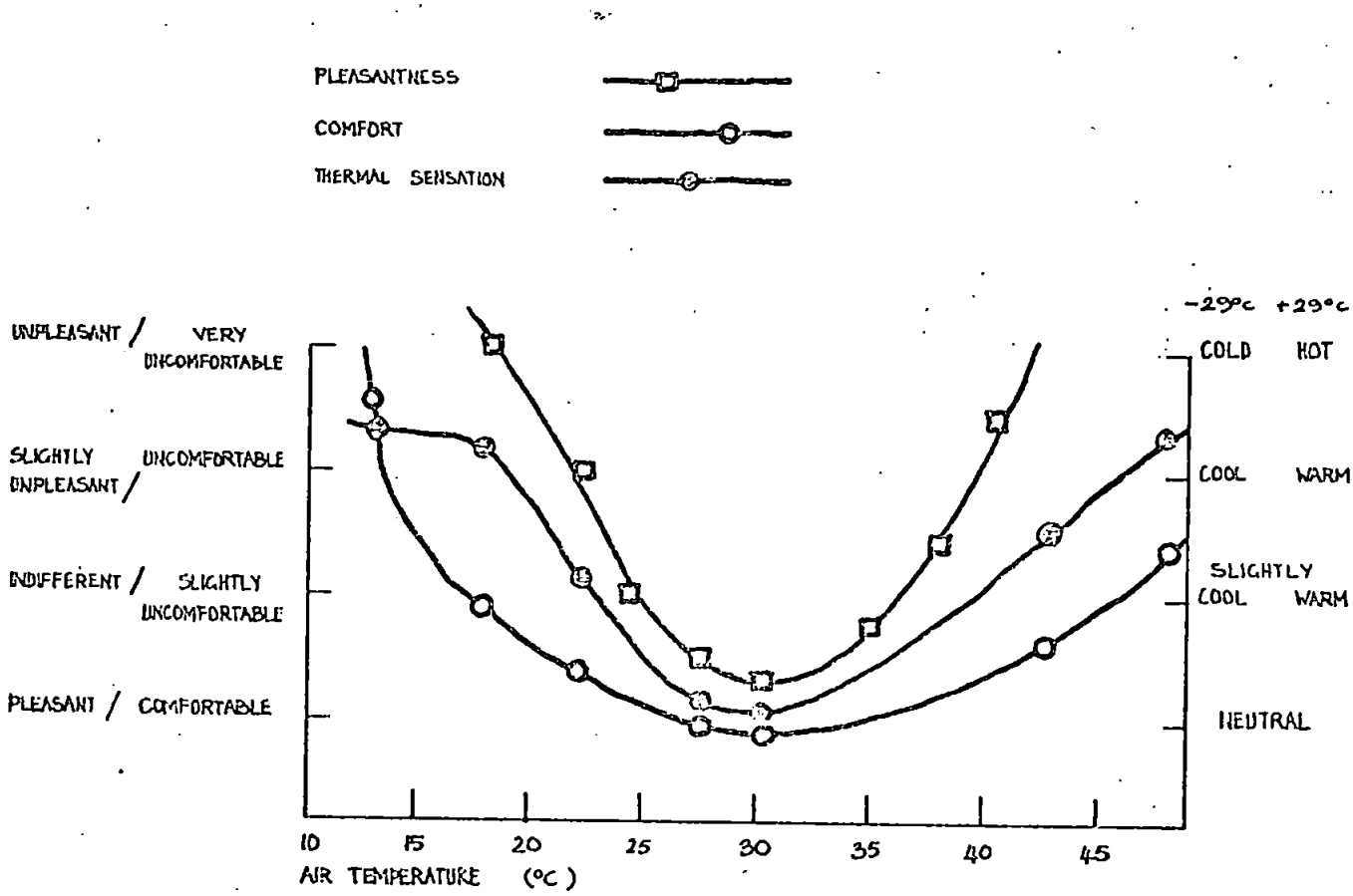

Figure 2.3.2 Variation of subjective estimates of pleasantness (□), comfort (○) and temperature sensation (⊖), with air temperature.

1	COLD
2	COOL
3	SLIGHTLY COOL
4	COMFORTABLE
5	SLIGHTLY WARM
6	WARM
7	HOT

Figure 2.3.3 Categories for comfort votes used by Rohles and Nevins (ref. 18)

VERY HOT

HOT

WARM

SLIGHTLY WARM

NEUTRAL

SLIGHTLY COOL

COOL

COLD

VERY COLD

Figure 2.3.4 Categories for temperature sensation used by Gagge and colleagues (ref. 19)

categories in a study of 'thermal sensation' (ref. 20). However, as shown above, the choice of these scales will have little effect on the estimation of comfortable or neutral temperatures.

The predictive model developed in the present study will be confined to thermal sensations, ranging from 'cold' through 'neutral' to 'hot'.

2.4 Methods of Scaling

The subjective estimates of warmth or comfort are obtained by means of rating scales, an example is shown in Figure 2.4.1. The number of categories on the scale can vary, seven being the most common, and the scales may be assymetrical about the mid point but with the possibility of a bias of results.

The two most commonly used scales are the Bedford scale (Fig. 2.4.1) and the scale used by the American Society of Heating, Refrigerating and Air conditioning Engineers (ASHRAE) shown in Figure 2.4.2 in its revised form (the word 'comfort' has been replaced by the word 'neutral').

Numbers are assigned to the categories which allows statistical analyses to be performed on the data collected with the scales and numerical predictions made which can be related to the verbal categories. The numbering of Bedford's scale (Fig. 2.4.1) is as originally used by Bedford and accounts for the negative correlation with the indices shown in table 2.2.1. Later workers have used this scale with the numbering system shown with the ASHRAE scale (ref. 20).

Numerical value	Sensation of warmth
1	MUCH TOO WARM
2	TOO WARM
3	COMFORTABLY WARM
4	COMFORTABLE
5	COMFORTABLY COOL
6	TOO COOL
7	MUCH TOO COOL

Figure 2.4.1 The Bedford scale of warmth

Numerical value	Thermal sensation
+3	HOT
+2	WARM
+1	SLIGHTLY WARM
0	NEUTRAL
-1	SLIGHTLY COOL
-2	COOL
-3	COLD

Figure 2.4.2 The ASHRAE scale of thermal sensations

In Bedford's original study the observer asked each respondent about his state of comfort and then classified his reply on the scale. However, voting slips and cards are often used for convenience. People's responses can also be recorded automatically (refs. 21 and 22).

The Bedford and ASHRAE scales have been compared (ref. 17) and have been found to behave in a similar manner; they show similar neutral temperatures and standard devitions, about votes, of 0.8 for closely controlled situations but increasing as the unusualness of the environment increases. Although the rate of change of vote with respect to temperature is slightly higher for the Bedford scale, the difference is not significant.

Humphreys suggests that the behaviour of the scales is influenced by the difference in the number of categories of the scales and not the terms used (ref. 23). However the Bedford and ASHRAE scales have the same number of categories. Comparison of the 'comfort' and 'temperature sensation' scales in Figure 2.3.2 shows that the rate of change of votes with respect temperature is higher for comfort than thermal sensation. Both scales have the same number of categories. Humphreys' data are taken from field studies, however, and McIntyre's and Gagge's from climate chamber work.

Other methods have been used in eliciting subjects' responses in thermal studies including dial voting, multidimensional scaling, direct determination and magnitude estimation.

The present study will be confined to predictions of thermal sensations using the ASHRAE seven point scale.

2.5 Limitations of the Environmental Indices

The environmental indices provide a method of comparing different environments, for example the Effective Temperature index allows us to predict that a sedentary man, lightly clad, would feel as warm in an environment with 32.2°C. globe temperature, 21.1°C. wet bulb temperature and air velocity of 3.05 m/sec. as he would in an environment with 24°C. globe temperature, 24°C. wet bulb temperature and 0.1 m/sec. air velocity.

Also, those indices based on data collected by verbal scales, for example Equivalent Warmth, allow predictions of the sensations of warmth. For example equation 2.5.1 relates comfort votes to environmental conditions from Bedford's data, disregarding changes in humidity which when moderate have little effect on comfort. Equation 2.5.1 allows us to substitute the value 4 (the numerical value equal to 'comfortable' on the Bedford scale, Fig. 2.4.1) for the variable S and determine combinations of environmental variables that will be felt comfortable.

$$S = 10{\cdot}89 - 0{\cdot}0318(t_a+32) - 0{\cdot}0292(t_w+32) + 0{\cdot}00162\sqrt{0{\cdot}005\,V}\,(100 - 0{\cdot}556(t_a+32)) \qquad 2.5.1$$

where S = sensation of warmth
ta = dry bulb temperature °C.
tw = wet bulb temperature °C.
and V = air velocity m/sec.

However, the environmental indices are not generally applicable to conditions of varying activity and clothing. An increase in the level of a person's activity increases the amount of heat generated internally by metabolic processes. Clothing provides an insulating layer around the body and therefore affects the heat lost from the body. Both these important factors are omitted from the environmental indices.

Although Effective Temperature has two charts, basic and normal, relating to different clothing insulation levels this does not allow comparison between clothing types. For example, if, of two environments, one is at an Effective Temperature of 21.1°C. on the basic scale and one at 21.1°C. on the normal scale what is implied is that in the first environment a man stripped to the waist will feel as warm as he would if he were similarly stripped in still and saturated air at 21.1°C., while in the second environment a man wearing normal clothing would feel as warm as if he were similarly clad in still and saturated air at 21.1°C. It does not mean that a man would feel as warm stripped to the waist in the one environment as he would fully clothed in the other (ref. 20).

2.6 The 'Rational' Approach

The importance of the rate of heat production in the human body and the insulation provided by clothing in determining the conditions of one's thermal sensations has led to the inclusion of these factors in some indices.

An early attempt at the inclusion of these two factors was in the Predicted Four Hours Sweat Rate (ref. 24). The index was determined by experiment and presented in the form of a nomogram with which predictions can be made of a Basic Four Hours Sweat Rate, to which corrections can be made for different activities and clothing weights. The index was developed for conditions not often met in buildings and is essentially for predicting conditions of stress.

The 'rational' approach is based on the heat balance between the human body and its environment.

When the body is doing no work the heat produced is equal to the total metabolic energy production. If the body is doing work, the heat produced is equal to the metabolic energy production less the energy expended in work. When the body temperature remains constant the heat loss from the body is equal to the heat produced within the body.

This energy balance is expressed by the following equation:

$$S = M - W - E + R + C \text{ watts} \qquad 2.6.1$$

where S = net rate of heat gain
M = the rate of metabolic heat production
E = total evaporative heat loss
R = heat gained by radiation
C = heat gained by convection
and W = work accomplished

The energy balance equation forms the basis of two further indices of thermal stress. The Heat Stress Index

of Belding and Hatch (ref. 25) predicts a numerical value for heat stress using the higher value from the following two equations:

$$S = \frac{E_{req}}{E_{max}} \times 100 \qquad 2.6.2$$

$$S = \frac{E_{req}}{516} \times 100 \qquad 2.6.3$$

where S = numerical value of stress
E_{req} = required evaporation in watts
and E_{max} = maximum evaporative capacity of the environment in watts

The constant 516 is the theoretical cooling value in watts of the evaporation of 1 litre of sweat, taken as the maximum sweating capacity per hour of an average person over an 8 hour period, setting the upper limit of the index.

The required evaporation is equal to the total heat stress on the body and is given by the following equation:

$$E_{req} = M \pm R \pm C \quad \text{watts} \qquad 2.6.4$$

Givoni's Index of Thermal Stress (ref. 26) develops this index and introduces the cooling efficiency of sweating. By expressing the value for heat stress in equation 2.6.2 as a fraction instead of a percentage and

allowing for energy to be used in work, equation 2.6.2 becomes:

$$S = [(M-W) \pm C \pm R]\, E_{max} \qquad \text{watts} \qquad 2.6.5$$

and by introducing the cooling efficiency of sweating instead of the maximum evaporative capacity of the air, we can derive Givoni's general formula:

$$S = [(M-W) \pm C \pm R]\,(1/f) \qquad \text{watts} \qquad 2.6.6$$

where $1/f$ is a function of both E_{max} and E_{req} .

The energy balance equation can be seen to form the basis of predictions of thermal responses at high temperatures, with the indices of thermal stress. It has also been used for predictions under more moderate conditions (refs. 1 and 27) which will be discussed later.

Returning to table 2.1.1, we can now extend the list of factors which need to be taken into account in a complete description of the factors affecting a person's thermal state and add:

internal heat production

clothing

The indices are essentially for predicting steady state conditions. However, the human body has evolved dynamic mechanisms, not accounted for in the indices, which work to maintain a steady state between the body's heat production and heat loss so that deep body temperature remains within narrow limits. These mechanisms will be discussed in the next section.

2.7 A Physiological Approach to the Human Thermal System

Three of the major dynamic responses of the body's thermoregulatory system are the control of metabolism, vascular control and control of sweating.

Metabolic rate is the rate at which the body utilises nutritive material from the oxidation of food. Metabolism is increased by exercise, muscular tension, shivering, chemical action, thermal stimulus and the specific dynamic action of foods. The energy given off by the oxidation process is converted mainly to heat. Although small amounts are converted to mechanical power and electrical currents these can be neglected for many cases.

Figure 2.7.1 illustrates the increase in metabolism, mechanical efficiency and heat production within the body due to increase in activity. Data is taken from Fanger (ref. 1) and heat production is calculated using his expression:

$$\frac{H}{A} = \frac{M}{A} \cdot (1 - \eta)$$

where H = rate of internal heat production watts
A = body area m^2
M = metabolic rate watts
and η = mechanical efficiency

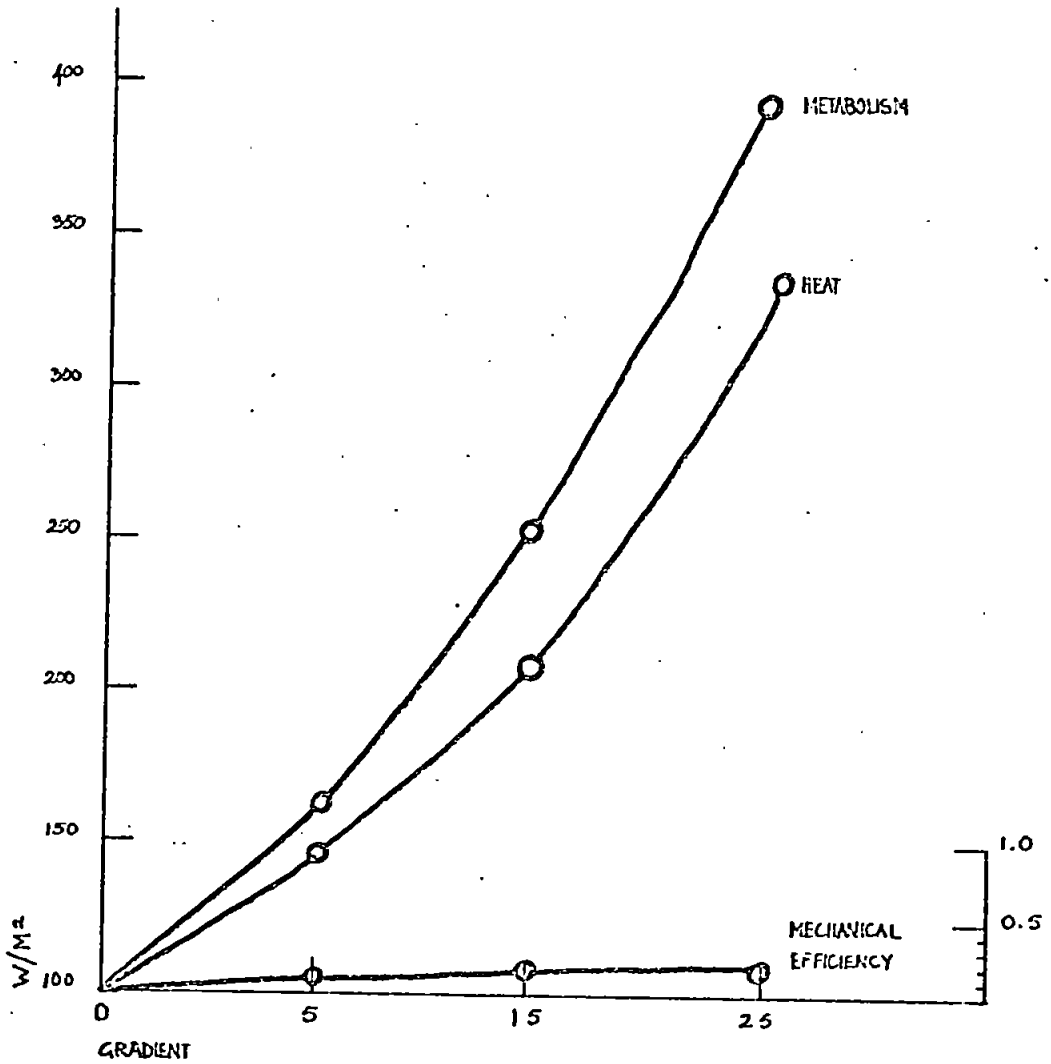

Figure 2.7.1 The increase in metabolic rate, mechanical efficiency and heat production, due to the increased activity in walking at 3·2 km/hr up various gradients

In hot environments the body responds with sudomotor activity (perspiration). At all times the body is losing heat by both evaporation from the surface of the skin and respiration, but the human thermal system has evolved to the stage where evaporation of moisture from the skin is the controlled method of body cooling. There is evidence to support the thesis that cooling by respiratory heat loss is an earlier and more general stage in evolution (ref. 28).

Moisture is transmitted to the skin surface by the eccrine sweat glands which are stimulated by the hypothalamus region of the brain (ref. 29) and local receptors in the skin (ref. 30). Sensible perspiration is the action of the sweat glands which is both controlled and noticed, producing a wetted skin surface. Insensible perspiration occurs constantly and is unnoticed, being the result of diffusion of water vapour through the skin (ref. 1) and evaporation of water from the lungs.

The action of the sweating response, as stimulated by the skin receptors, is illustrated in Figure 2.7.2, where regression lines are drawn through data obtained by Stolwijk and Hardy (ref. 31). Evaporative heat loss from the body is plotted against skin temperature.

However, Benzinger (ref. 29) has shown conditions under which this dependence of evaporative heat loss on skin temperature breaks down and he attributes the response to control by the hypothalamus. Figure 2.7.3 illustrates his conditions. Air temperature is held constant but the

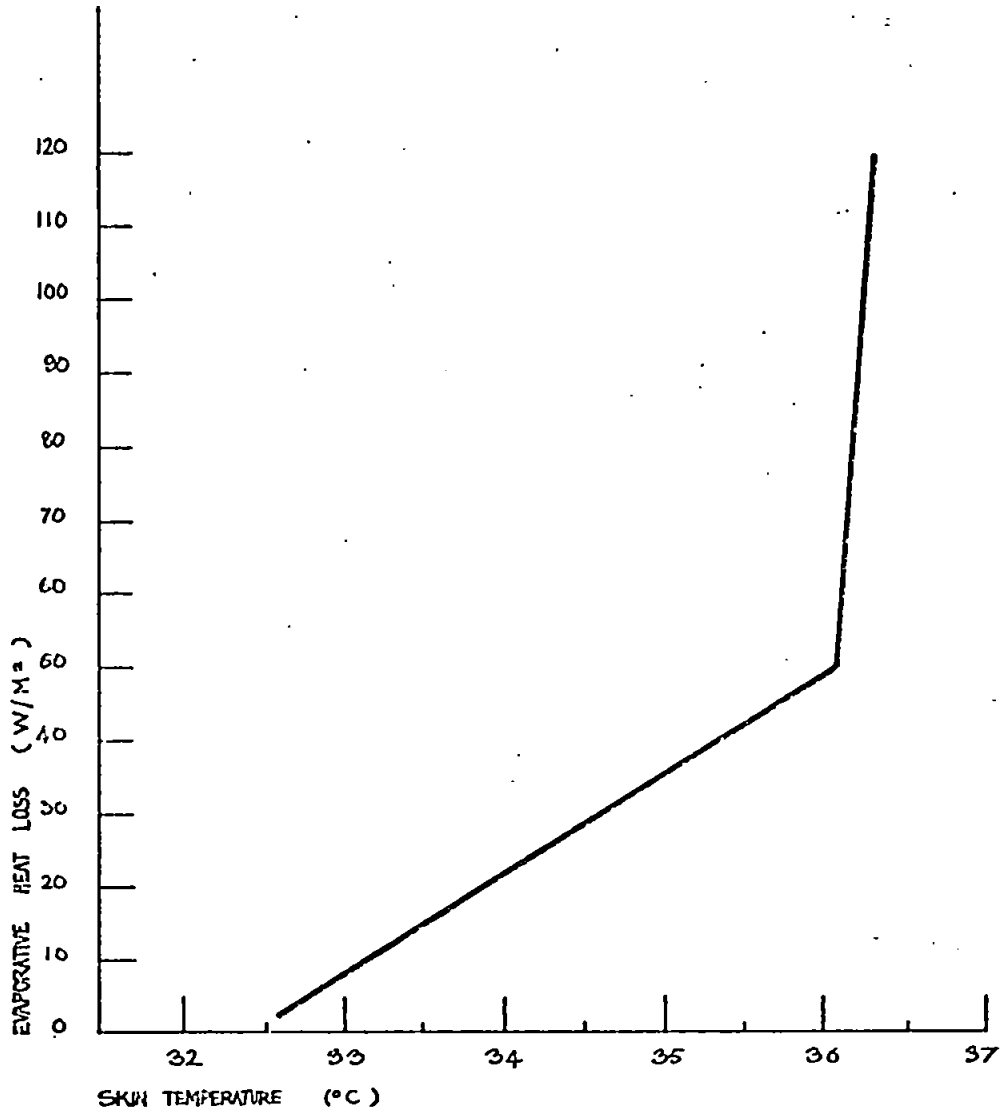

Figure 2.7.2 Evaporative heat loss as a function of average skin temperature, from Stolwijk and Hardy (ref. 31)

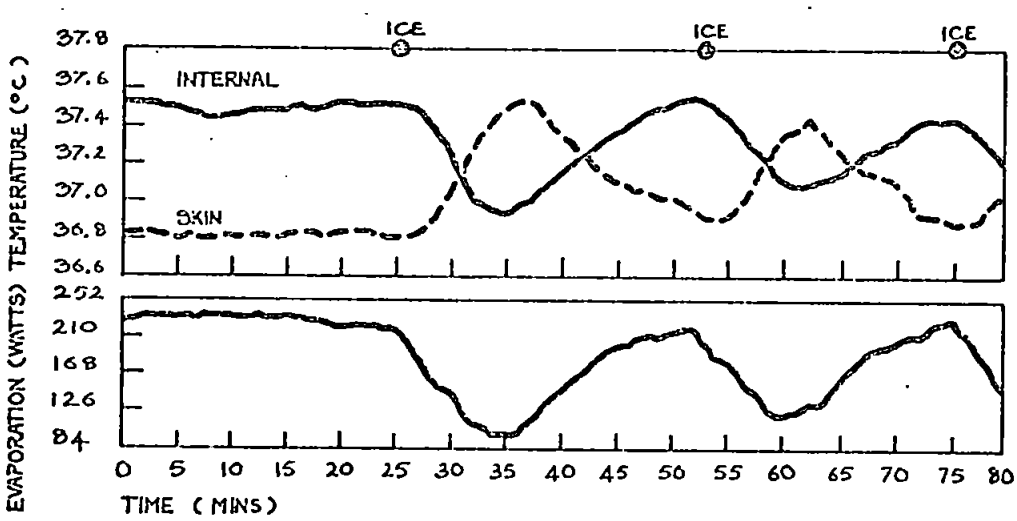

Figure 2.7.3 Evaporative heat loss and associated internal and skin temperatures on ingestion of ice, from Benzinger (ref. 29)

internal temperature of the subject's body is lowered by the ingestion of ice. The rate of evaporative heat loss drops with a drop in internal temperature while skin temperature rises.

Vasomotor response is the action of the vascular nerves in controlling blood flow. The muscles which control contraction and relaxation of the arteries remain in a state of partial contraction known as 'tone'. The heat produced in the body by metabolic action can only pass to the surface of the body to be dissipated from the surface, if the surface is at a higher temperature than its immediate environment (normally air). Blood flow is one of the means by which the body controls this temperature gradient, by conveying heat from the core to the periphery.

When stimulated by cold, the vasoconstriction nerves contract the blood vessels, so reducing blood flow and therefore heat flow to the surface, reducing heat loss. When stimulated by warmth the vasodilator nerves widen the vessels, so increasing blood flow and heat flow to the surface, increasing heat loss (ref. 30).

In considering the temperature regulating system of the body, it is convenient to postulate three zones of environmental thermal conditions stimulating the different responses; the thermally neutral zone (vasomotor response); the hot zone (sudomotor and vasodilation responses); and the cold zone (metabolic and vasoconstriction responses).

The thermally neutral zone, as determined in the climate chamber, is for a man lying quietly without activity or food (i.e. basal metabolic state) between 28 and 31°C. This zone

is characterised by vasomotor control. On prolonged exposure, there is no shivering or sweating, slight sensations of warmth, coolness and absence of sensation. Heat is being lost constantly from the body by insensible perspiration but control of heat loss is by slight constriction and dilation of the blood vessels (ref. 32).

The body's thermal receptors, in the hypothalamus, skin, respiratory tract and in other tissues act in the thermoregulatory system but vasomotor control is stimulated primarily by receptors in the skin (ref. 32). The receptors detect slight cooling of the skin and constriction occurs with a consequent rise of skin temperature due to a decrease in the rate of heat loss. The receptors detect this temperature rise, resulting in dilation, increase in the rate of heat loss and decrease of temperature.

The cold zone which for a nude man can be experienced on sudden exposure to mild cold (10 - 15°C.) is characterised by both metabolic and vasomotor responses. On experiencing the cold, the peripheral receptors of the respiratory tract and skin detect a change of air temperature and skin temperature respectively, stimulating both constriction of the blood vessels, decreasing heat loss, and periodic shivering, increasing metabolic rate by as much as three times normal level. The steady state between heat production and heat loss is reached after three to twelve hours, depending on the individual.

If exposure to the cold is gradual, the receptors in the skin may not be stimulated. Internal temperature may continue to fall until the hypothalamus stimulates shivering.

Sensation can be regarded as an important output from the thermoregulatory system, active in stimulating the behavioural responses of adding more clothing and exercising. Where exercising may not be possible, a posture may be adopted which restricts heat loss from the body, limbs being kept close to reduce effective surface area. The use of exercise is, however, not as efficient as shivering at decreasing heat loss because the body activity involved increases air movement and consequently convective heat loss.

The sensation of cold stimulates shivering which, in turn, causes a rise in skin temperature and a feeling of warmth. Heat loss is increased and shivering again stimulated. Internal body temperature may drop to a level where shivering is continuous and equilibrium is reached if the body does not become exhausted and can generate, by metabolism, the required heat. If this is not possible then the body can be regarded as being in a zone of inevitable cooling which, continued, will result in collapse due to hypothermia.

There is also evidence that, in extreme cold, vasodilation takes place with the adverse effect of increasing body heat loss (ref. 33).

On exposure of a resting man to the change from a neutral to a warm environment, skin temperature rises,

stimulating the warmth receptors in the skin which initiate vasodilation and sweating. As the sweat evaporates the skin is cooled, decreasing stimulation of the receptors until the sweat dries sufficiently and skin temperature rises again. If the man remains resting and the warmth is very mild (31 - 33°C.) this action would be sufficient to maintain equilibrium which is usually established in less than an hour (ref. 32).

On exposure to a warm environment from a cold one vasoconstriction is released, with a consequent lowering of internal temperature, possibly stimulating shivering. As the body temperature rises vasodilation occurs and sweating begins. The sensation of warmth, like the sensation of cold, is active in stimulating behavioural responses such as removal of clothes and a relaxed posture (ref. 34), increasing effective surface area.

To the extreme of this hot zone, is a zone of inevitable heating. Sweat secretion may continue with rising internal temperature but evaporation from the skin surface has become ineffective, due to the increasing area of wetted skin. The theoretical maximum value for skin wettedness is unity but the critical point of failure is when the skin is about 80 per cent covered with sweat (ref. 35).

2.8 Laboratory Studies of Thermal Transients

The physiological study of the mechanisms of human thermal control has led to a number of laboratory experiments

investigating adjustments of the human body to changes in the thermal environment. Gaining support from the American space and heating, ventilating and air conditioning industries, these studies have noted the effects on normal and diseased people of environments more extreme than normally encountered in buildings in the British climate. However they do provide quantitative evidence for the regulatory mechanisms outlined in section 2.7.

Glückman and colleagues conducted a series of climate chamber experiments in which subjects sat in a room for one hour, moved into a second room and sat for one or two hours, then returned to the first room and sat for another hour. Room 1 was maintained at a dry bulb temperature of 76°F. ± 0.5 (24.4°C. ± 0.3), globe thermometer temperature ranging between 76.2 and 76.6°F. (24.6 and 24.8°C.), one of three relative humidities, 30, 60 or 80 per cent and constant air velocity of 25 ft./min. (0.13 m/s). This room was designated 'comfortable'. Room 2, designated 'hot', was maintained at 98.5 ± 1°F. (36.9°C. ± 0.6) air temperature, globe temperature between 97.2 and 98.8°F. (36.2 and 37.1) and relative humidity 66 per cent. Air velocity was the same as the 'comfortable' room.

Figure 2.8.1 is a replot of some of their data (ref. 36) illustrating the rise in average skin temperature which is seen to be almost complete after the first ten minutes. There is a corresponding drop in internal temperature, with a maximum value of 0.6°F. (0.33°C.) for which they give the

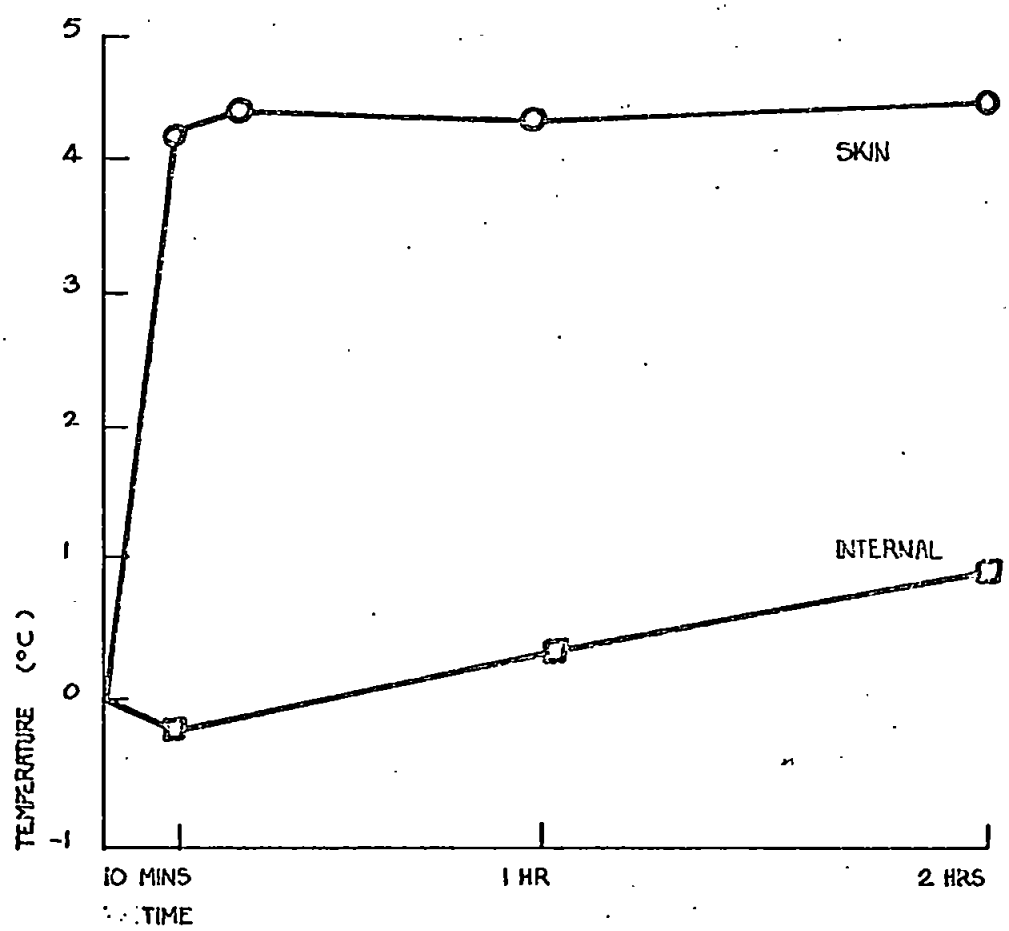

Figure 2.8.1 Replot of data from Glickman and colleagues (ref. 36). Changes in internal and skin temperatures on moving from a comfortable to a hot room

following explanation. On entering the hot room, dilation occurs resulting in rapid redistribution of blood and consequently a transfer of heat from the deep to the superficial tissues. This raises skin temperature, stimulating activity of the sweat glands and increasing heat loss.

On return to room 1, the opposite effect was found. Within the first ten minutes, internal temperature increased (a maximum value of 0.5°F., 0.28°C.), indicating the temporary storage of heat due to constriction and reduced blood flow.

In section 2.7 the action of sweating was associated with skin temperature and internal temperature. Glickman and colleagues observed the onset of sweating in this series of experiments when the subjects moved from the 'comfortable' room to the 'hot' room. Dressed in union suits, men were found to start sweating, on average, about 10 minutes after entry to the hot room, whilst women started at an average of 20 minutes. However, skin temperature levels attained in 10 minutes were the same for both sexes (ref. 37). Although the difference in starting times is significant, it is worth noting that there was a large variation between subjects and within subjects between experiments. In the study on men, the earliest that perspiration was noticed was 2½ minutes and the latest 29 minutes. One subject perspired between 2½ and 4½ minutes throughout six experiments whilst another perspired as early as 10 minutes and as late as 29 minutes (ref. 36).

The role of the hypothalamus in stimulating sweating was discussed in section 2.7. Hardy and Stolwijk (ref. 38) provide evidence for the role of the hypothalamus in stimulating shivering. Figure 2.8.2 shows their data for a four hour exposure at 13°C. Shivering is indicated by the sharp increase of metabolism at about the 180th minute. At this point, no change is registered in skin temperature or rectal temperature. However, there is a fall in tympanic temperature of about 1°C. Although no causation is necessarily implied by the behaviour of these two curves, it is difficult to attribute the changes of metabolism to other causes.

If we suppose that as the skin temperature has been falling gradually throughout the experiment (Fig. 2.8.2) it has reached a particular temperature after 3 hours which stimulates skin receptors, triggering the increase in metabolism (shivering), then we would expect that as the skin temperature continues to fall, metabolic rate would continue to rise. This is not the case. At about the 200th minute, metabolic rate is shown to decrease and a corresponding increase in tympanic temperature is observed. Rectal temperature behaves in much the same way as does skin temperature and a similar analysis could be applied.

The rapidity with which the body regulates the heat losses and gains is indicated by Figure 2.8.3, taken from Hardy and Stolwijk (ref. 38). The arrows indicate the time at which a change of environment was made. The symbols refer

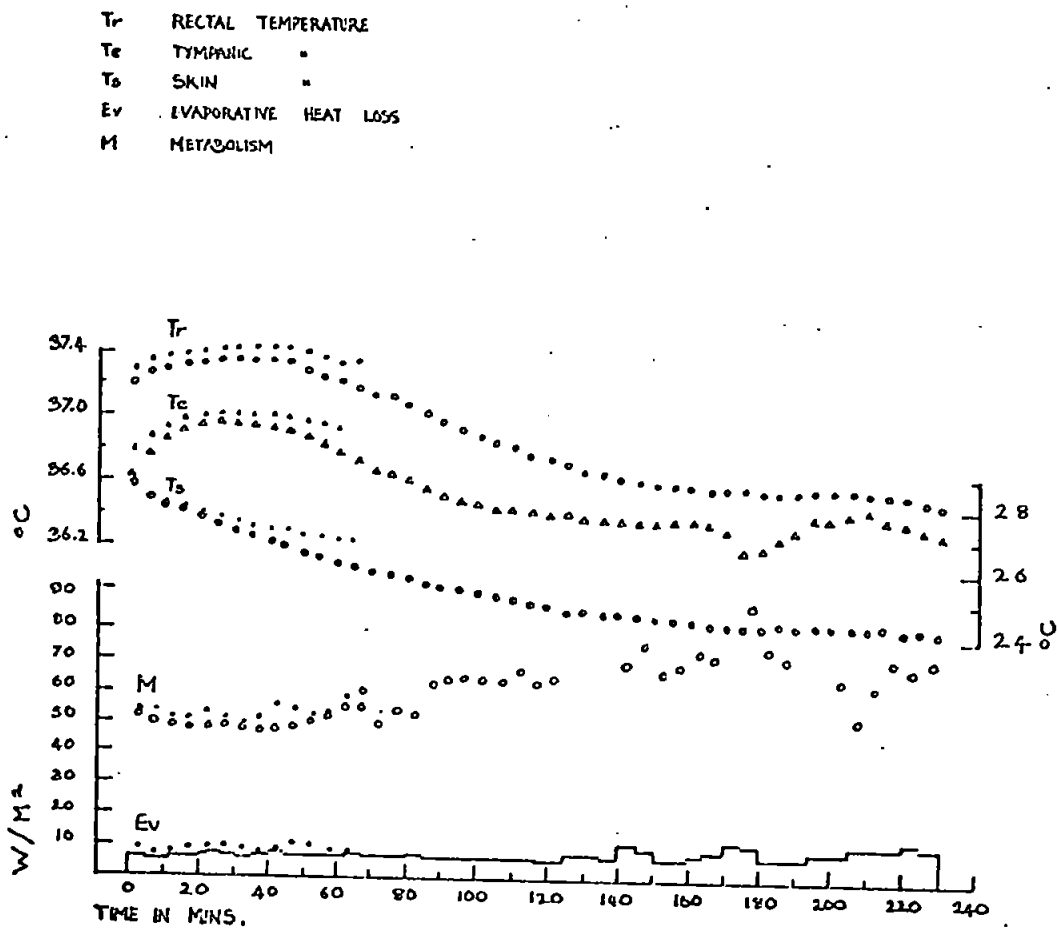

Figure 2.8.2 Averaged data for 1-hr exposure at 13 deg. C and single 4-hr exposure at 13 deg. C. Taken from Hardy and Stolwijk (ref. 38)

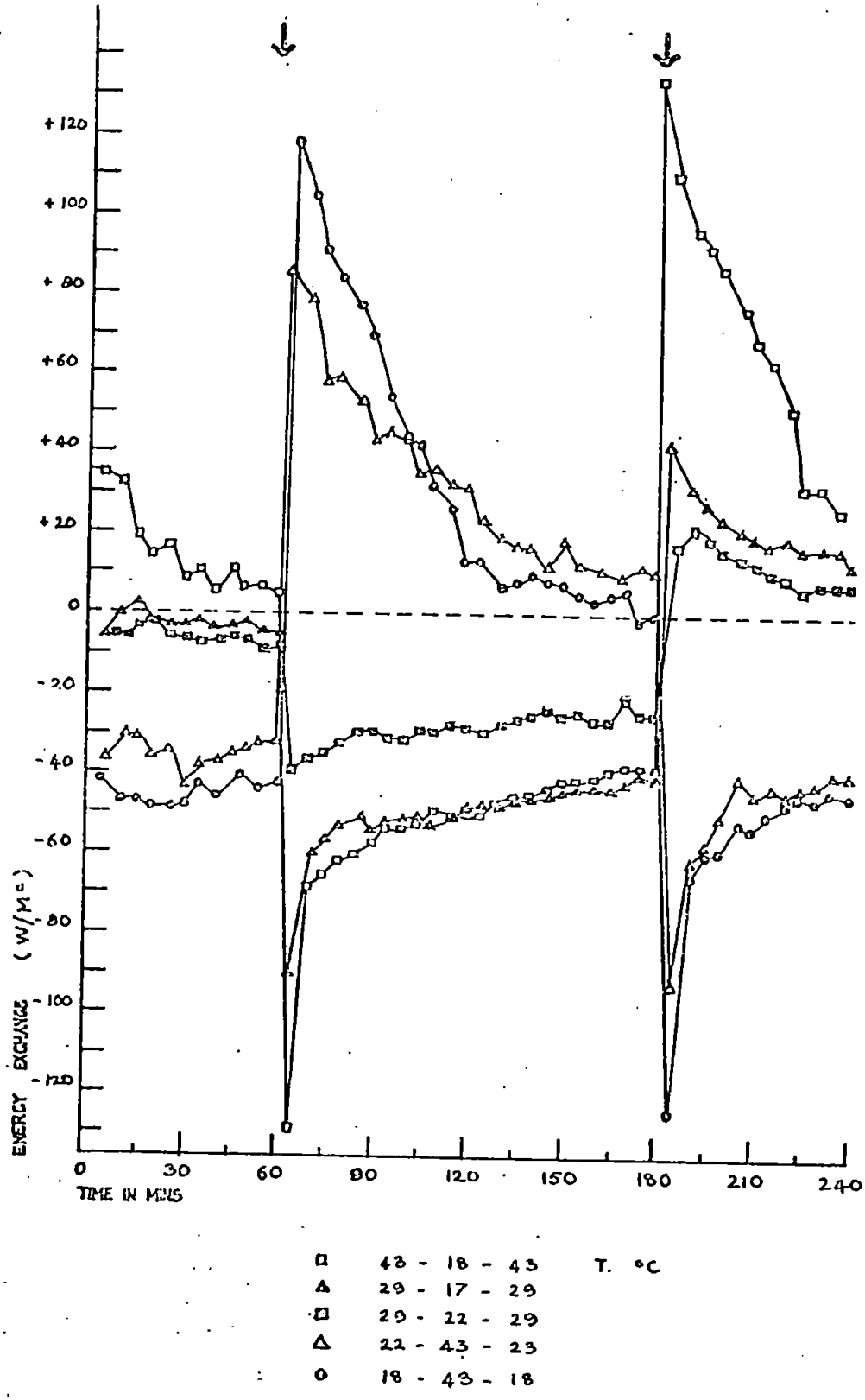

Figure 2.8.3 Rates of energy exchange during steady states and transients. Taken from Hardy and Stolwijk (ref. 38)

to temperatures in the test rooms. Values of energy exchange are determined from the differences between the rates of heat production and loss.

When the subjects moved from cold conditions (rate of energy exchange is about -40 w/m^2, representing a continuing heat loss) to the hot conditions, a rapid storage of heat takes place, decreasing rapidly at first and brought to minimum levels after the 2 hour period.

The change from hot environments (energy exchange approximately zero) to cold ones causes a rapid loss of body heat followed by a sharp and then more gradual decrease of heat loss. The sharp decrease is attributed to vascular constriction. However, the heat losses are still evident (at about -30 to -40 w/m^2) after the 2 hour period. In these experiments the body appears better fitted to restoring heat balance in the hot environments than in the cold ones.

2.9 Concluding Remarks

Psychophysical scales have been used which allow us to record and analyse people's thermal sensations (or state of comfort). It is also possible to make numerical predictions which can be related to these scales and, therefore, allow us to make predictions about people's thermal sensations (or state of comfort).

These numerical predictions must relate to a person's interaction with the thermal environment, which is complex and involves many factors. The major environmental and physiological factors have been discussed.

The factors which must be taken into account when considering the effect of a changing thermal environment on a person's sensations are:

The dynamic regulatory mechanisms of the body

Internal heat production of the body

Clothing

Air temperature

Air velocity

Air humidity

Radiation from surrounding surfaces

References, Section Two

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3. Modelling the Human Thermal System

3.1 Control Systems

In early attempts at computer simulation of the human thermal system it was seen that the heat exchange, between the body and its environment is regulated by the physiological mechanisms outlined in section 2.7, in an attempt to maintain constant deep body temperature (ref. 1). On the assumption that the body's methods of heat production and loss are regulated about a 'set point', with this aim, the technology of control systems has been applied to simulating the thermoregulatory system.

Hardy outlines four basic types of 'closed loop' control systems (ref. 2). Closed loop control systems have the characteristic of using feedback (the use of output from the system to affect input), in an attempt to control the system within a prescribed deviation from the set point. Figure 3.1.1 illustrates the theoretical temperature of a system due to four types of control.

The 'on/off' regulator is one of the simplest regulators, characterised by an all or nothing response (Fig. 3.1.1a). The normal thermostat is an example of the on/off regulator which switches on with deviation from the desired temperature. The greater the thermal load, the longer the 'on' period of the regulator and the greater the value of the controller output, the greater the ability of the system in controlling heat loss or gain.

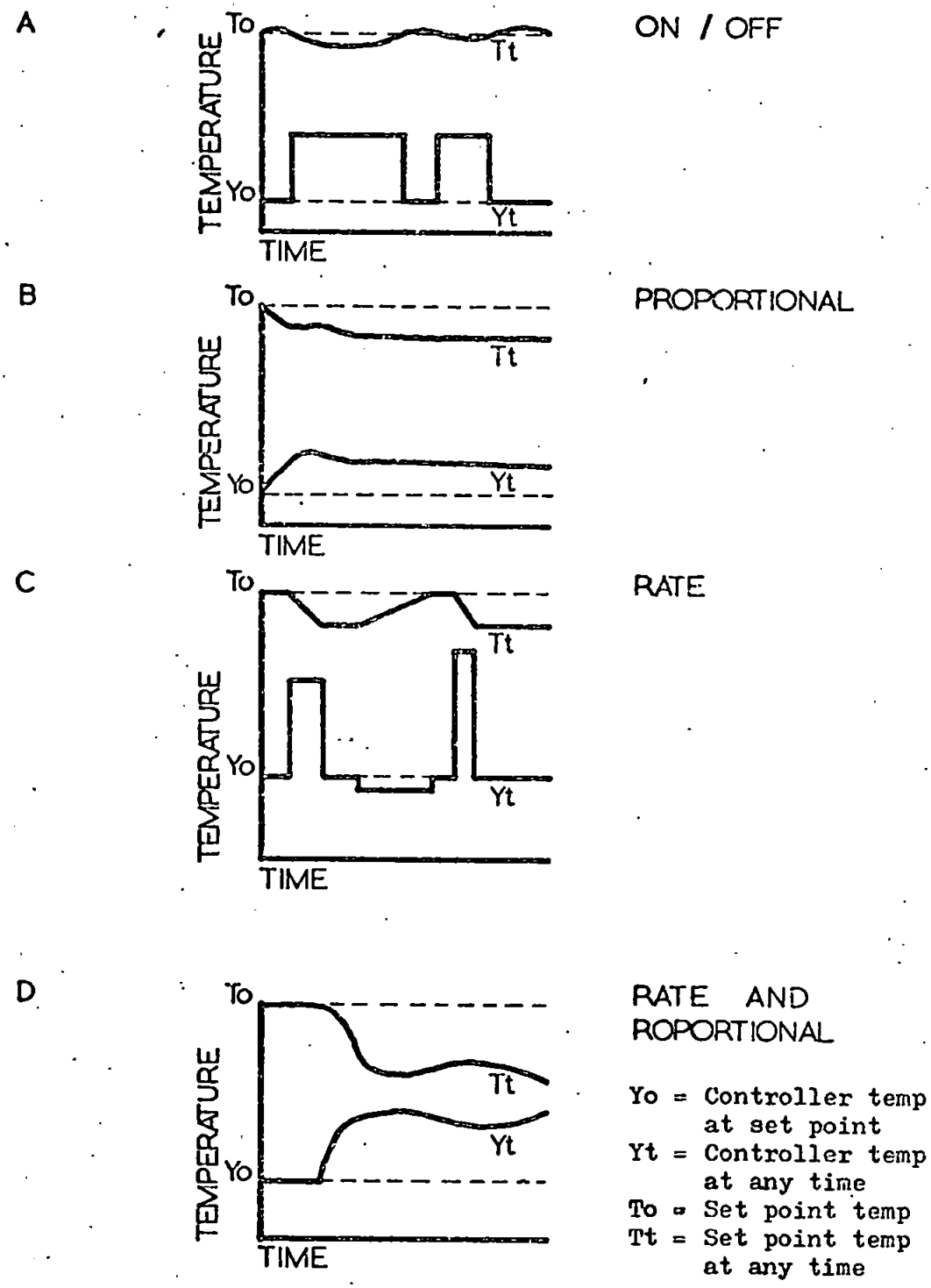


Figure 3.1.1 Theoretical temperature regulating control systems, showing the type of response to deviation of the system from the set point

This response can possibly be seen, in the thermo-regulatory system, in controlling shivering which can occur in bursts. The length of time spent shivering will increase with the cooling load and the 'on' periods may fuse into a continuous effort. By acclimatisation, the capacity of the regulating system, and hence its ability to regulate, may be increased.

With on/off regulators, due to thermal lags in a system, there must always be oscillations in temperature about the set point. Where close control is required, this may be unacceptable.

A stable type of regulation is 'continuous proportional control' (Fig. 3.1.1b). In a thermal system this is characterised by a relationship between the controlled temperature error, the deviation from the set point (input), and the maghitude of effector action (output). This type of control is illustrated by the fact that body temperature (and therefore the cooling load of the system) rises in proportion to exercise, over a range of cold and warm environments, the cooling system therefore being driven in proportion to the difference between body temperature in exercise and the body temperature at rest.

A third type of control is 'rate control' (Fig. 3.1.1c), characterised by a relationship between the rate of change of temperature and the magnitude of effector action. It can be seen that this type of regulator will quicken the response of a system but not regulate temperature at a fixed

level. This type of control, being responsive to rate, can be said to 'recognise', at once, the magnitude of a thermal load and is sometimes called 'anticipatory', possibly producing what may appear as over corrections. It is often combined with proportional control, providing a more rapidly responding system.

Stolwijk and Hardy have suggested that the rapid response of the body in restoring the heat balance when the environment changes from 28° to 38°C. compared with a much slower response, when the change is from 28° to 33°C. (Fig. 3.1.2) may indicate that the thermoregulatory system has a significant degree of rate control (ref. 3).

It has been suggested that this simplified view of the thermoregulatory system, as a typical negative feedback loop, differs in several particulars from the biological control system that it is (ref. 4). However, models of physiological temperature regulation in man have been produced.

Control systems alone do not describe the body's thermal regulating system. Equations describing body temperature equilibrium (the set points) and body heat transfer (the passive system) together with control systems provide a more complete description.

3.2 The Development of Mathematical Models of Temperature Regulation

One of the earliest models of the human thermal system was a model of the human forearm, developed by Pennes (ref. 5).

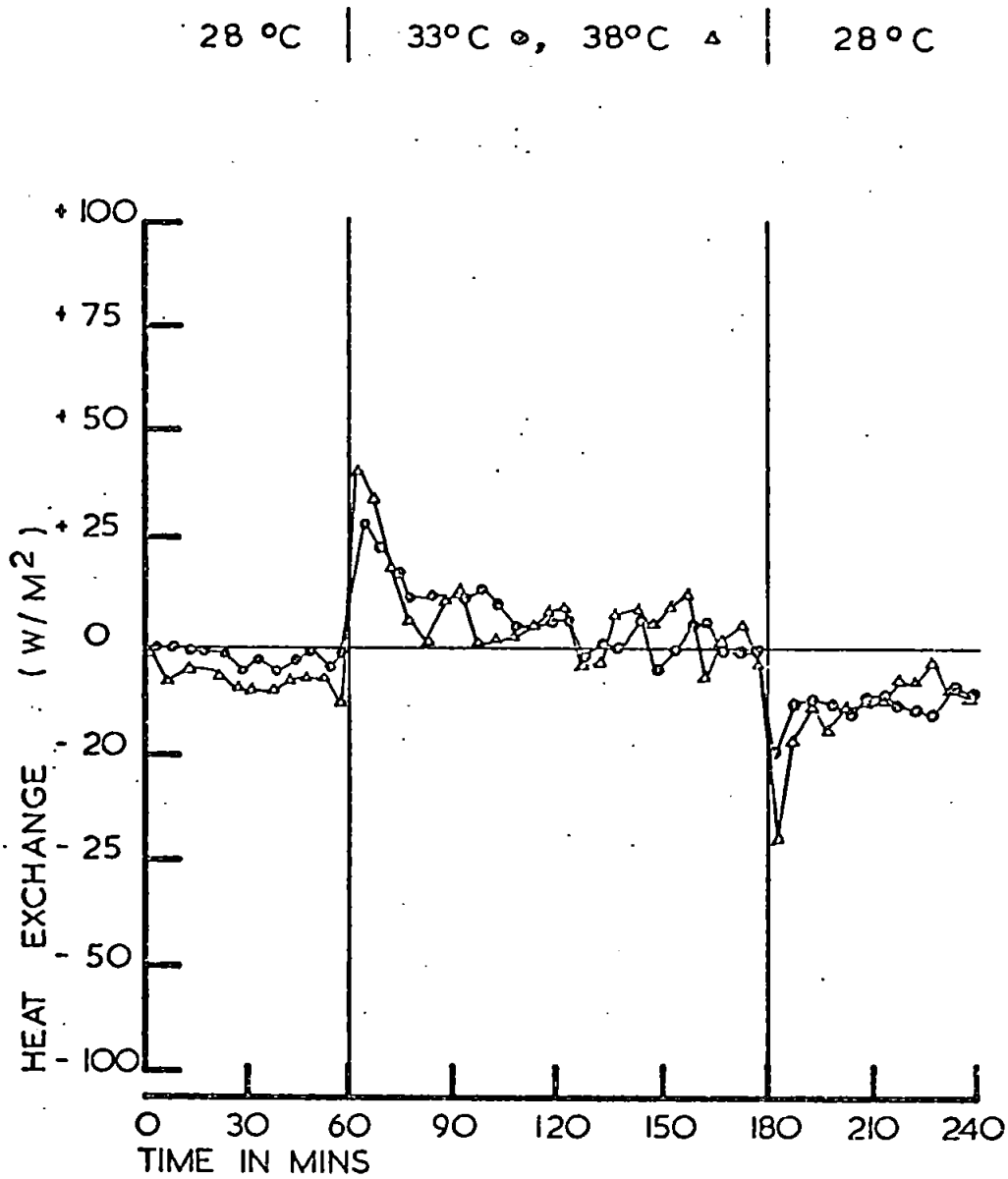


Figure 3.1.2 Comparison of rate of restoration of heat balance during thermal transients, from Stolwijk and Hardy (ref. 3)

A description of this model is not necessary here but it is worth noting that an important aspect of the model was its simplification of the geometry of the arm, approximating it to a cylinder.

Machle and Hatch presented the following model as the basic equation of heat balance and introduced the concept of concentric shells, referring to the core and shell of the body (ref. 6).

$$M + D - V = R + C + E \quad \text{watts} \qquad 3.2.1$$

where M = metabolic rate
D = rate of change of body heat content
V = rate of heat loss by respiration
R = rate of heat exchange with the environment due to radiation
C = rate of heat exchange with the environment due to convection
E = rate of heat exchange with the environment due to evaporation

Crosbie and colleagues considered heat transfer through the human body in a model of even more simple geometry, that of a slab (Fig. 3.2.1). However, they made an important advance by including the regulatory mechanisms of temperature control (ref. 7).

The slab's cross section is divided into three layers, of appropriate thickness, representing the body's skin layer, muscle layer and core. Each layer is assumed to have uniform thermal properties and each layer will lose heat to or gain heat from its adjacent layer, in proportion to the temperature

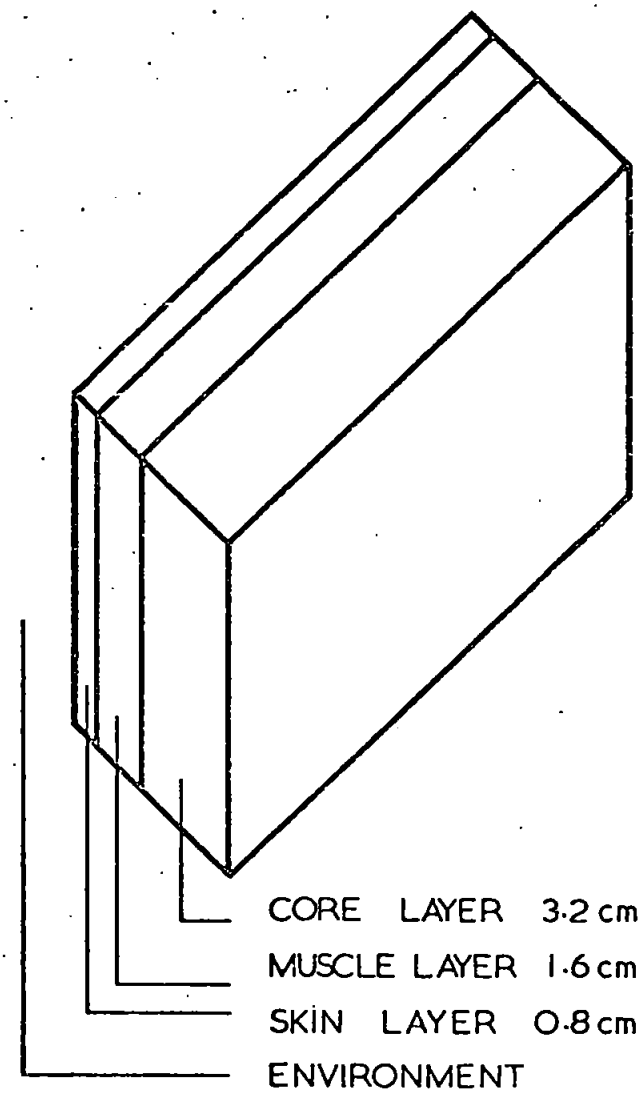


Figure 3.2.1 Diagrammatic representation of heat flow from interior of body to skin surface, in the model of physiological temperature regulation by Crosbie and colleagues (ref. 7)

difference between it and its adjacent layer. The heat flow is unidirectional (from core to surface) and the core is ideally insulated except for heat flow to the surface.

The heat transfer, for the whole model, is given by equation 3.2.2 (symbols for equations are given in Appendix A).

$$\rho c \frac{dT}{dt} = K \frac{d^2T}{dX^2} + M' - R' - V' \qquad 3.2.2$$

Equation 3.2.2 states that the rate of thermal energy stored, in a unit volume, is equal to the rate of heat conducted into the system, plus the rate of heat generated by metabolism M', minus the rate of heat loss, by radiation and convection R', minus the rate of heat loss by vaporisation V'. Crosbie and colleagues approximated equation 3.2.2 by writing heat balance equations for each layer. Thus, equations 3.2.3, 3.2.4 and 3.2.5 give the amount of heat stored per unit time, per unit cross sectional area, in the outer, middle and core layers respectively.

The Passive System

$$\rho c \Delta X_S \frac{dT_S}{dt} = \overbrace{\frac{K}{\Delta X_{S1}}(T_1 - T_S)}^{\text{CONDUCTIVE (FROM MSCL.)}} - \overbrace{h(T_S - T_A)}^{\text{RADIATION CONVECTION}} - \overbrace{V}^{\text{VAPORISATION}} \qquad 3.2.3$$

$$\rho c \Delta X_1 \frac{dT_1}{dt} = \overbrace{\frac{K}{\Delta X_{12}}(T_2 - T_1)}^{\text{CONDUCTIVE (FROM CORE)}} - \overbrace{\frac{K}{\Delta X_{S1}}(T_1 - T_S)}^{\text{CONDUCTIVE (TO SKIN)}} - \overbrace{\Delta M}^{\text{SHIVERING EXERCISE}} \qquad 3.2.4$$

$$\rho c \Delta X_2 \frac{dT_2}{dt} = \overbrace{M_0}^{\text{BASAL METABOLISM}} - \overbrace{\frac{K}{\Delta X_{12}}(T_2 - T_1)}^{\text{CONDUCTIVE (TO MUSCLE)}} \qquad 3.2.5$$

We can see from the above equations how the thermal system is represented. $h(T_S - T_A)$, heat loss by radiation and convection and V, heat loss by vaporisation, are surface effects only. Δ M, additional metabolic heat, is generated in the muscle layer, due to shivering and exercise. Mo, basal metabolism, is a property of the core.

The system, as represented so far, in terms of control systems, is an 'open loop'. There is no feedback to the controlling system; change of metabolism, conductance and vaporisation. Physiologically these represent muscle tension, shivering and exercise; vasomotor activity; and sudomotor activity respectively.

The average body temperature is calculated on a weighted basis according to layer thickness, as in equation 3.2.6.

The Set Point

$$T_{B_0} = \frac{\Delta X_S T_{S_0} + \Delta X_1 T_{1_0} + \Delta X_2 T_{2_0}}{\Delta X_S + \Delta X_1 + \Delta X_2} \qquad 3.2.6$$

Basal average body temperature represents the set point of the system. Changes in body temperature cause changes in the controlling system, as described by equations 3.2.7 and 3.2.8.

The Controlling System

If body temperature is greater than basal:

$$\left.\begin{aligned} K &= K_0 \left(1 + \alpha k + \Delta T_B + \gamma k \frac{dT_B}{dt}\right) && \text{[VASOMOTOR RESPONSE]} \\ \Delta M &= E && \text{[METABOLIC RESPONSE]} \\ V &= V_0 + \delta_E \left(\alpha_V \Delta T_B + \lambda_V \Delta T_B^4\right) && \text{[SUDOMOTOR RESPONSE]} \end{aligned}\right\} \quad 3.2.7$$

If body temperature is less than basal:

$$\left.\begin{aligned} K &= K_o\left(1 + \alpha_k - \Delta T_B + \gamma_k \frac{dT_B}{dt}\right) && \text{[VASOMOTOR RESPONSE]} \\ \Delta M &= -\alpha_m \Delta T_B + E && \text{[METABOLIC RESPONSE]} \\ V &= V_o && \text{[SUDOMOTOR RESPONSE]} \end{aligned}\right\} \quad 3.2.8$$

Crosbie and colleagues used an analogue computer to solve the equations describing the model and made predictions for various transient situations. Figure 3.2.2 shows the case where a person is suddenly moved from a warm environment, 32°C. air temperature, to a cold one at 16°C. (ref. 7). Superimposed on these predictions are data from an earlier experiment by Hardy (ref. 8). Predictions of skin temperature and rectal temperature correlate well with data. Heat loss and metabolic rate do not correlate so well.

The curves predicted by the model are shown again in Figure 3.2.3. Superimposed on these curves are curves taken from other data by Hardy and Stolwijk (ref. 9), for two similar conditions. The curves for skin and rectal temperature illustrate changes from 28°C. to 18°C. and from 43°C. to 17°C. The predicted curve of rectal temperature changes more slowly with respect to time and is higher than both these curves, for the first two hours, although the curves are within the range to be expected between individuals (ref. 9). Similarly, the predicted curve of skin temperature changes more slowly than curves fitted to data, although these too are within the range expected between individuals.

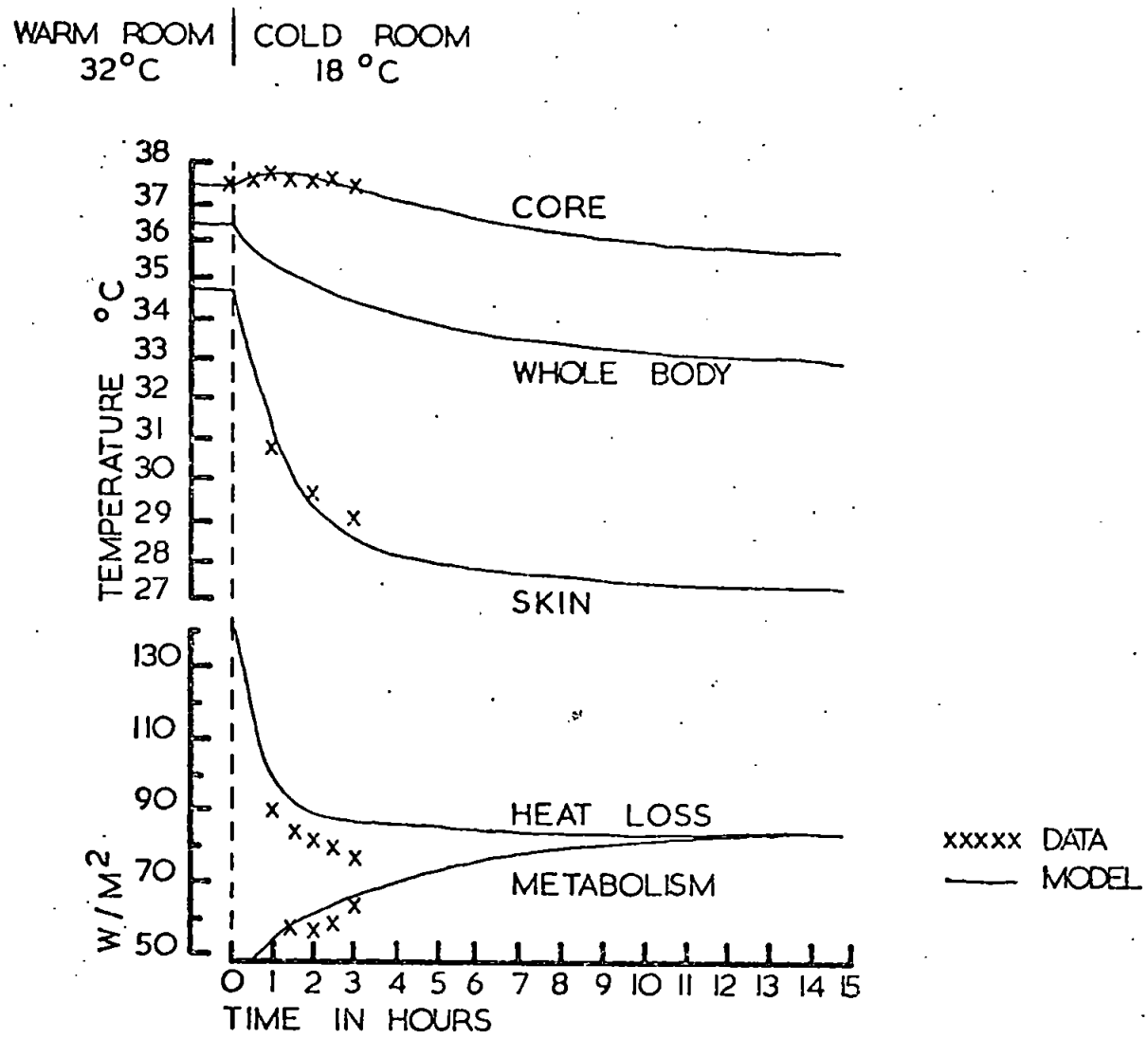


Figure 3.2.2 Predictions by Crosbie of transient response, when moved from a warm room to a cold room, with data from Hardy (ref. 8) for the first 3 hrs

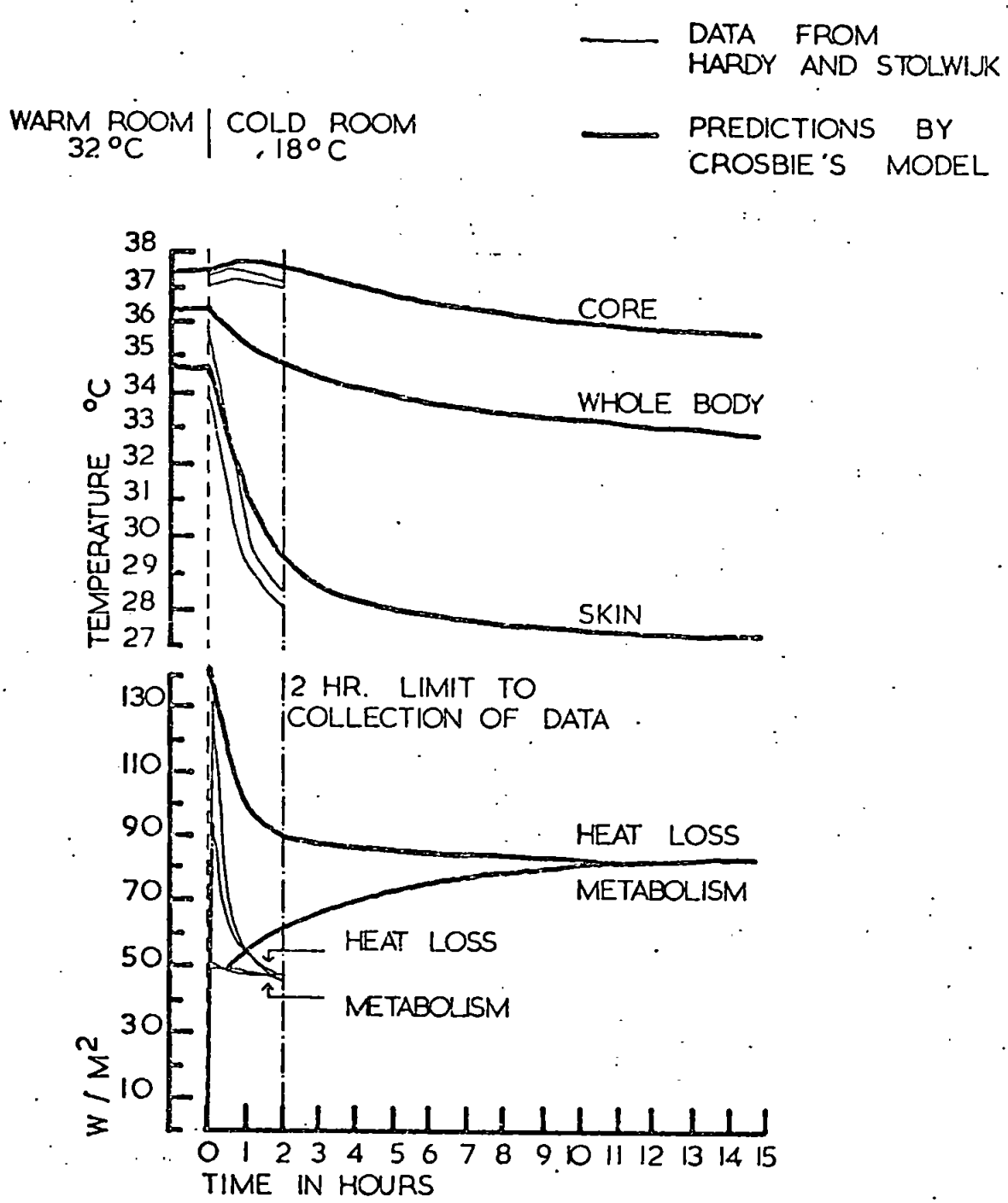


Figure 3.2.3 Predictions by Crosbie for thermal transients compared with data for first 3 hrs from Hardy and Stolwijk (ref. 9)

The curves for metabolic rate are fitted to data for the same transient conditions. The heat loss curve is fitted to data for the transient conditions 29°C. to 17°C. and 43°C. to 18°C.

The predicted curve shows an immediate increase in heat loss falling sharply for the first hour and having almost levelled off after the second hour to an almost steady value of 95 w/m^2 (heat loss). In contrast, curves fitted to the data are not so steep in the increase of heat loss within the first ten minutes, but after two hours have reduced to an almost steady value of 45 w/m^2. The difference between the predictions and data is outside the limits to be expected.

The increase of metabolic rate which the model predicts as a function of body temperature in an attempt to balance the predicted heat loss is consistent within the model (metabolic rate finally reaches the same value as heat loss) but unrealistic when compared with the data.

The data show that with only small fluctuations, metabolic rate is seen to drop slightly over the two hour period recorded. The general level is around 45 w/m^2, balancing against the 45 w/m^2 heat loss. The difference between the prediction of metabolism and that taken from data is well outside the expected limits (a range of 40 to 58 w/m^2 at 17°C.).

Returning to Figure 2.8.2 which shows the metabolic increase taken from Hardy and Stolwijk for more severe cold conditions, we can see that over a four hour period, there is a slight rise in metabolic rate (from 52 to 81 w/m^2, with a short peak at 95 w/m^2).

continued on page 84

As noted earlier, this curve of metabolic rate shows a close reciprocal relationship with the curve of tympanic temperature, indicating the action of the hypothalamus. This suggests that Crosbie's equation for metabolic rate control 3.2.9 would be better founded as a function of internal temperature rather than whole body temperature, with its over-emphasis on skin temperature.

$$\Delta M = -\alpha m \Delta T_B + E \qquad 3.2.9$$

This is indicated by Crosbie's prediction also. Figure 3.2.3 shows a similar reciprocal relationship between the predicted rectal temperature and metabolic rate data over the first two hours.

A model devised by Stolwijk and Hardy (ref. 10) makes several advances on this model. As Crosbie and colleagues realised, the body could be better represented by a cylinder and the model by Stolwijk and Hardy proposes a series of three cylinders to represent the human body (Fig. 3.2.4). The model contains another important addition, in taking into account blood flow and containing a central blood pool (contained within the trunk). Each cylinder loses heat to the environment radially and heat is transferred between cylinders via the blood.

The head is represented by two concentric cylinders (core and skin); the extremities are similarly represented by two concentric cylinders; and the trunk is represented by three concentric cylinders (core, muscle and skin).

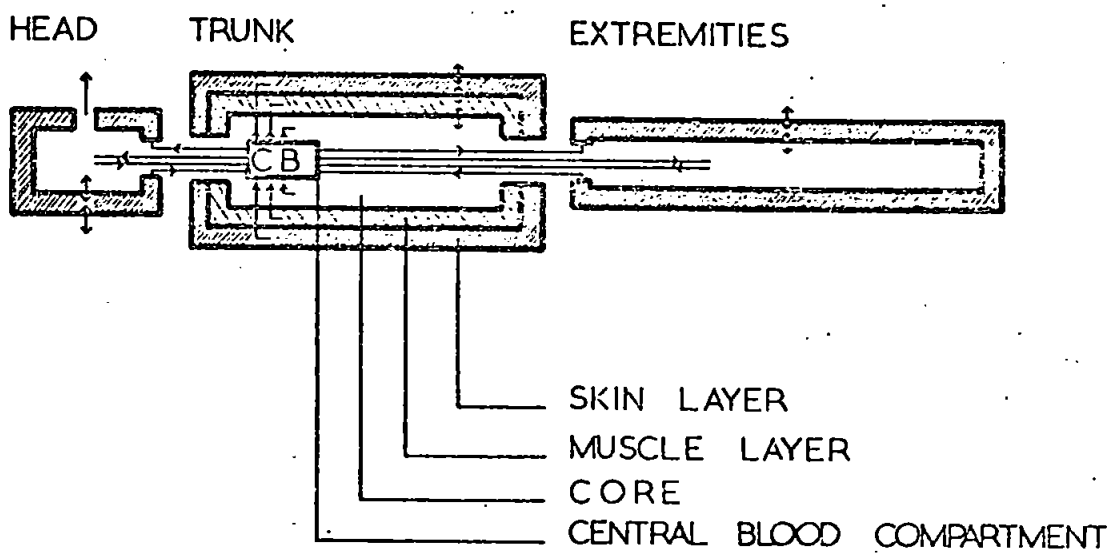


Figure 3.2.4 Block diagram of thermal model of man, showing heat exchanges (arrows), as proposed by Stolwijk and Hardy

The whole system is again seen as comprising two parts, the passive system and the controlling system. The passive system does not exhibit control characteristics but represents a complex transfer function between controller and disturbance (regulatory response and receptor message). The controlling system accepts signals, from the passive system (receptor message) and exerts corrective actions on the passive system, if the receptor message indicates deviation from preferred conditions (set point (s)).

A series of heat flow equations, 3.2.10 to 3.2.17, one for each layer, describes the passive system.

The Passive System

Heat flow through head core

$$C_{HC} \cdot \frac{dT_{HC}}{dt} = \overbrace{\alpha_{HC}\, qc \times 48(T_{CB} - T_{HC})}^{\text{CONVECTIVE (BLOOD)}} + \overbrace{M_{oHC}}^{\text{BASAL METABOLISM}} + \overbrace{0.04\,\Delta M}^{\text{SHIVERING METABOLISM}} \qquad 3.2.10$$

$$- \overbrace{K_{HC\,HS}(T_{HC} - T_{HS})}^{\text{CONDUCTIVE (TO SKIN)}} - \overbrace{E_{VR} - E_V}^{\text{(AIRWAYS) EVAPORATIVE}}$$

Heat flow through head skin

$$C_{HS} \cdot \frac{dT_{HS}}{dt} = \overbrace{K_{HC\,HS}(T_{HC} - T_{HS})}^{\text{CONDUCTIVE (FROM CORE)}} + \overbrace{M_{oHS}}^{\text{BASAL METABOLISM}} - \overbrace{0.09\,E_{V_{oHS}}}^{\text{INSENSIBLE PERSPIRATION}} - \overbrace{0.09\,E_V}^{\text{EVAPORATION}} \qquad 3.2.11$$

$$+ \overbrace{\alpha_{HS}\, qc \times 0.138\,SBF(T_{CB} - T_{HS})}^{\text{CONVECTIVE (BLOOD)}} - \overbrace{A_{HS}.h_o(T_{HS} - T_a)}^{\text{RADIATION / CONVECTION}}$$

Heat flow through core of extremities

$$C_{EC} \cdot \frac{dT_{EC}}{dt} = \overbrace{\alpha_{EC}\, q_C \times 0.58 MBF (T_{CB} - T_{EC})}^{\text{CONVECTIVE (BLOOD)}} - \overbrace{K_{ECES}(T_{EC} - T_{ES})}^{\text{CONDUCTIVE (TO SKIN)}} \qquad 3.2.12$$

$$\overbrace{+\ 0.58\ \Delta M}^{\text{SHIVERING}} \quad \overbrace{+\ 0.58\ E}^{\text{EXERCISE}}$$

Heat flow through skin of extremities

$$C_{ES} \cdot \frac{dT_{ES}}{dt} = \overbrace{K_{ECES}(T_{EC} - T_{ES})}^{\text{CONDUCTIVE (FROM CORE)}} + \overbrace{M_{0ES}}^{\text{BASAL METABOLISM}} - \overbrace{\beta_{ES} E_{V0}}^{\text{INSENSIBLE EVAPORATION}} - \overbrace{\beta_{ES} E_V}^{\text{EVAPORATION}} \qquad 3.2.13$$

$$+ \overbrace{\alpha_{ES}\, q_C \times 0.535 MBF (T_{CB} - T_{ES})}^{\text{CONVECTIVE (BLOOD)}} - \overbrace{A_{ES} . h_0 (T_{ES} - T_a)}^{\text{RADIATION / CONVECTION}}$$

Heat flow through core of trunk

$$C_{TC} \cdot \frac{dT_{TC}}{dt} = \overbrace{M_{0TC}}^{\text{BASAL METABOLISM}} + \overbrace{\alpha_{TC}\, q_C \times 210 (T_{CB} - T_{TC})}^{\text{CONVECTIVE (BLOOD)}} - \overbrace{K_{TCTM}(T_{TC} - T_{TM})}^{\text{CONDUCTIVE (TO MUSCLE)}} \qquad 3.2.14$$

$$\overbrace{-\ E_{VTC}}^{\text{RESPIRATORY WATER VAPOUR}}$$

Heat flow through trunk muscles

$$C_{TM} \cdot \frac{dT_{TM}}{dt} = \overbrace{M_{0TM}}^{\text{BASAL METABOLISM}} + \overbrace{0.38\ \Delta M}^{\text{SHIVERING}} + \overbrace{0.38\ E}^{\text{EXERCISE}} - \overbrace{K_{TMTS}(T_{TM} - T_{TS})}^{\text{CONDUCTIVE (TO SKIN)}} \qquad 3.2.15$$

$$+ \overbrace{\alpha_{TM}\, q_C \times 0.38 MBF (T_{CB} - T_{TM})}^{\text{CONVECTIVE (BLOOD)}} + \overbrace{K_{TCTM}(T_{TC} - T_{TM})}^{\text{CONDUCTIVE (TO CORE)}}$$

Heat flow through trunk skin

$$C_{TS} \cdot \frac{dT_{TS}}{dt} = \overbrace{M_{oTS}}^{\text{BASAL METABOLISM}} + \overbrace{K_{TMTS}(T_{TM} - T_{TS})}^{\text{CONDUCTIVE (FROM MUSCL)}} - \overbrace{\beta_{TS} E_{Vo}}^{\text{INSENSIBLE EVAPORATION}} - \overbrace{\beta_{TS} E_V}^{\text{EVAPORATION}} \qquad 3.2.16$$

$$+ \overbrace{\alpha_{TS}\, q_C \times 0.286\, SBF(T_{CB} - T_{TS})}^{\text{CONVECTIVE (BLOOD)}} - \overbrace{A_{TS} \cdot h_o\, (T_{TS} - T_a)}^{\text{RADIATION / CONVECTION}}$$

Heat flow through central blood compartment

$$C_{CB} \cdot \frac{dT_{CB}}{dt} = \overbrace{-\alpha_{HC}\, q_C \times 51.3\,(T_{CB} - T_{HC}) - \alpha_{HC}\, q_C \times 0.138\, SBF}^{\text{ALL TERMS CONVECTIVE}} \times \qquad 3.2.17$$

$$(T_{CB} - T_{HS}) - \alpha_{EC}\, q_C \times 0.60\, MBF(T_{CB} - T_{EC}) - \alpha_{ES}\, q_C$$

$$\times\ 0.535\, SBF(T_{CB} - T_{ES}) - \alpha_{TC}\, q_C \times 2.10(T_{CB} - T_{TC})$$

$$- \alpha_{TM}\, q_C \times 0.4\, MBF(T_{CB} - T_{TM}) - \alpha_{TS}\, q_C \times 0.286\, SBF(T_{CB} - T_{TS})$$

Crosbie's model used basal average body temperature as the set point. Stolwijk and Hardy use three set points.

The Set Points

$$T_{HC_o} = 36.6\,°C\ , \quad \bar{T}_{S_o} = 34.1\,°C\ , \quad \bar{T}_{M_o} = 35.88\,°C$$

The choice of set points is based on the assumption that receptors are located in the head core (brain), in the muscles and evenly distributed about the skin. The following four equations 3.2.18 to 3.2.21 describe the system responses.

The Controlling System

$$E_V = (T_{HC} - 36.6)(\bar{T}_S - 34.1)68 + (\bar{T}_M - 35.88)(T_{HC} - 36.6)200 \qquad 3.2.18$$

$$SBF = 10.6 + 36(T_{HC} - 36.6)(\bar{T}_S - 34.1) + 0.93(\bar{T}_S - 34.1) \qquad 3.2.19$$

$$MBF = 15 + \alpha\int_{t_1}^{t_2}(\Delta M + E - \beta MBF\omega)\,dt + (\bar{T}_S - 34.1)2.5 \qquad 3.2.20$$

$$\Delta M = 60(T_{HC} - 36.6)(\bar{T}_S - 34.1) \qquad 3.2.21$$

Equation 3.2.18 is the complete expression for evaporative heat loss control (sudomotor activity). The value of the equation is set to zero if T_{HC} is below the set point (36.6°C.) to prevent a negative evaporative heat loss. The term includes average skin temperature ($\bar{T}_S$) and average muscle temperature ($\bar{T}_M$), to take into account both resting and exercising states.

Vasomotor response is described by equation 3.2.19 and can be seen to increase or decrease with the fluctuation of skin temperature above or below its set point, 34.1°C. Skin blood flow is set to zero if the terms of the equation are negative.

Muscle blood flow, as given in equation 3.2.20, is seen to be under the control of metabolic activity (either shivering or exercise) and is responsive to the rate of change of metabolism.

Muscle blood flow is also under the control of average skin temperature and is set to zero if the value of the equation is negative. Metabolic response is given by equation 3.2.21 and controlled by receptors in the brain and skin.

Conditions for the above controlling equation are that $M \geqslant 0$ and $(T_{HC} - 36.6) \leqslant 0$, assuming that the brain contains the major cold receptors, for the stimulation of shivering.

Stolwijk and Hardy compared predictions by this model with experimental data from earlier experiments. Figure 3.2.5 shows a comparison of their predictions with data from Hardy and Stolwijk (ref. 9), the same data as used for my comparison with Crosbie's model. Skin and internal temperature are again closely predicted. Metabolic rate is also well in accord with data, although there is a short period of shivering predicted. Their prediction of internal temperature is for tympanic temperature (head core temperature) which now plays a part in control of metabolic rate (equation 3.2.21). Further validation of this controller is provided by the ability of the model to simulate the ice ingestion experiment (see Section 2.7 and Figure 2.7.3), Figure 3.2.6.

This model by Stolwijk and Hardy was modified by Kuznetz (ref. 11), having a total of 14 layers or nodes (each equation in the passive system represents a layer or node) and was compared by Wissler (ref. 12) to his 250 node

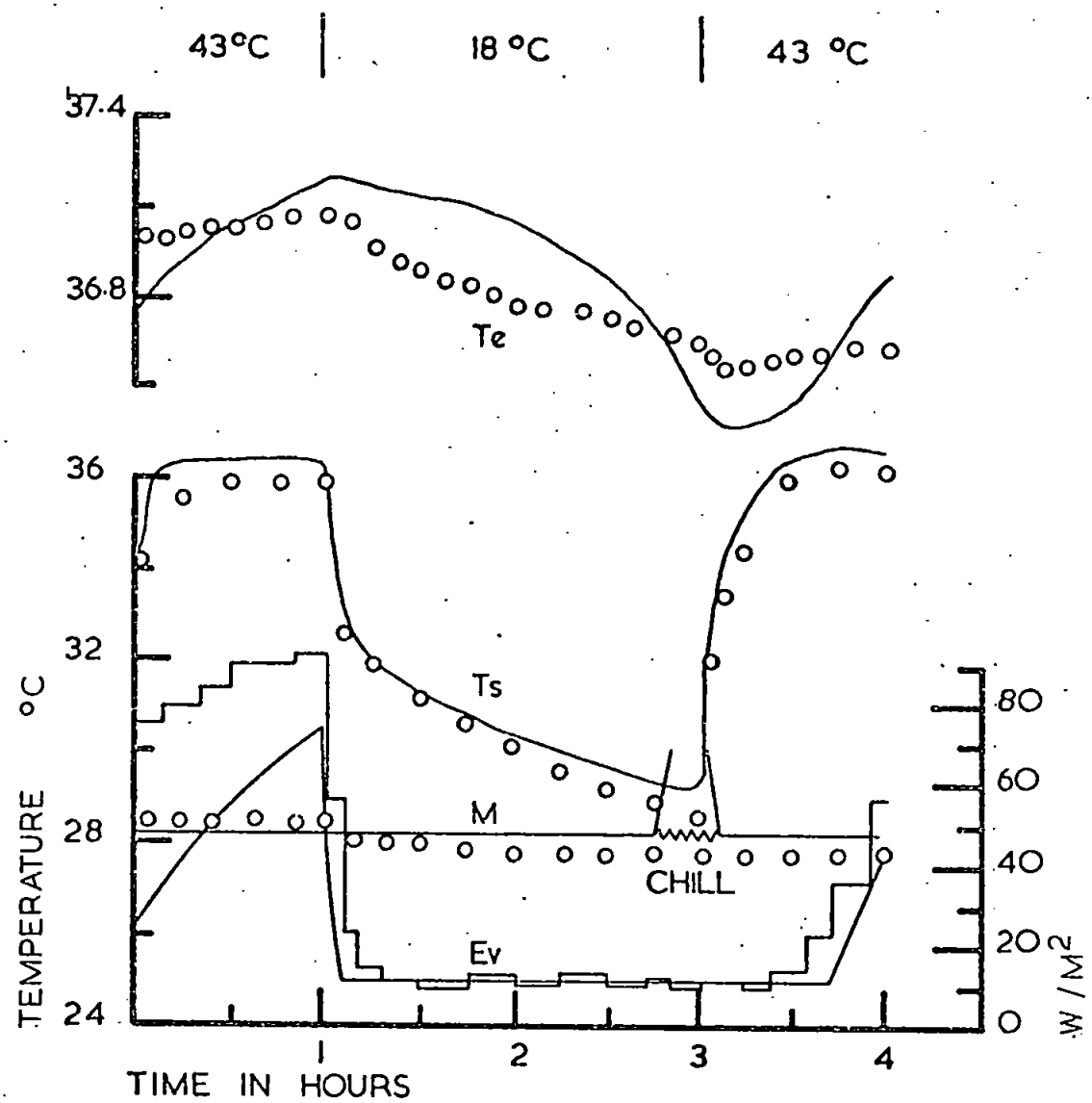


Figure 3.2.5 Theoretical and experimental results compared for conditions of thermal transient. Te, tympanic temperature, Ts, mean skin temperature, Ev, evaporative heat loss and M, metabolic rate. Data is from Hardy and Stolwijk (ref. 9)

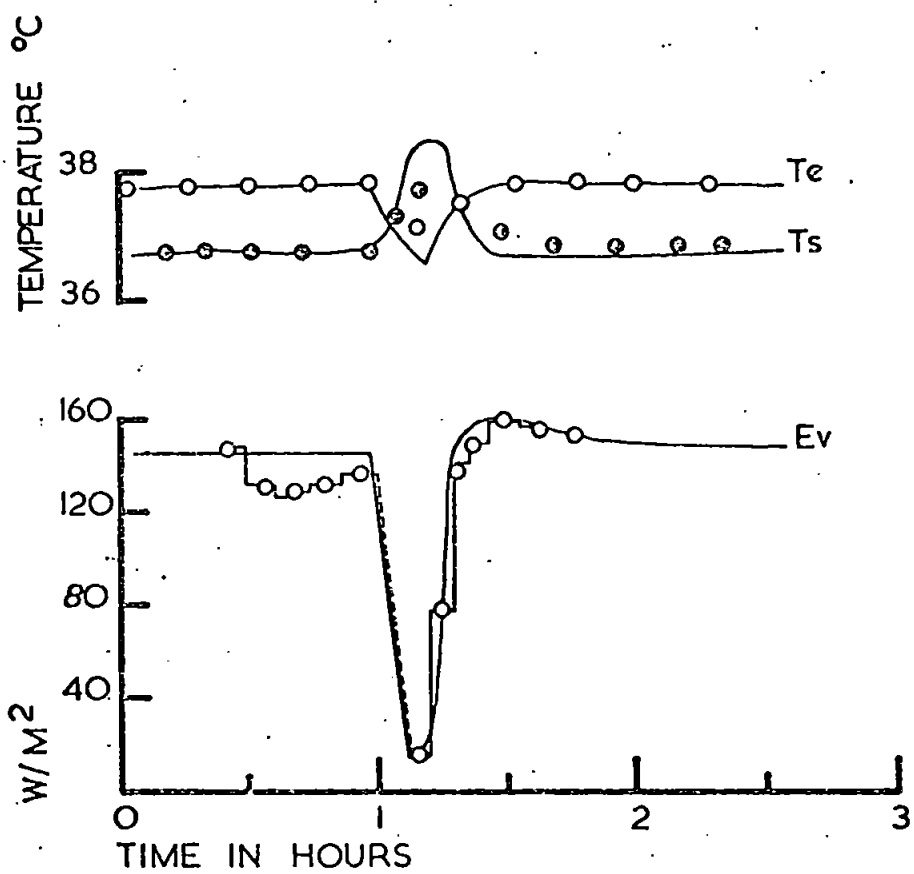


Figure 3.2.6 Effect of ingestion of ice cream on evaporative heat loss (Ev), mean skin temperature (Ts) and tympanic temperature (Te) during heat exposure. Room temperature 42 deg C. Data from Stolwijk and Hardy (ref. 10)

model (Fig. 3.2.7). Wissler's model contained only the passive system but he proved what Crosbie (ref. 7) had previously stated, that the more layers the model contains (the more each layer approaches the infinitesimally small) the more accurate the model will be.

Wissler formulates a thermal energy balance for an infinitesimal element of tissue by equation 3.2.22.

$$\rho C \frac{\partial T}{\partial t} = \underbrace{\frac{1}{r}\left[\frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial t}\right)\right]}_{\text{THERMAL CONDUCTION THROUGH TISSUE}} + \underbrace{h m}_{\text{METABOLIC HEAT}} + \underbrace{Q_c \left(T_a - T\right)}_{\text{HEAT TRANSFER FROM BLOOD TO CAPILLIARIES}}$$

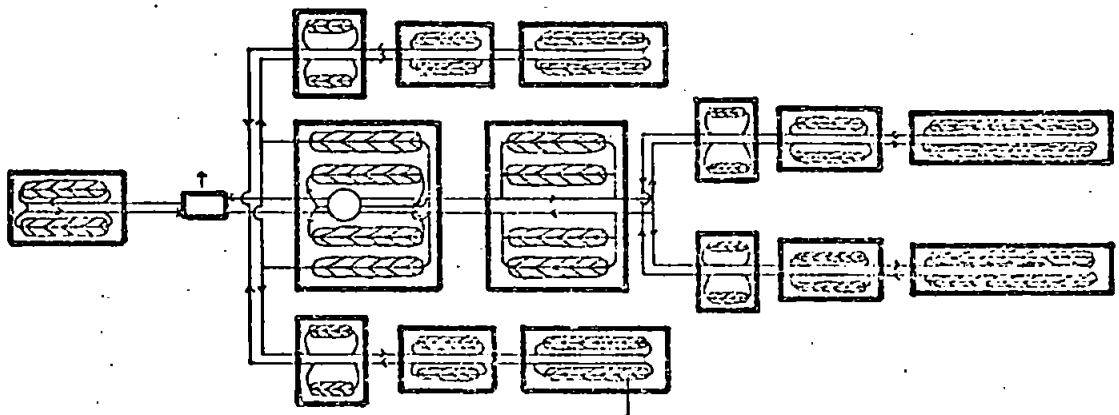
$$+ \underbrace{h_a \left(T_a - T\right)}_{\text{HEAT TRANSFER FROM BLOOD TO ARTERIES}} + \underbrace{h_v \left(T_v - T\right)}_{\text{HEAT TRANSFER FROM BLOOD TO LARGE VEINS}} \qquad 3.2.22$$

When an element is divided into radial shells, equation 3.2.22 is integrated over a given shell. For say the third shell one obtains equation 3.2.23.

$$(\rho C)_3 \frac{d T_3}{d t} = K_{34} (T_4 - T_3) - K_{23} (T_3 - T_2) + h_{m3} + Q_{c3} (T_{a3} - T_3)$$

$$+ h_{a3} (T_{a3} - T_3) + h_{v3} (T_{v3} - T_3) \qquad 3.2.23$$

$(T_{a3} - T_3)$ and $(T_{v3} - T_3)$ are the mean thermal differences for computing rates of heat transfer from blood to tissue.



Each element is divided into 15 - 21 radial shells each containing an arterial and venous pool

Figure 3.2.7 Schematic diagram of the human thermal system, its elements and circulatory system, as proposed by Wissler

However, Figure 3.2.8 shows two different temperature profiles which do have equal means for adjacent shells, n and n + 1.

Curve 1 is typical of a steady state profile and Curve 2 is more representative of a transient state generated during cooling (ref. 12). Although $(T_{n+1} - T_n)$ is identical for both profiles, the thermal flux for Curve 1 is greater than for Curve 2. The magnitude of this problem diminishes as the size of the elements is reduced.

Wissler concluded that the use of simple models is probably justified in cases of pronounced vasodilation (Curve 2 in Figure 3.2.8 represents the case where vascular constriction is taking place) and small differences between central and surface temperatures (i.e. moderate conditions).

The models of Crosbie and colleagues and Stolwijk and Hardy were implemented on analogue computers. Stolwijk advanced on the model by Stolwijk and Hardy and implemented it on a digital computer. The program describing the model was written in FORTRAN (ref. 13). Equations are here given in FORTRAN notation.

The model differs in several respects from its predecessor. Stolwijk's model approximates, geometrically, more closely to the human body (Fig. 3.2.9). The head is represented as a sphere and the extremities are represented by four elements; arms, hands, legs and feet. Crosbie had represented the body as having three layers or nodes, Stolwijk and Hardy's model had two or three nodes in each

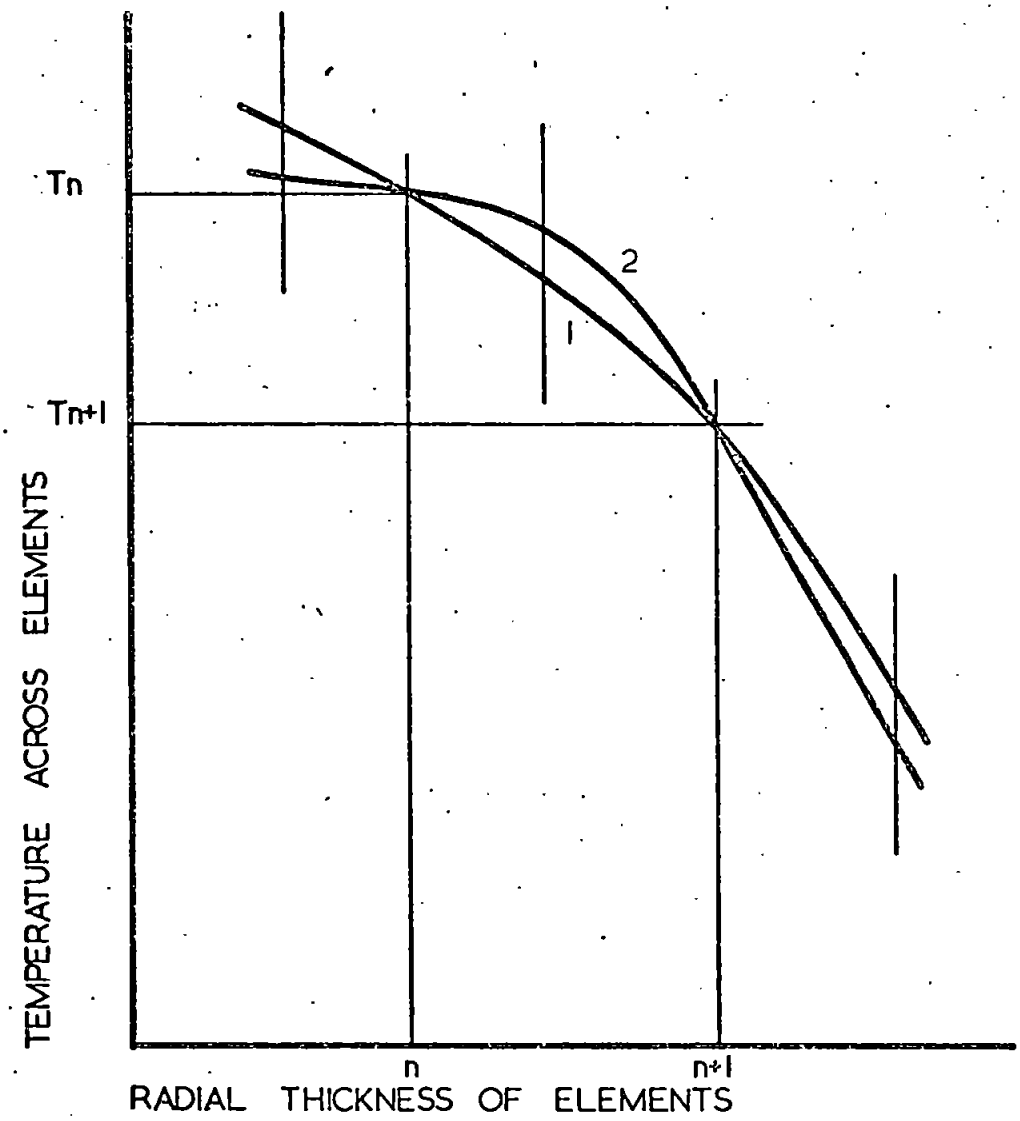


Figure 3.2.8 Two possible temperature profiles having identical means

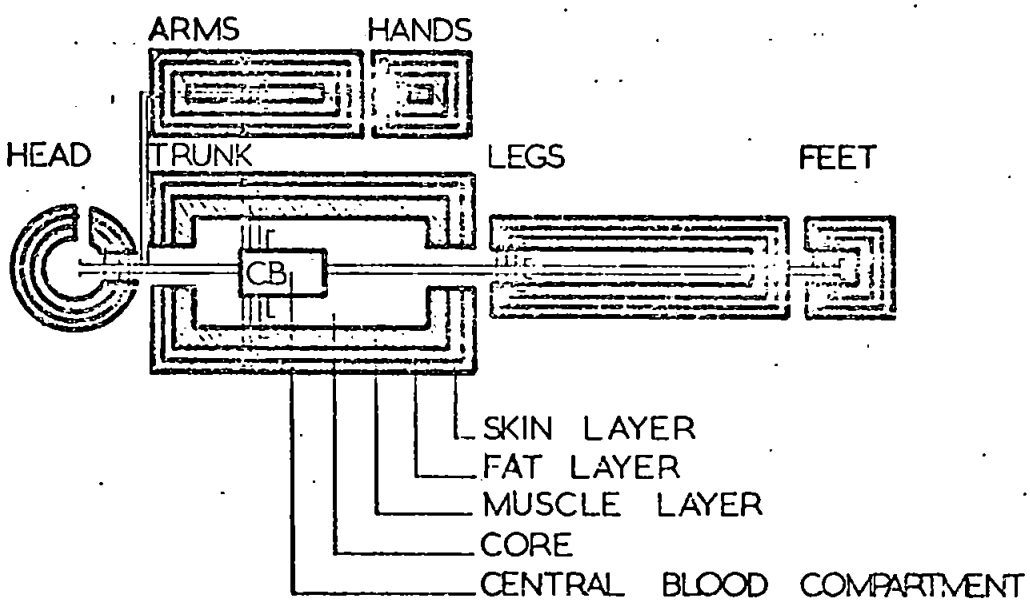


Figure 3.2.9 Diagrammatic representation of the mathematical model of physiological temperature regulation in man, by Stolwijk

body element. Stolwijk's model contains four nodes, in each element, representing the core, muscle, fat and skin layers. The earlier model contained three set points, for the controlling system, positioned in the brain, skin and muscles, while in the later model set points are assigned to each node. Each node is also assigned its own basal metabolism and blood flow rate.

One of the reasons for producing models of the human thermal system has been to develop a more detailed knowledge of the controlling system. For this purpose, Stolwijk's model subdivides the controlling system into three distinct parts. The first part contains the sensing mechanisms, which recognise the thermal state of the passive system. The second part receives information regarding the thermal state, integrates it and sends out appropriate commands to the effector systems (metabolism, vasomotor and sudomotor responses). The third part of the controlling system receives the effector commands and, if appropriate, modifies them according to the conditions at the periphery of the body, before translating the commands into action.

In the model, thermal receptors are in all layers. The receptor signal is given as the deviation from the set point, plus a term describing the dynamic sensitivity of the receptor (if known). Central receptors are assumed to be in the brain.

The equations describing the passive system and the controlling system are given in equations 3.2.24-3.2.30 and 3.2.31-3.2.39.

The Passive System

BC(K)	=	BF(K)*(T(K)-T(25))	3.2.24
TD(K)	=	TC(K)*(T(K)-T(K+1))	3.2.25
HF(K)	=	Q(K)-E(K)-BC(K)-TD(K)	3.2.26
HF(K+1)	=	Q(K+1)-BC(K+1)+TD(K)-TD(K+1)	3.2.27
HF(K+2)	=	Q(K+2)-BC(K+2)+TD(K+1)-TD(K+2)	3.2.28
HF(K+3)	=	Q(K+3)-BC(K+3)-E(K+3)+TD(K+2)-H(I)* (T(K+3)-TAIR)	3.2.29
HF(25)	=	HF(25)+BC(K)	3.2.30

The Controlling System

ERROR(N)	=	(T(N)-TSET(N)+RATE(N)*F(N)	3.2.31
COLD(N)	=	ERROR(N) if negative	3.2.32
WARM(N)	=	ERROR(N) otherwise	3.2.33
WARMS	=	WARMS+WARM(K)*SKINR(I)	3.2.34
COLDS	=	COLDS+COLD(K)*SKINR(I)	3.2.35
SWEAT	=	CSW*ERROR(1)+SSW*(WARMS-COLDS) +PSW*WARM(1)*WARMS	3.2.36
DILAT	=	CDIL*ERROR(1)+SDIL*(WARMS-COLDS) +PDIL*WARM(1)*WARMS	3.2.37
STRIC	=	CCON*ERROR(1)-SCON*(WARMS-COLDS) +PCON*COLD(1)*COLDS	3.2.38
CHILL	=	CCHIL*ERROR(1)-SCHIL*(WARMS-COLDS) +PCHIL*COLD(1)*COLDS	3.2.39

Stolwijk compared predictions by the model with data from earlier experiments (refs. 3 and 9). Figure 3.2.10 illustrates the comparison. Predicted skin temperature and evaporative heat loss correlate well with the data but again metabolic rate, predicted by the model, is too high after a period of about 45 minutes in the cold (a predicted bout of shivering) with a corresponding drop in internal temperature at this point.

Stolwijk attributes this error to the effect described above by Wissler. "Since each of the segments in the controlled system consists of only 4 layers, there will be errors in the finite difference method of solution during the development of new gradients in the relatively thick muscle and core layers." (ref. 13)

During heat stress, convective heat transfer in the circulatory system reduces these gradients but in the cold this convective heat transfer largely disappears due to constriction and gradients appear. The remedy is to use more layers.

3.3 Gagge's Model

The models described so far have been concerned with predicting the response of the physiological system and have been validated against measured curves of skin temperature, rectal temperature and evaporative heat loss etc., produced by the model, with curves produced from experimental results.

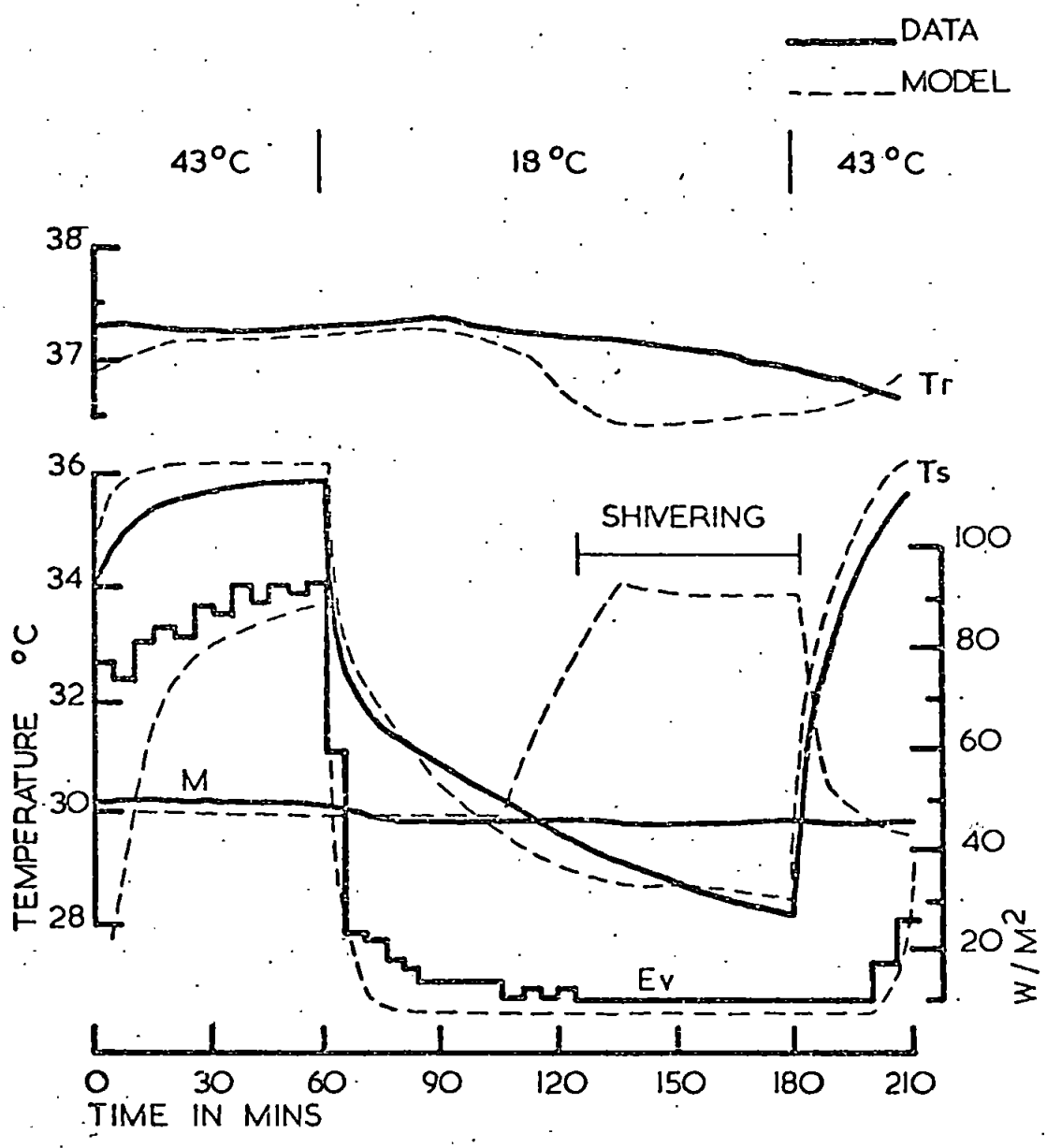


Figure 3.2.10 Comparison of predicted results of response to thermal transients with data. Predictions by model (Stolwijk ref. 13) and data from Hardy and Stolwijk (ref. 9)

A model has been devised by Gagge and colleagues (ref. 14), based on earlier models by Gagge and colleagues (ref. 15) and Stolwijk and Hardy (ref. 10), which relates the human thermoregulatory system to thermal discomfort and thermal sensation.

As this model forms the basis of a model devised later for the prediction of the transient experience of a person moving through different environmental conditions, some of its main factors are worth noting.

The model is of simple geometry (Fig. 3.3.1), representing the human body as a single cylinder, having a core and a shell (2 nodes). The shell layer contains an important addition in clothing.

Thermoreceptors are assumed to be in the skin and core and the set points are given in equations 3.3.1 and 3.3.2.

The Set Points

$$TSK = 34.0 \qquad 3.3.1$$

$$TCR = 37.0 \qquad 3.3.2$$

The equations describing the passive system and the controlling system are given by equations 3.3.3 and 3.3.4 and 3.3.5 to 3.3.7 respectively.

The Passive System

$$HFCR = RM-ERES-CRES-WK-(5.28+1.163*SKBF)*(TCR-TSK) \qquad 3.3.3$$

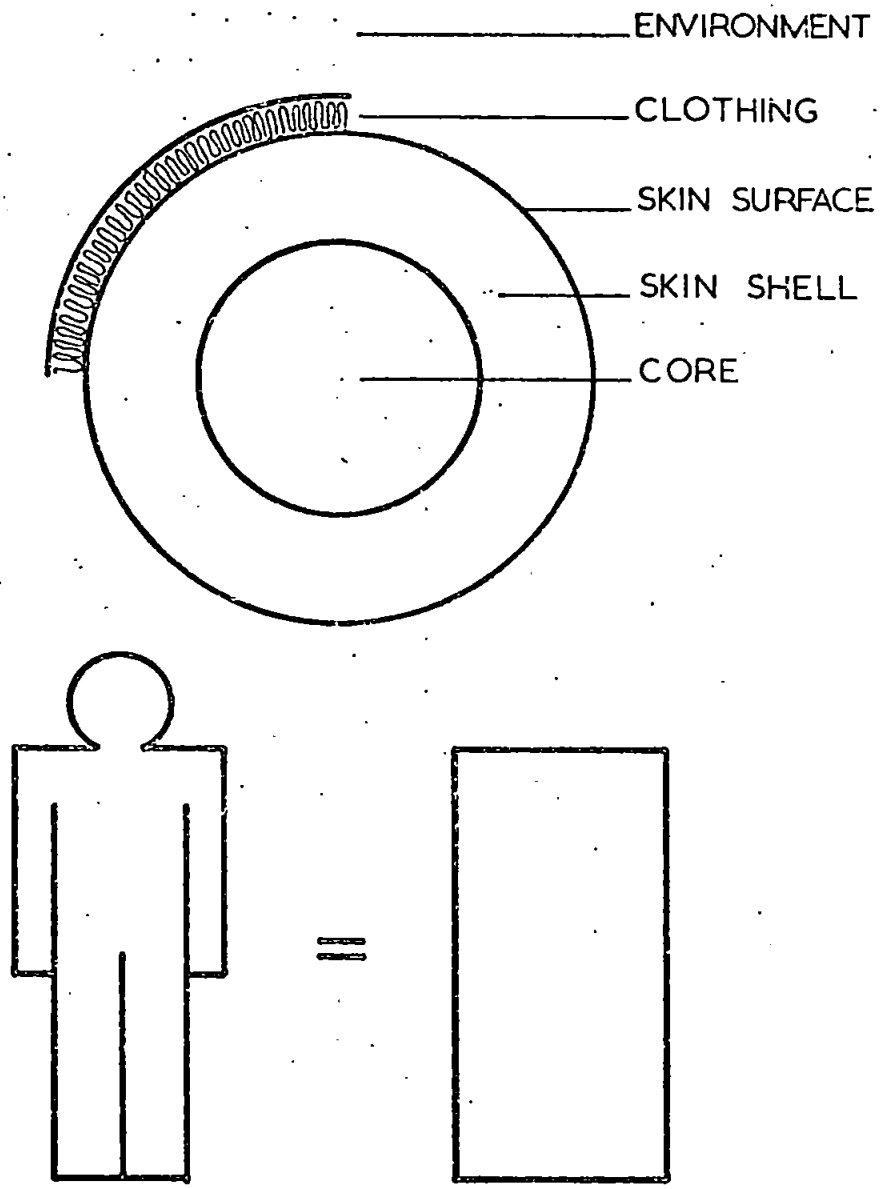


Figure 3.3.1 Diagrammatic representation of simple concentric shell model of man and his environment, by Gagge and colleagues

HFSK = (5.28+1.163*SKBF)*(TCR-TSK)-DRY-(EV-ERES) 3.3.4

The Controlling System

REGSW = 250*(ALPHA*SKSIG+(1-ALPHA)*CRSIG)*EXP (SKSIG/10.7) 3.3.5

SKBF = (6.3+DILAT)/(1+STRIC) 3.3.6

RM = MR+19.4*COLDS*COLDC 3.3.7

Considering now the prediction of thermal sensation, Gagge states that for any combination of independent environmental variables there is a unique value for skin temperature (TSK) and area of skin covered by sweat (w) at any point in time. These two variables are predicted by the physiological model described above.

Humid operative temperature is defined as the imaginary temperature at which the body will lose the same heat as it would by radiation, convection and evaporation in the actual environment. Heat is lost to the environment from the skin surface.

Considering the case of equilibrium, the heat flow through the skin surface is dependent on the temperature difference between the skin and the operative environment.

$$M_{sk} = C\left(T_{sk} - T_{oh}\right) \qquad 3.3.8$$

where

$$C = A + wB$$

$$A = h F_{cl}$$

and

$$B = 4.2 \; h_c F_{pcl}$$

T_{oh} is by definition

$$T_{oh} = (A.T_o + wB.T_{dew}) / C \qquad 3.3.9$$

Gagge compared predictions of Toh for three values of clothing with E.T. (Effective Temperature) (ref. 15) and found close correlation between the two. The closest correlation was with the 1 clo prediction, the clothing value of Houghten and Yagloglou's original subjects, for the normal scale (ref. 16).

On this basis, Gagge states, "although it (E.T.) was constructed originally by empirical experimentation it can now be derived on a physical and physiological basis." This allows Gagge to revise the old E.T. in terms of 0.6 clo instead of 1 clo, making it more representative of the types of clothing worn today. This forms the basis of the new Effective Temperature or E.T.*. This is however still expressed in terms of 100% relative humidity, a level of saturation not normally encountered in buildings.

Comparing the humid operative temperature (100% R.H.) and standard humid operative temperature (50%), for the same mean skin temperature, for the total heat exchange (Total), from the skin surface:

$$T_{otal} = C \; (T_{sk} - T_{oh})$$

from 3.3.8

and

$$T_{otal} = C_s \; (T_{sk} - T_{soh})$$

It follows that $T_{soh} = (c/C_s)T_{oh} + (1 - c/C_s)\overline{T}_{sk}$,

where the suffix s refers to the standard (50% R.H.) environment.

For each value of T_{soh} there is a unique value of S.E.T.* (E.T.* related to a standard 50% R.H. environment). This can be determined by iteration from equation 3.3.10.

$$T_{soh} = \left[A_s\,(\text{S.E.T.}*) + w B_s \left\{ 0{\cdot}5\, P_{\text{S.E.T.}*} + 25{\cdot}3/1{\cdot}92 \right\} \right] / C_s \qquad 3.3.10$$

derived from equation 3.3.9 for standard conditions and substituting S.E.T.* as the operative temperature.

Thus, having established an operative temperature based on environmental conditions and physiological reactions an Effective Temperature is established in terms of environmental conditions only. This Effective Temperature (S.E.T.*) is now used to predict thermal sensations.

The multiple regression equation derived by Rohles and Nevins (ref. 17) from data on more than 1000 subjects is used to predict thermal sensations. Their equation is:

$$T_s = 0{\cdot}245 T_a + 0{\cdot}033 P_{dp} - 6{\cdot}471 \qquad 3.3.11$$

where

T_a = air temperature °C

and

P_{dp} = saturated vapour pressure at T_a mm Hg

Gagge substitutes S.E.T.* for T_a as the Effective Temperature and the equation becomes:

$$T_S = 0.245\,SET* + 0.033\,P_{SET*} - 6.471 \qquad 3.3.12$$

The prediction of thermal sensation, T_S , therefore takes into account the environmental variables and the physiological responses to those variables via the index S.E.T.*.

3.4 Fanger's Model

Fanger has also developed a complex model based on the energy balance equation (ref. 18). Fanger writes the heat balance as such:

$$H - Ed - Esw - Ere - L = K = R + C \qquad 3.4.1$$

where H = internal heat production
Ed = heat loss by water vapour diffusion through skin
Esw = heat loss by evaporation of sweat
Ere = latent respiration heat loss
L = dry respiration heat loss
K = heat transfer from skin to outer surface of the clothed body
R = heat loss by radiation from outer surface of the clothed body
C = heat loss by convection from outer surface of the clothed body
(all terms in kcal/hr, x 1.163 = watts)

Essentially, what Fanger is presenting is a complex passive system. The regulatory mechanisms of sweating, metabolic rate and vascular control are omitted on the assumption that these can be neglected in conditions of

comfort. Thus, heat input into the body, skin temperature and evaporative heat loss due to sweating are given as functions of activity only.

$$H = M(1-\eta) \qquad \text{kcal/hr} \quad (\times 1.163 = \text{watts})$$

$$\bar{T}_s = 35.7 - 0.032\frac{H}{A_{DU}} \qquad °C$$

$$E_{sw} = 0.42\, A_{DU}\left(\frac{H}{A_{DU}} - 50\right) \qquad \text{kcal/hr} \quad (\times 1.163 = \text{watts})$$

If Fanger only considers the comfort condition, how does he predict other thermal sensations deviating from this condition? Fanger asserts: "It is therefore reasonable to assume that the degree of discomfort is greater, the more the load on the effector mechanisms deviates from the comfort condition." (ref. 18).

Thermal sensation (or comfort as Fanger calls it) at a given activity is therefore a function of the thermal load of the body or the metabolic increase needed to restore this load to zero. Thermal sensation Y is given by the general expression:

$$Y = f\left(L\frac{H}{A_{DU}}\right) \qquad 3.4.2$$

where L is given by:

$$L = \frac{M}{A_{DU}}(1-\eta) - 0.35\left[43 - 0.061\frac{M}{A_{DU}}(1-\eta) - pa\right] -$$

$$0.42\left[\frac{M}{A_{DU}}(1-\eta) - 50\right] - 0.0023\frac{M}{A_{DU}}(44 - pa) - 0.0014$$

$$\frac{M}{A_{DU}}(34 - ta) - 3.4.10^{-8} fcl\left[(tcl + 273)^4 - (tmrt + 273)^4\right] -$$

$$fcl.hc(tcl - ta) \qquad 3.4.3$$

The evidence in support of this is conflicting. Humphreys (ref. 19) criticises the model for a dependence on temperature which is not in practice encountered, proposing that in the absence of sweating a better agreement would be between thermal sensation and change in skin temperature required to restore equilibrium.

Inouye and colleagues (ref. 20), in a study on the effect of change of environment, found after a change from comfortable to a hot humid environment, that continued increases of heat storage over a two hour period were not followed by a change of thermal sensation.

Fanger finally derives the following equation for the prediction of thermal sensation ($Y = 0$ is neutral) where L, the thermal load, is given by equation 3.4.3.

$$Y = \left(0.352\, e^{-0.042\left(\frac{M}{A_{DU}}\right)} + 0.032 \right) L \qquad 3.4.4$$

In a study of thermal transients Hardy and Stolwijk (ref. 9) provide data on the energy exchange (thermal load) during steady states and transients (Fig. 2.8.3). In another study on transients (ref. 21), Gagge recorded thermal sensations for the same environmental conditions (Fig. 3.4.1). We can therefore compare this data with predictions using Fanger's equation (3.4.4).

Table 3.4.1 gives the data for comparison, extracted from Figures 2.8.3 and 3.4.1, with the metabolic data from Fanger together with the resulting predictions using equation 3.4.4. Figure 3.4.2 is a plot of the predicted votes and votes taken from the data (Fig. 3.4.1).

The dependence of Fanger's predictions on the energy exchange (thermal load) is clear. The general trend of the predicted vote follows that of the data and after a two hour period there is a difference of 1 unit on the thermal sensation scale. However, during the first minutes of the transient, Fanger's model predicts a much lower vote than data, a difference of 3.5 votes, well outside acceptable limits.

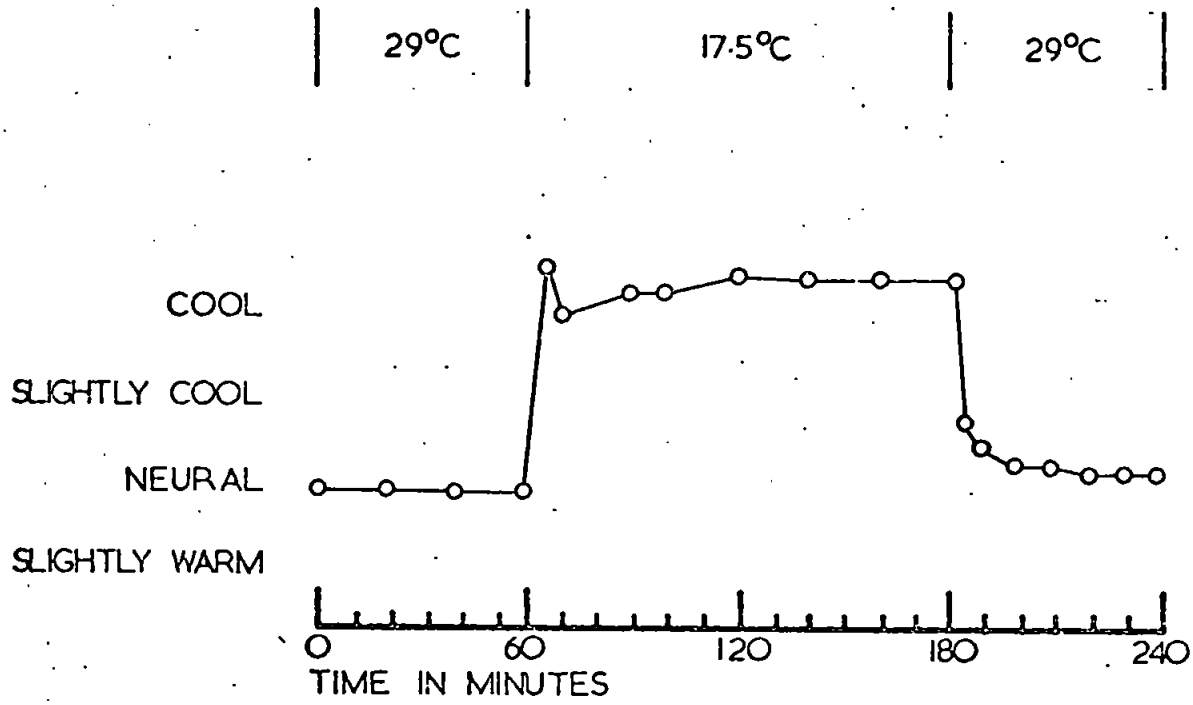


Figure 3.4.1 Thermal sensations during thermal transients. Data from Gagge (ref. 21)

Time	Gagge vote	Hardy/Stolwijk L		Fanger M/A_{Du}		Fanger predicted vote
		$kcal/m^2/hr$	w/m^2	$kcal/m^2/hr$	w/m^2	
65 mins	-2.5	-80	-93	50	58	-6
70 mins	-2	-55	-64	50	58	-4
90 mins	-2.2	-45	-52	50	58	-3.38
120 mins	-2.3	-45	-52	50	58	-3.38
180 mins	-2.3	-40	-47	50	58	-3

Table 3.4.1

3.5 Concluding Remarks.

It is possible, using control systems, to model the dynamic regulatory mechanisms of the human thermal system. Together with a description of heat transfer through the body and clothing these provide a more complete description of the human thermal system.

I have discussed a few of the many models developed to illustrate the major features of these models and some of their relative merits.

Gagge's model (ref. 14) takes us almost full circle back to Houghten and Yagloglou's E.T., although this is now revised and is susceptible to prediction using the physiological model.

Stolwijk's model (ref. 13) has the advantage that it contains a greater number of layers and represents the body more exactly and, therefore, should have greater accuracy

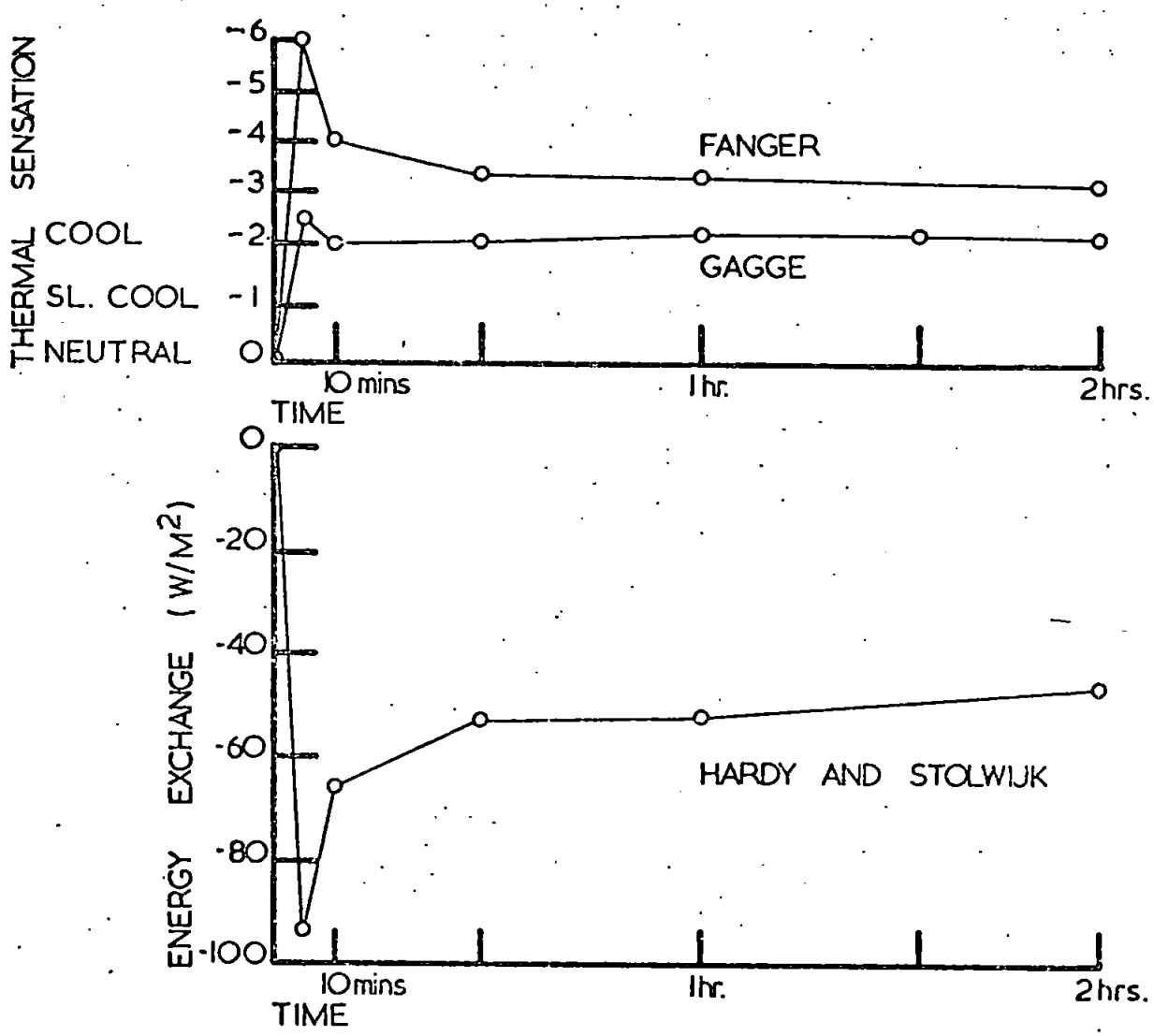


Figure 3.4.2 Comparison of predicted vote using Fanger's equation with data from Gagge (ref. 21)

of prediction. Whether such sophistication is needed requires consideration of whether the descriptive scales of discomfort and sensation warrant such accuracy. Furthermore, Wissler (ref. 12) has shown that for moderate conditions the use of simple models is justified.

Stolwijk's model also provides a better approximation to the human body and this may provide a better description of the thermal state of the body, for example whether the hands are cold or the feet hot.

However, as all experimental results for thermal sensations are based on mean responses for the whole body, representation of the body as a single cylinder may be justified (ref. 22).

Gagge's model has two advantages. Clothing insulation is included and in most cases we would want to simulate clothed conditions although swimming baths could be an exception. This can in principle be included in Stolwijk's model by modifying the skin layer of the passive system. Secondly, Gagge's model relates physiological predictions to thermal sensation using data from over 1000 subjects (ref. 17).

Fanger's model has been included in the above discussion to illustrate the difficulties in trying to predict thermal sensations with a model that contains none of the regulatory mechanisms.

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Section Four. The Problem of Motion

4.1 Description of Movement

For our present purpose, we can confine a description of movement to specifying a route through a building and modes of progression along the route. A series of points, defined by their 3-D co-ordinates, is sufficient to describe the geometry of the route. Modes of progression, including two stationary modes, are confined to sitting, standing, walking slow and walking fast. Slow walking is assumed to be at a speed of 3.2 km/hr (2 m.p.h.) and fast walking to be at a speed of 6.4 km/hr (4 m.p.h.). By reference to these four modes and to the co-ordinate system, the list can be expanded to the following, in Table 4.1.1.

1.	Sitting	Explicit
2.	Standing	
3.	Walking slow	
4.	Walking fast	
5.	Walking slow upstairs	Implicit
6.	Walking fast upstairs	
7.	Walking slow downstairs	
8.	Walking fast downstairs	

Table 4.1.1. Modes of activity showing explicit and implicit modes

If either Mode 1 or Mode 2 is specified, then the stationary period must be specified. Figure 4.1.1 is a typical input statement describing a route. Figures in brackets are not part of the input statement but are the

modes of progression referred to in Table 4.1.1. Distances are in metres.

Each mode of progression or stationary state is represented in the model as a level of activity.

INPUT XYZ MODE	0.0	0.0	0.0	3	(3)
INPUT XYZ MODE	10.0	10.0	0.0	3	(5)
INPUT XYZ MODE	10.0	13.0	3.0	4	(4)
INPUT XYZ MODE	10.0	15.0	3.0	2	(2)
TIME IN MINS AND MODE TO NEXT POINT 2.5.4					(4)
INPUT XYZ MODE	8.0	15.0	3.0	10	(*)

*NOTE mode 10 terminates input

Figure 4.1.1 Typical input statement for a route

4.2 The Physiological and Physical Variables Associated with Movement

Study of the models described in Section 3 shows that a change in activity incurs possible change in the following independent physiological variables:

Metabolic rate (MR) w/m^2

Work rate (WK) w/m^2

Convective heat transfer coefficient (CHC) $w/m^{2o}C$.

and the Ratio of the body's radiating surface to the surface area of the whole body (RTO)

Table 4.2.1 shows the corresponding values given to each variable for each activity, with reference to sources. The values for Mode 1 have been chosen to agree with that specified by the Kansas State University ASHRAE project as being the one most descriptive of man's typical everyday environment (ref. 1).

MODE	MR W/M^2	WK W/M^2	CHC $W\ M^2\ {}^oC$	RTO
1	58.2 (+)	0.0 (+)	2.9 (*)	0.696 (+)
2	69.8 (+)	0.0 (+)	3.1 (**)	0.725 (+)
3	116.3 (+)	0.0 (+)	8.0 (**)	0.725 (+)
4	221.0 (+)	0.0 (+)	11.6 (**)	0.725 (+)
5	422.85 (++)	58.067 (++)	8.0 (**)	0.725 (+)
6	782.28 (++)	58.72 (++)	11.6 (**)	0.725 (+)
7	199.64 (++)	58.067 (++)	8.0 (**)	0.725 (+)
8	369.33 (++)	58.72 (++)	11.6 (**)	0.725 (+)

(+) ref. 2, (++) ref. 3, (*) ref. 1, (**) ref. 4.

Table 4.2.1. Modes of progression and associated values for independent physiological variables

Metabolic rate increases with activity and for the present study takes values from 58.2 to 646.1 w/m^2. A point of note is that walking down stairs (modes 7 and 8) incurs a greater metabolic rate than walking on the level at both

speeds (Modes 3 and 4). This is in agreement with the results given by Orsini and Passmore (ref. 3) and as they explain is due to the extra muscular activity in maintaining body posture whilst lowering the body.

The values for metabolic rate are extrapolated from data provided by Orsini and Passmore (ref. 3). Data from two subjects, whose total load was little more than their nude weight, was used. Subject 1 had a weight of 63 kg and height of 1.82 m. Therefore his body area, according to the Dubois formula (ref. 5) for estimating body area from height and weight, was 1.817 m^2. Subject 2 had a weight of 77 kg and a height of 1.77 m. His body area was therefore 1.939 m^2. The metabolic cost of walking up and down stairs, for the two subjects, taken from Orsini and Passmore, is given in Table 4.2.2 in watts, together with the cost per m^2 body area and finally the totals and average metabolic costs converted to w/m^2.

Subject	Cost of Walking		
	Up	Down	
1	558.240	290.750	watts
2	628.020	267.49	
1	307.232	160.016	w/m^2
2	323.889	137.953	
Total	631.121	297.969	w/m^2
Average	315.561	148.985	

Table 4.2.2. Metabolic rates for walking up and down stairs at speeds of 2.23 km/hr

Fanger (ref. 2) shows that walking up a gradient of 25%, with 100% increase in speed, metabolic rate increases by approximately 85%. The data given in Table 4.2.2 apply to a walking speed of 2.23 km/hr. An increase of 1.07 km/hr (slow walking is 3.2 km/hr) is equal to an increase of 40% in metabolic rate. The average values from Table 4.2.2 are therefore corrected for the slow speed by a 40% increase and these values corrected by an increase of 85% for the fast speed. The new values are given in Table 4.2.3.

Speed	Up	Down	
slow	422.852	199.640	W/m^2
fast	782.276	369.334	

Table 4.2.3. Final values for metabolic rate walking up and down stairs

The values of work rate for the sedentary modes and walking on the level (Modes 1, 2, 3 and 4) are derived from the equation:

$$\eta = \frac{W}{M} \qquad \text{(ref. 2)} \qquad 4.2.1$$

where η = mechanical efficiency
W = work rate w/m2
and M = metabolic rate w/m2

The values of η are given by Fanger as zero for the sedentary state and light activities.

Work rate increases with activity but it can also take negative values when external work is transferred into heat, for example when walking down hill or stairs.

Values for work rate when walking up and down stairs have been extrapolated from the Orsini and Passmore data. For the two subjects the metabolic rates and work rates are given in Table 4.2.4

Subject	Metabolic rate	Work rate
1	558.24	95.366
2	628.02	106.996

watts

Table 4.2.4. Metabolic rates and work rates

Fanger (ref. 2) shows that an increase of 100% in walking speed is equal to an approximate increase in mechanical efficiency of 1%. Using equation 4.2.1 we can derive the following values for mechanical efficiency (η) from Table 4.2.4.

Subject	η	3.2 km/hr	6.4 km/hr
1	0.170	0.171	0.173
2	0.183	0.184	0.186

Re-arranging equation 4.2.1 we can now determine the following values for work rate (W):

Subject	$W = M\eta$ 3.2 km/hr	$W = M\eta$ 6.4 km/hr	
1	95.459	96.576	
2	115.556	116.812	watts
Average	105.508	106.694	
	58.067	58.72	w/m^2

Except for Mode 1, all values of the convective heat transfer coefficient (CHC), in Table 4.2.1, have been taken from Nishi and Gagge (ref. 4) who give a comparison of measured values of the coefficient. Examples are quoted of both higher and lower values of the coefficient, for various conditions, and as their results fall in between the extremes it would seem appropriate to use them.

The values of CHC are derived by direct measurement and related to the power function:

$$CHC = AV^B \qquad 4.2.2$$

where for free walking in still air A = 8.6
V = walking speed m/sec
B = 0.531

Walking speed determines the relative velocity of air across the body in an environment of still air. However, we can see from the results of Nish and Gagge (ref 4) that it would be erroneous to decrease the value of V to zero when walking in the same direction as the air movement at

the same speed as the body is not simply a rigid plane moving in one direction, but consists of limbs moving both with and against the general direction of body movement. In this case it would be appropriate to use their values for treadmill walking, where, using equation 4.2.2, A = 6.51 and B = 0.391.

The ratio of the effective area of the body's radiating surface to the total surface area of the body (RTO) has been shown by Fanger (ref. 2) to differ with activity. A value of 0.696 was found for the sedentary body and 0.72 for standing posture. These values were found to be independent of sex, weight, height or area.

All values in Table 4.2.1 are mean values and considerable deviations can occur. However, as a tentative table it should provide reasonably accurate values for the environmental conditions to be simulated.

The insulation value of clothing can also be affected by body movements (as well as tailoring and fit).

The insulation value of a particular clothing ensemble (measured in 'clo' units, 1 clo = 0.155 m^2 $^oC/w$) is dependent on both the conductive resistance of the textile itself and the layers of air in between the various textiles. Its reduction would be related to relative air velocity, permeability of the textiles, looseness of garments and vigour of movements.

As yet no data are available for clo values of clothing ensembles on moving bodies and as a first approximation it

is proposed that a clothing ensemble having a value 0.6 clo or lower will be affected by fast walking and a reduction of 25% will take place.

No account is taken of the increase which may occur in clo values, for example due to sitting in a well upholstered chair.

4.3 Further Modifications

The physiological model devised by Gagge (ref. 6, see section 3.3) was modified to allow change of the activity variables discussed in the previous section (4.2). Further modifications were also made.

The increase in radiation area of the body, due to clothing (FACL) is given as 15%, Fanger (ref. 2). However, a more recent study has shown this to be approximately 25%, based on rough measurements of two uniforms (ref. 7). This value has been included in the present model.

The constant 70 (body weight in kg of a 'standard man') affects both the thermal capacity of the body core and the thermal capacity of the skin shell. This constant has been replaced by the variable *BDYW* in the following equations (in FORTRAN notation):

```
TCCR   =   0.97*(1-ALPHA)*70.
```

and

```
TCSK   =   0.97*ALPHA*70.
```

where TCCR = Thermal capacity of the core (whr/°C)
TCSK = Thermal capacity of the shell (whr/°C)
and ALPHA = Ratio of mass skin shell to mass core

The constant 1.8 (body area in m^2 of a standard man) affects both the rate of change in core temperature and rate of change in skin shell temperature. This constant is replaced by the variable BDYA in the following equations:

$$DTCR = (HFCR*1.8)/TCCR$$

$$DTSK = (HFSK*1.8)/TCSK$$

where DTCR = rate of change in core temperature °C/hr
HFCR = heat flow from core to shell °C
DTSK = rate of change of skin temperature °C/hr
HFSK = heat flow from skin to environment °C

Body area (BDYA) is not a convenient term from a program user's point of view. Therefore BDYA is determined by the Dubois formula (ref. 5):

$$A = 0.00718 \times W^{0.425} \times H^{0.725} \ (M^2) \quad \text{(ref. 5)}$$

where A = surface area in m^2
W = body weight in kg
and H = body height in cm

As body height and weight are now defined as variables, the program user can vary the physique of the model.

No attempt has been made to include other personal differences such as sex and age. Fanger (ref. 2), after

experiments with Danish and American subjects, shows no difference in comfort conditions between elderly and college age persons and no significant difference between males and females, either country, college age or elderly. More recently Humphreys (ref. 8) in a survey of field studies finds little or no significant sex related difference in thirteen studies mentioned. The tendency if any is for women to feel slightly cooler in the same environment.

Rohles and Nevins (ref. 9) found similar results in that men are shown to differ from women in their rate of adaptation, men being significantly warmer over the first hour of exposure. They also show that the relative importance of temperature and humidity is not the same for men as for women.

No attempt has been made to include differences in personality. Although there is some evidence that comfort requirements may partly depend on personality factors (ref. 10) there is none to suggest that personality affects thermal sensations.

Gagge's model contains a routine for numerical integration (Fig. 4.3.1a) in which iteration to simulate regulation is at one minute intervals or by a change in core or skin temperature of not more than 0.1°C. Where we are concerned with predictions of the thermal state of the body at time intervals of less than one minute, say at 5 seconds, this time interval of one minute is too large and should be reduced. The routine for integration was therefore modified

a

```
      DTIM = 1./60
      U = ABS(DTSK)
      IF(U-0.1)5,10,10
   10 DTIM = 0.1(U*60.)
    5 CONTINUE
      U = ABS(DTCR)
      IF(U-0.1)105,110,110
  110 DTIM = 0.1/(U*60.)
  105 CONTINUE
```

b

```
      VTIM = 60./TINC
      DTIM = (1./60.)VTIM
      U = ABS(DTSK)
      IF(U-(0.1/VTIM))5,10,10
   10 DTIM = (0.1/VTIM)/(U*60.)
    5 CONTINUE
      U = ABS(DTCR)
      IF(U-(0.1/VTIM))105,110,110
  110 DTIM = (0.1/VTIM)/(U*60.)
  105 CONTINUE
```

DTIM = increment for numerical integration, U is a local variable, ABS( ) is the FORTRAN absolute function, DTSK = rate of change in skin temperature $^{o}C/hr$, DTCR = rate of change of core temperature $^{o}C/hr$, TINC = desired print out interval and VTIM is a local variable

Figure 4.3.1. Routines for numerical integration

to vary with the time interval (print out interval) desired by the user and output at say one minute intervals along the route will use a relatively coarse integration whilst output at say one second intervals will use a relatively fine integration.

The increment for numerical integration (DTIM) is set initially at the print out interval in hours, in agreement with Stolwijk (ref. 11). If the change in skin temperature is greater than 0.1/VTIM (where VTIM is 60/print out interval in seconds) then DTIM is reduced. Similarly, if the change of core temperature is greater than 0.1/VTIM then DTIM is reduced, so that for each iteration the maximum temperature change in either skin or core is 0.1/VTIM (Fig. 4.3.1b).

It can be seen that at a print out interval of one minute the routine is in agreement with that of Gagge (ref. 6).

The environmental variables within the model are TA (air temperature °C), TR (mean radiant temperature °C) and PPHG (vapour pressure, mm mercury). Air velocity is implicit in the established value for CHC (convective heat transfer coefficient).

The model presented by Gagge is set for prediction of values at 50% relative humidity. The relative humidity constant occurs in the equations for linear dew temperature and temperature sensation, Gagge (ref. 6). The constant has therefore been replaced by the variable RH. Relative humidity is a more common description of the water vapour

content of air and has been chosen to replace vapour pressure as the input variable. RH is related to vapour pressure within the model by the equation:

$$PPHG = RH * SVP(TA)/100$$

where PPHG = vapour pressure (mm mercury)
RH = relative humidity (%)
and SVP(TA) = saturated vapour pressure at air temperature TA (^{o}C)

A comparison of results from the two models is given in Table 4.3.1. Also included are values predicted by the regression equation of Rohles and Nevins (ref. 9) after a survey of over 1000 subjects. These are taken as the basis for comparison.

From Table 4.3.1, the general trend is for the present model to be slightly more accurate at relative humidities of 50% and 100% and slightly less accurate at 0%.

The values of thermal sensation (TSENS) are given to four decimal places to illustrate the trend. The four decimal places represent ten thousand incremental steps in between each consecutive verbal category on the TSENS scale, for example between 'slightly warm' and 'warm' and therefore it should not be inferred that a change in value represents a noticeable change in sensation. Values for TSENS given by Rohles and Nevins, TA (air temperatures) and PPHG (vapour pressure) have been determined by eye from the data given by Gagge (ref. 6).

	TSENS	TA = TR	PPHG	RH%
G P R,N	- 0.0879 - 0.0930 0.0	26 26	0	0
G P R,N	1.3857 1.3840 1.7	32 32	0	0
G P R,N	2.6181 2.6173 3.0	37 37	0	0
G P R,N	4.7990 4.8227	46 46	0	0
G P R,N	0.0280 0.0537 0.0	25 25	11	50
G P R,N	2.7270 2.8433 3.0	35.1 35.1	20	50
G P R,N	4.5943 4.6156 4.7	41.25 41.25	29.4	50
G P R,N	0.3315 0.3346 0.2	24.5	22.9	100
G P R,N	1.6409 1.6581 1.7	29.1 29.1	30	100
G P R,N	2.9072 2.0128 3.0	33.1 33.1	37.9	100

G: Gagge (1972b), P: present model, R,N: Rohles and Nevins (1971).
TSENS: temperature sensation, TA: air temperature, TR: mean radiant temperature, PPHG: vapour pressure (mm mercury), RH: relative humidity (%)

Table 4.3.1 Comparison of results for a man of 'Standard Characteristics', sedentary, with clothing value 0.6 clo after one hour exposure (Standard Characteristics are body weight, 70 kg, body surface area 1.8 ^{2}m , ratio of body's radiating surface to total area 0.72, minimum skin conductance 5.28 w/m^2 ^{o}C and normal skin blood flow 6.3 L/m^{2}hr).

4.4 The Initial State

In climate chamber studies, care is often taken so that subjects start the experiment in a condition characterised by basal or near basal conditions (of metabolic rate and blood flow rate etc.), by comfort and neutral thermal sensations.

However, someone entering a building may have walked for some distance, cycled even or just alighted from a bus or car.

The variety in activity, clothing and climatic conditions can define innumerable conditions affecting one's thermal state under which one may enter a building.

However, we may also define a person's initial thermal state in terms of his or her thermal sensation, which if seen to be effective in determining later thermal sensations, can be usefully incorporated in a model for prediction.

Gagge's model assumes that the initial condition is one of neutral thermal sensations and basal activity of the physiological system. Skin temperature (TSK), core temperature (TCR), the radiation heat transfer coefficient (CHR), evaporative heat loss (EV), the ratio of the mass skin shell to the mass core (ALPHA) and skin blood flow rate (SKBF) are physiological variables which are assumed to be at basal levels for the initial state. For the sedentary case the model was used to establish values for each of these variables corresponding to each thermal sensation on the seven point scale used (Fig. 2.4.2). These values, shown in Table 4.4.1, are incorporated into the program as a table and their selection determined by the program user's choice of the initial thermal sensation of the model.

TSK	TCR	ALPHA	SKBF	EV	CHR	TSENS	
35.7879	37.1575	0.0559	29.9260	56.7378	5.3340	3	Hot
35.3044	37.1074	0.0605	21.5074	42.6320	5.1984	2	Warm
34.6925	37.0582	0.0676	15.0259	29.3991	5.0638	1	Slightly Warm
33.9294	37.0286	0.0785	10.2306	16.2084	4.9230	0	Neutral
31.8754	37.0172	0.1259	4.3074	12.6388	4.7642	- 1	Slightly Cool
30.1999	36.9988	0.2068	2.1724	12.4761	4.6209	- 2	Cool
29.0322	36.9571	0.2397	1.8083	12.5108	4.4878	- 3	Cold

Table 4.4.1. Values for independent physiological variables and associated initial thermal sensation

4.5 Concluding Remarks

A physiological model, described by Gagge (ref. 6), discussed in section 3.3, has been modified to allow predictions to be made of thermal sensations as the model simulates the activity of walking about (or sitting or standing in) a series of different environments, defined by air temperature (°C), mean radiant temperature (°C) and relative humidity. Air velocity is implicit in the derivation of the convective heat transfer coefficient. Effects of clothing are also incorporated.

The model has also been modified to allow for differences in body build and for the initial sensation of the model to be changed.

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Section Five. Validation Studies

5.1 Introduction

A field survey was conducted with 70 subjects who gave verbal statements of thermal sensations as they walked along a set route through a building. Data from the survey was analysed and compared with predictions made by the model described in the previous section. Environmental conditions were monitored to provide input for the computer program.

5.2 Subjects

The subjects were chosen mainly from the School of Architecture as they were the most readily available. They were, therefore, mainly British (all had been living in the country for some years); college age; male; familiar with the building and had been working in it for most of the day. Each subject was asked whether or not he had had a meal within the last hour or two. Table 5.2.1 shows the number of subjects in each of these groups.

The height and clothed weight of each subject was measured. A list of garments being worn by each subject was recorded together with an indication of whether the total ensemble was light or dark in colour (the ensemble was divided into top and bottom). The average height of the subjects was 1.81 m; the average clothed weight was 73.44 kg and the average clothing insulation value (see sub-section 5.5) was 0.97 clo.

5.3 Procedure

Each subject was handed a form giving a brief introduction to the purpose and procedure of the survey (see

Male	64
Female	6
Familiar with the building	65
Unfamiliar with building	5
College age (18 - 28)	57
Over college age	13
Meal within last hour or two	13
No meal	57

Table 5.2.1 Classification of subject groups

Fig. 5.3.1). Personal details of each subject were taken and height and weight measured. The information relating to each subject was noted on a standard form (see Fig. 5.3.2).

The route was described to each subject (three subjects not from the School were shown the route) and each subject was informed that each point along the route, at which he was to state his thermal sensations, was marked by a red triangle placed on the floor. It was stated that these were at approximately five second intervals along the route. The observer walked along the route with each subject, for a distance of three markers, to indicate the desired speed (approximately 0.9 m/s).

Before walking along the route, each subject was asked to state his thermal sensation according to the scale shown in Figure 5.3.3. This having been recorded, the subject walked the length of the route and back. The observer walked behind him recording his statements on the standard form (Fig. 5.3.2). The statements were made according to the scale shown in Fig. 5.3.3, a copy of which each subject carried.

The total travelling time was recorded and it was found that subjects were not able to walk at the desired speed while thinking about and stating their thermal sensations, and they automatically reduced their walking speed to an approximate mean of 0.7 m/s.

The purpose of this study is to record your thermal sensations, that is how you feel whilst walking through the building.

you are asked to walk along a prescribed route through the building, at a constant speed and to state your thermal sensations using a prescribed scale, at five second intervals.

You will be shown the route, and the speed at which to walk will be indicated. The intervals along the route at which you are to state your sensations are marked on the floor. You must not stop at any of these points but proceed along the whole length of the route without stopping.

The scale by which you will state your sensations is given below (Temperature Sensation). You will also be given a copy of this to carry with you.

Temperature Sensation

COLD	COOL	SLIGHTLY COOL	NEUTRAL	SLIGHTLY WARM	WARM	HOT

You are also asked to give your state of comfort or discomfort due to thermal sensations. The scale by which you will state your comfort or discomfort is given below (Discomfort). You will also be given a copy of this to carry with you.

Discomfort

COMFORTABLE	SLIGHTLY UNCOMFORTABLE	UNCOMFORTABLE	VERY UNCOMFORTABLE
0	1	2	3

You may find it quicker to give your discomfort vote by stating the corresponding number, as shown above.

Figure 5.3.1 Introduction to survey handed to each subject.

DATE: _____ TIME: _____ NAME: _____

NATIONALITY (LENGTH OF TIME IN THIS COUNTRY): _____

MEAL WITHIN THE LAST HOUR OR TWO ? _____ CLOTHES (LIGHT OR DARK?): _____

AGE: _____ SEX: _____ HEIGHT: _____ WEIGHT: _____

LIST OF GARMENTS BEING WORN:

DISCOMFORT: _____ TEMPERATURE SENSATION: _____

HOT	
WARM	
SLIGHTLY WARM	
NEUTRAL	
SLIGHTLY COOL	
COOL	
COLD	

TIME TAKEN:

Figure 5.3.2 Standard form for collection of data

(a)

COLD	COOL	SLIGHTLY COOL	NEUTRAL	SLIGHTLY WARM	WARM	HOT

(b)

COMFORTABLE	SLIGHTLY UNCOMFORTABLE	UNCOMFORTABLE	VERY UNCOMFORTABLE
0	1	2	3

Figure 5.3.3

(a) Verbal Scale for thermal sensation vote

(b) Verbal Scale for comfort vote

5.4 Environmental Conditions

A route was chosen through the School of Architecture which traversed the length and height of the building. The route, or parts of it, are well used as it encompasses the main entrance; the student coffee bar; the ground floor corridor; and the only internal staircase. The route passed out of the building into part of the court uncovered on one side. This side was screened off each evening just before the survey to reduce air velocity at this point.

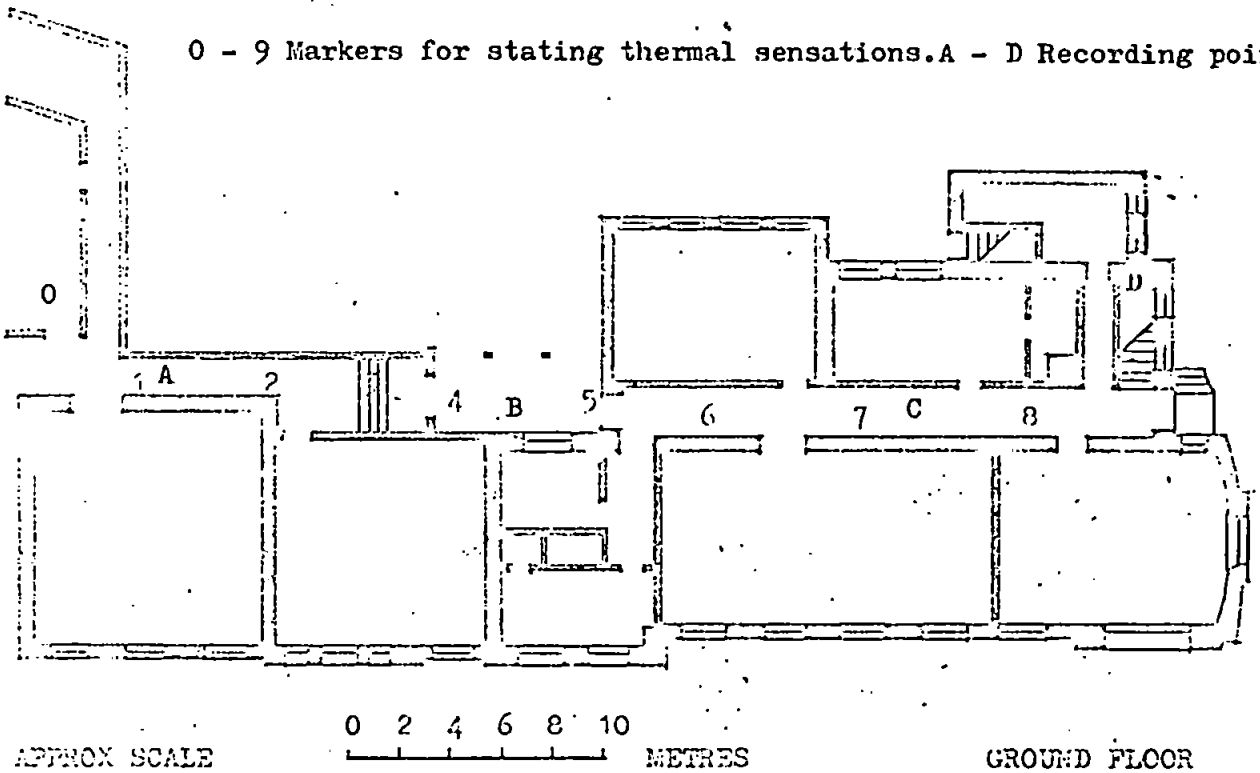
Figure 5.4.1 shows the route through the building, the points at which thermal sensations were stated and the positions at which environmental recordings were taken.

Globe thermometer temperature (°C.) at a point approximately 1.14 m above floor level, dry bulb and wet bulb air temperature (°C.) and air velocity (by Kata thermometer) were recorded at seven points (see Fig. 5.4.1) along the route at the beginning and end of each evening's survey. Relative humidity was deduced from the wet and dry bulb readings. Globe thermometer readings are affected by both radiant temperature and air velocity. If air velocity is known, globe readings can be converted to mean radiant temperature. Mean radiant temperature is given by:

$$tr = tg\,(1 + 2.35\sqrt{v}) - (2.35.\,ta\sqrt{v})$$

where tr = mean radiant temperature °C.
tg = globe thermometer temperature °C.
ta = air temperature °C.
and v = air velocity m/s (ref. 1)

0 - 9 Markers for stating thermal sensations. A - D Recording points



10 - 16 Markers for stating thermal sensations. E - G Recording points

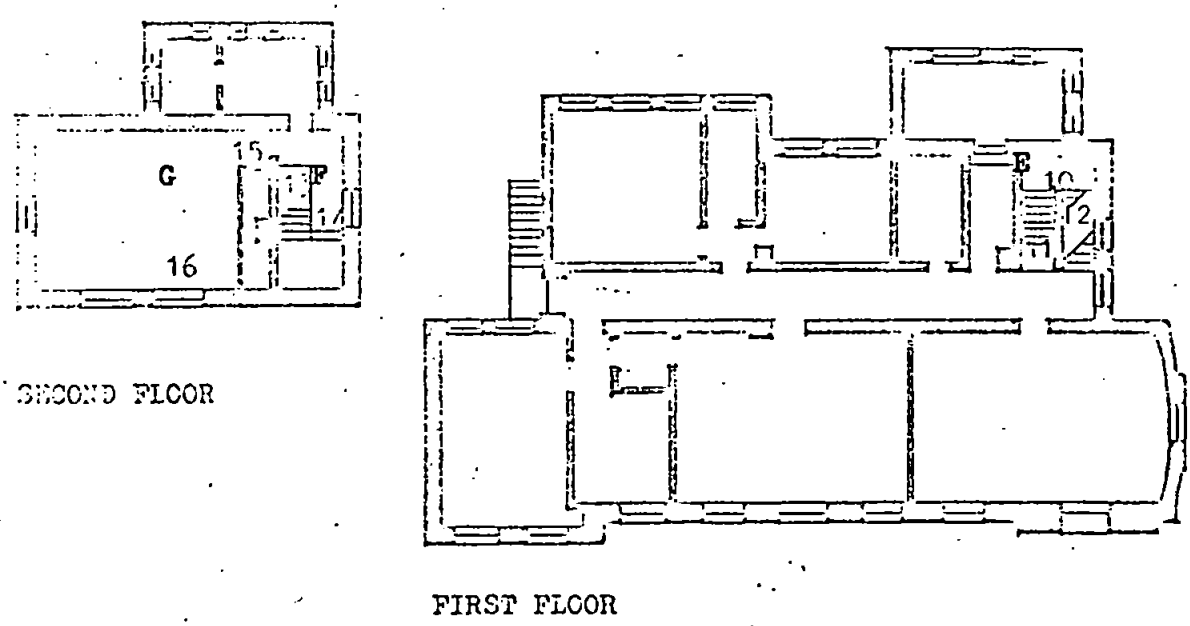


Figure 5.4.1 Plans of building used in the first thermal study

The survey was conducted in the evenings, when few people were in the building, for two reasons. Firstly, rapid fluctuations in air temperature due to opening of doors and windows would be reduced. Secondly, fluctuations in air velocity due to people moving and opening doors and windows would be reduced.

The survey was conducted on ten separate days in November and fluctuations in conditions occurred both between and within each day's survey. Table 5.4.1 gives the maximum and minimum values for each of the four variables recorded at each point throughout the whole survey.

To facilitate comparison between results each thermal sensation vote was given a value -3 to +3 and all values were normalised about one standard sequence of environmental conditions. The standard conditions are shown in Table 5.4.2. These were the conditions recorded on the occasion when the lowest temperatures were recorded at recording point B.

A point on the route was chosen at which votes were consistently lowest (marker 4). For each evening's survey the mean vote was established at this point together with the mean air temperature, mean radiant temperature, relative humidity and air velocity.

The following multiple regression equation was established, relating change of thermal sensation to changes in the environmental conditions:

Marker	A	B	C	D	E	F	G	
max	23.8	22.2	21.4	21.4	21.7	14.7	19.6	
Ta min	19.6	18.75	19.3	19.5	17.7	8.6	14.5	°C
max	23.8	22.0	21.8	22.0	21.3	15.7	19.6	
Tr min	20.7	18.9	19.5	20.0	19.1	8.7	15.0	°C
max	57.0	60.5	62.0	58.0	61.0	90.0	86.0	
RH min	30.8	28.0	35.0	32.5	35.8	52.0	48.3	%
max	0.1	0.25	0.25	0.25	0.25	0.26	0.20	
V_A min	0.04	0.05	0.05	0.05	0.05	0.05	0.04	M/S

Table 5.4.1 Maximum and minimum values for environmental variables

Recording Point	A	B	C	D	E	F	G
Ta °C	15.0	8.6	18.7	20.0	19.8	18.75	19.6
Tr °C	15.5	9.6	19.8	20.4	20.4	19.7	21.6
RH %	49.0	54.5	39.0	36.0	37.0	41.0	40.0
Va m/s	0.08	0.14	0.15	0.25	0.22	0.15	0.06

Table 5.4.2. Standard sequence of environmental conditions to which all votes were normalised

$$\Delta Ts = 0.049 - 0.022\Delta Ta + 0.132\Delta Tr - 0.001\Delta RH - 0.375\Delta Va$$

where ΔTs = change of thermal sensation
ΔTa = change of air temperature (°C.)
ΔTr = change of mean radiant temperature (°C.)
ΔRH = change of relative humidity (%)
ΔVa = change of air velocity (m/s)

The assumption was made that the change in environmental conditions for each evening's survey was linear with respect to time.

The environmental conditions for each thermal sensation vote were stated as deviations from the standard conditions (Table 5.4.2) and using the regression equation a new value for each vote was established, normalised with respect to the standard conditions.

5.5 Clothing

For our purpose clo values (clo units are a measure of clothing insulation, 1 clo = 0.155 $m^2 {}^oC/W$) for clothing ensembles may be more usefully stated as values for individual garments rather than whole ensembles, providing for a large combination of garments and the possibility of more nearly suiting most ensembles.

Seppanen and colleagues (ref. 2) have determined clo values using a heated manikin, and present tables of clo values for various male and female ensembles. It is possible to extract from these values for individual items of clothing.

These values do differ for some ensembles. For example, the difference between ensembles 18 and 19 (Table 5.5.1) is a tie with no difference in clo value. With a tie having no clo value one would expect the difference between ensembles 11 and 18 to be that caused by a sleeveless undershirt. This then has a value of 0.03 clo. Comparing ensembles 12 and 10 where the only difference is again a sleeveless undershirt, the difference in clo is 0.11.

However, values for individual garments have been derived from the tables and these are given in Tables 5.5.3 and 5.5.4.

Clo values have been re-established from Tables 5.5.3 and 5.5.4, for the various ensembles, for comparison and are given in Tables 5.5.1 and 5.5.2.

An attempt has been made to maintain the re-established values as close as possible to the original measured values. Where values differ, they have been made to err on the high side for the re-established ensembles. It is normally assumed that British clothing ensembles have higher insulation values than do American ones.

An attempt has also been made to retain the existing order of increasing insulation for the ensembles, except where these appear to contradict common sense. For example in Table 5.5.1 the difference between ensembles 13 and 12 is the difference between a short sleeved undershirt and a sleeveless undershirt. The latter is given a higher clo value in the Seppanen estimates. These two ensembles now

Table 5.5.1 Clothing insulation values for men's ensembles.

Ensemble No.	under shirt	socks	trousers	shirt	tie	sweater	jacket	CLO 1	CLO 2
15		cool	cool	SS-cool				0.48	0.48
24		cool	cool	LS-cool				0.49	0.49
23		cool	jeans	SS-woven				0.49	0.49
10		cool	cool	SS-woven				0.51	0.51
16		cool	cool	SS-warm				0.52	0.52
14		warm	cool	SS-woven				0.57	0.56
13	SS	cool	cool	SS-woven				0.59	0.63
26		cool	warm	SS-woven				0.61	0.61
12	SL	cool	cool	SS-woven				0.62	0.62
17	SL	cool	cool	LS-woven				0.65	0.65
25		cool	cool	LS-woven				0.76	0.73
21	SL	cool	cool	SS-woven		LS-cool		0.81	0.81
11		cool	cool	SS-woven	narrow		cool	0.89	0.89
22	SL	cool	cool	SS-woven		LS-warm		0.9	0.9
18	SL	cool	cool	SS-woven			cool	0.92	1.00
19	SL	cool	cool	SS-woven	narrow		cool	0.92	1.00
20	SL	cool	cool	SS-woven	narrow		warm	0.92	1.00
27	SL	cool	warm	SS-woven	narrow		warm	1.00	1.10

cool and warm refer to low and higher thermal resistance of the garment respectively.

SL = sleeveless, SS = short sleeves, LS = long sleeves
all ensembles include cotton briefs and low quarter shoes
CLO 1 - values provided by Seppanen et al (ref 2)
CLO 2 - values re-established from individual values in Table 5.5.3

Table 5.5.2 Clothing insulation values for women's ensembles.

Ensemble No.	dress	skirt	slacks	blouse	sweater	jacket	underwear	CLO 1	CLO 2
45	SL-cool						1	0.21	0.21
44	SL-cool						11	0.21	0.21
65	SL-cool			SS-cool			11	0.32	0.32
60		cool		SS-cool			11	0.33	0.32
51		cool		LS-cool			11	0.36	0.34
49		cool			LS-cool		11	0.4	0.39
53		cool		SS-cool	SL-cool		11	0.42	0.40
62		cool		LS-cool		LS-cool	11	0.45	0.50
63		cool		SS-cool		LS-cool	11	0.49	0.48
50		warm		LS-warm			11	0.51	0.55
57			cool	SS-cool			11	0.51	0.51
55			cool		LS-cool		11	0.58	0.58
59			cool	SS-cool	SL-cool		11	0.58	0.60
47		warm			LS-warm		11	0.65	0.65
48		warm			LS-warm		1	0.65	0.65
46		warm			LS-warm		V.	0.66	0.66
42	LS-warm						11	0.68	0.68
66		warm			LS-warm		V1	0.68	0.68
41	LS-warm						111	0.69	0.69
40	LS-warm						1V	0.71	0.71

'cool' and 'warm' refer to low and higher thermal resistance of garment respectively.

Underwear is as in Table 5.5.4

CLO 1 - values provided by Seppanen et. al. (ref 2)

CLO 2 - values re-established from individual values in Table 5.5.4

Table 5.5.3 Clothing values for individual garments of men's ensembles

Garment			CLO
Undershirt	SS		0.12
Undershirt	SL		0.11
Socks		cool	0.03
Socks		warm	0.08
Trousers		cool	0.22
Trousers		warm	0.32
Jeans			0.20
Shirt	SS	cool	0.22
Shirt	SS	woven	0.25
Shirt	SS	warm	0.26
Shirt	LS	cool	0.23
Shirt	LS	woven	0.28
Shirt	LS	warm	0.47
Sweater	LS	cool	0.19
Sweater	LS	warm	0.28
Jacket		cool	0.38
Jacket		warm	0.38
Briefs			0.01

Abbreviations as in Table 5.5.1

Table 5.5.4 Clothing values for individual garments for women's ensembles

Garment			CLO
Dress	SL	cool	0.20
Dress	LS	warm	0.67
Skirt		cool	0.20
Skirt		warm	0.35
Slacks		cool	0.39
Slacks		warm	0.59
Blouse	SS	cool	0.11
Blouse	LS	cool	0.13
Blouse	LS	warm	0.19
Sweater	SL	cool	0.09
Sweater	LS	cool	0.18
Sweater	LS	warm	0.29
Jacket	LS	cool	0.16
Jacket	LS	warm	0.29
I	cotton bra, acetate panties		0.01
II	cotton bra, acetate panties, nylon pantie hose		0.01
III	II plus full length nylon slip		0.02
IV	III plus elastic nylon lycra girdle		0.04
V	II plus nylon half slip and elastic nylon lycra girdle		0.02
VI	II plus knee socks		

Abbreviations as in Table 5.5.2

naturally reverse position. Similarly, ensembles 62 and 63 in Table 5.5.2 change position, the difference being between a short sleeved blouse and a long sleeved blouse.

Clo values have been established for each subject's clothing ensemble. The distribution of values is shown in Figure 5.6.3.

5.6 Results

The median response, together with confidence limits of plus or minus one standard deviation, for the whole group is shown in Figure 5.6.1.

The influence of the lower temperature of the court is clear. There are slight changes in thermal sensation within the building but there is a sudden drop on entering the court and a steep rise on re-entering the building from the court.

From the total data we can see that the response given at Point 1 is significantly higher at the end of the route than at the beginning. The almost spontaneous explanation of this is that it is due to the increase in metabolism in having walked through the building and up and down stairs. However, another explanation can be offered which can better account for the response.

In considering thermal sensation votes at Points 1, 2 and 3 which are all higher at the end of the route than at the beginning, it is notable that the vote preceding these three is significantly different on both occasions. Initially they are preceded by a mean vote of 0.2 (neutral) and on the second occasion 2.3 (cool).

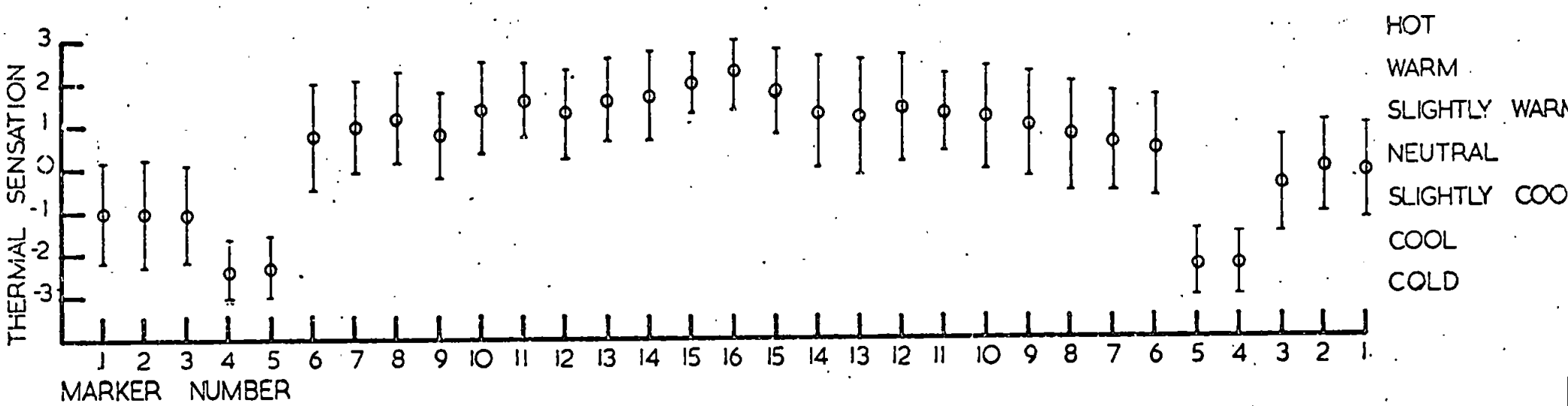


Figure 5.6.1 Median responses of 70 subjects, calculated using adjusted votes (section 5.4) as grouped data.

The effect is similar to the old trick of putting the right and left hand in hot and cold water respectively and simultaneously putting them both in tepid water. The sensation of each hand on placing in the tepid water is affected by the previous condition.

If this is the cause of the higher votes at the end of the route, we would expect the same trend to be evident when comparing other points along the route.

If we consider votes at Point 6 then we find this holds true. Initially preceded by the cooler experience of the courtyard the vote is 0.8 and secondly when preceded by the warmer experience of the building the vote is 0.5.

This influence of the previous experience holds true for all sub-groups irrespective of starting condition, clothing and sex.

It is interesting to note at this point that Houghten's original experiment (ref. 3) was conducted with men walking from one room to another (see section 2.2). Criticism of this aspect was later levelled by Yaglou (ref. 4). In a different experiment, Houghten and colleagues (ref. 5) reported a 'reasonably good correlation' between the degree of warmth before entering a cooled space and the comfort vote on entrance. This correlation was negative, suggesting that the higher the vote in the hot room, the lower the vote will be on entrance to the cooler room.

The mean standard deviation for the whole group is 1.1 . McIntyre (ref. 6) has shown that a minimum standard deviation of 0.8 is found in closely controlled climate

chamber work with homogeneous sedentary groups and that this can be increased by variations in activity and clothing and novelty of environment.

Two people acted as subjects on more than one occasion (in one evening) to see how much votes might be expected to vary within subjects. M.O. participated four times and D.P. ten. The mean probable error for M.O. was 0.7 and for seven occasions by D.P. (those having the same initial thermal sensation) 0.3 .

The lower mean probable error for the two individuals is mainly due to using a sample of one subject, but may partly be accounted for by memory. Indeed D.P. said he had been trying hard not to remember votes on previous runs. This factor, though effective to a much lesser degree, cannot be ruled out for the whole group as almost all subjects were familiar with the building.

The groups defined by initial thermal sensation are compared in Figure 5.6.2. In general the groups retain their order of magnitude of votes throughout the route. The influence of previous experience is displayed within each group (see Points 1 and 6 on outward and return journey of route), yet not consistently between groups.

Little else can be drawn from the comparison. Considering the cool experience (Points 4 and 5) with respect to the initial sensation, the magnitude of drop can be related to the magnitude of initial thermal sensation, although the closeness of voting between groups at Points

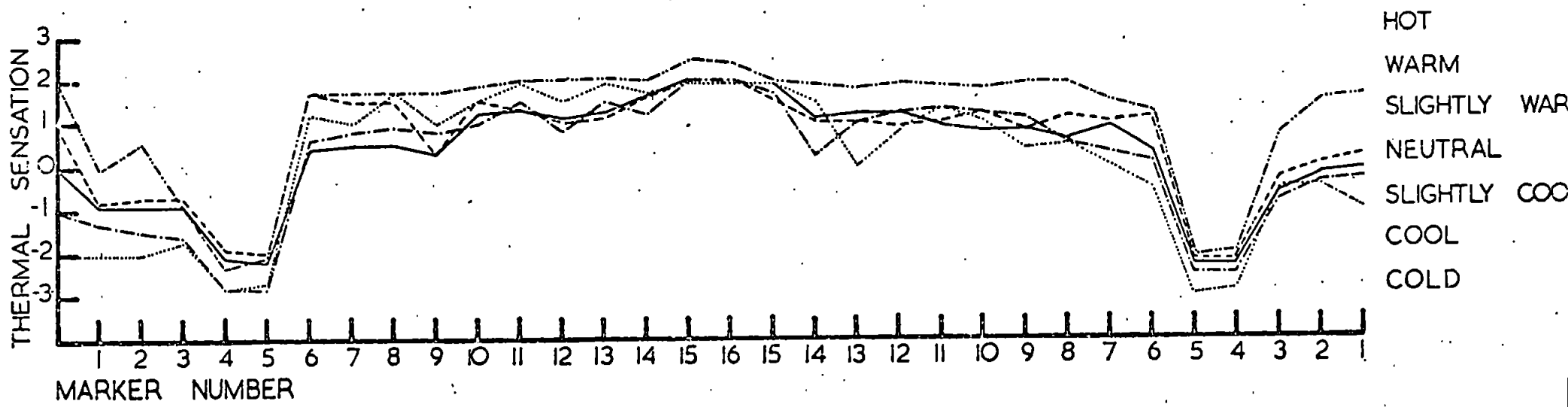


Figure 5.6.2 Median responses of subjects defined by initial thermal sensation.

4 and 5 also suggests a closer dependence on environmental conditions at these points. This closeness of voting is also evident at the warmest part of the route (Point 16). This is also partly due to bunching at the ends of the scale.

Figure 5.6.3 shows the distribution of clothing insulation values. The distribution is bimodal with the total group divided almost equally about the mean of 0.97 clo (36 subjects 0.97 ; 34 subjects 0.96). The difference between the means of the two groups is 0.33 clo.

The two groups are taken as the basis of comparison. Figure 5.6.4 shows the votes of each group. It can be seen that as may be expected, an overall increase in the level of votes is given in the higher clo value group (a mean difference between group votes of 0.3). However, the difference is less than that between individuals in each group. The mean probable error for the two groups is 1.1.

Two groups defined by initial thermal sensation were then compared for each clothing group. Figures 5.6.5 and 5.6.6 show the results. For the group initially voting 'slightly cool' the mean difference between the two clothing group votes is 0.7 and for the group initially voting 'warm' 0.1.

However, a closer inspection of the data shows that the effect of increase in clothing insulation on the 'slightly cool' group is in votes above the 'neutral' vote

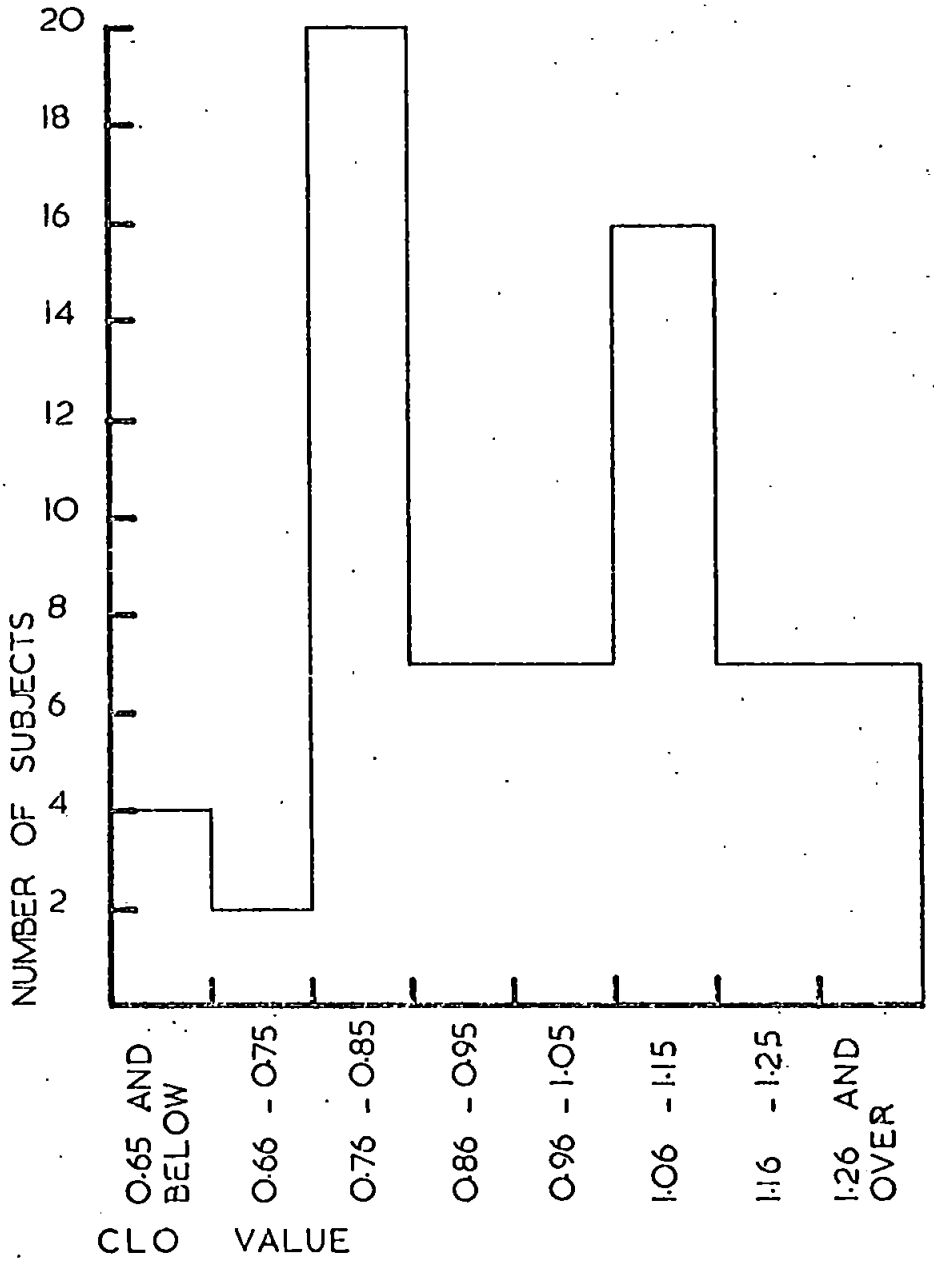


Figure 5.6.3 Distribution of clothing values

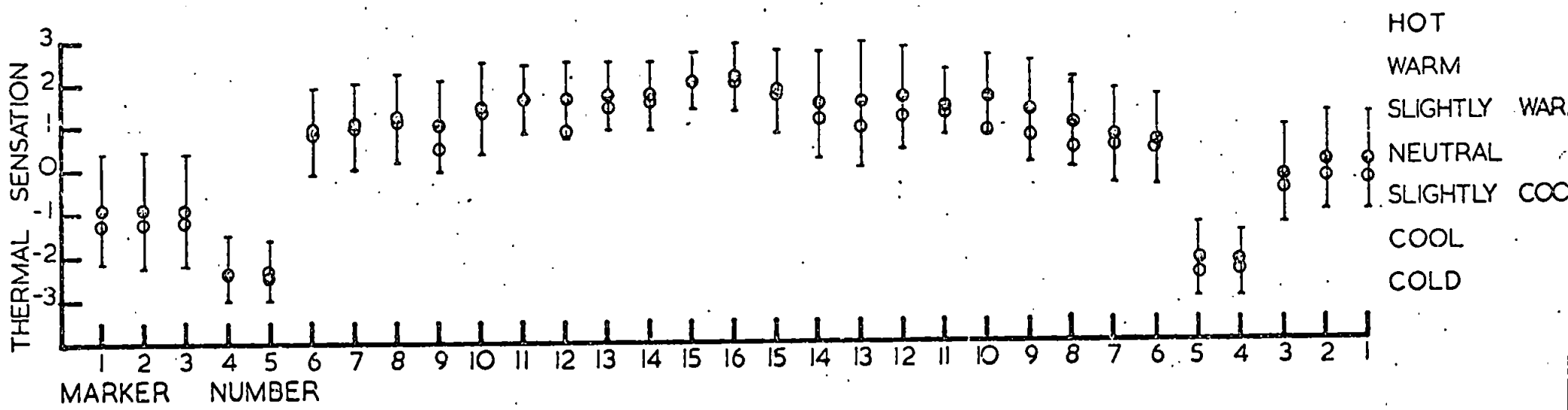


Figure 5.6.4 Median responses of two groups. ⊙ = 0.97 clo +, o = 0.96 clo −.

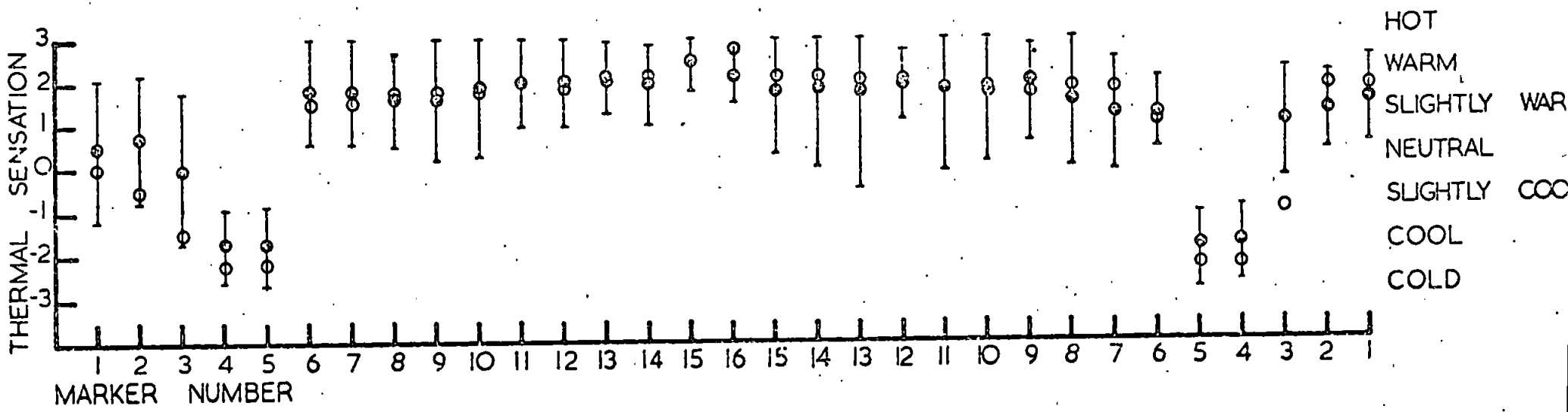


Figure 5.6.5 Median responses of two groups initially voting 'warm'. ⊙ = 0.97 clo +, o = 0.96 clo −.

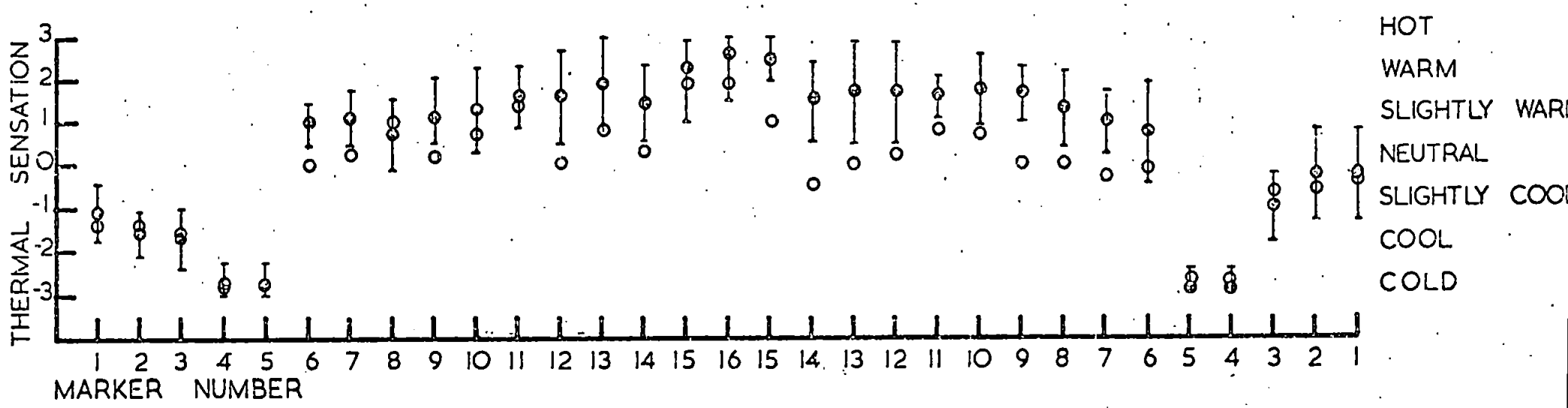


Figure 5.6.6 Median responses of two groups initially voting 'slightly cool'.
⊖ = 0.97 clo +, o = 0.96 clo −.

(a mean difference of 0.8 above 'neutral' and 0.0 below 'neutral'). For the 'warm' group the effect of the increase of clothing insulation is in votes below the 'neutral' vote (a mean difference of 0.0 above 'neutral' and 0.7 below 'neutral').

The role of clothing as a buffer to changes of environment has been studied elsewhere (ref. 7). Figure 5.6.4 shows a very slight tendency to this effect. The higher clo group were less cool on immediate entry to the low temperature court on both occasions. This is more evident for the group initially voting 'warm' (Fig. 5.6.5). However, there is a tendency for this to reverse for the group initially voting 'cool' (Fig. 5.6.6).

Figure 5.6.7 shows the difference in response between the male and female groups, together with confidence limits of probable error for the male group. The overall votes of women are seen to be lower than those of men. The mean difference is 0.3.

However, the two groups have different clo values. The mean clo value for men is 0.99 and for women is 0.77 (a mean difference of 0.22). We can see from Figures 5.6.3 and 5.6.4 that a difference of 0.33 clo would account for a difference in votes of 0.3. The mean clo difference between the groups of 0.22 can therefore account for a difference in votes of 0.2.

The college age group (range 18 to 28 years, mean 21.8) was compared with the over college age group (range 29 to 49, mean 37). The votes for the two groups are shown in Figure 5.6.8, together with the confidence limits of probable error for the college age group.

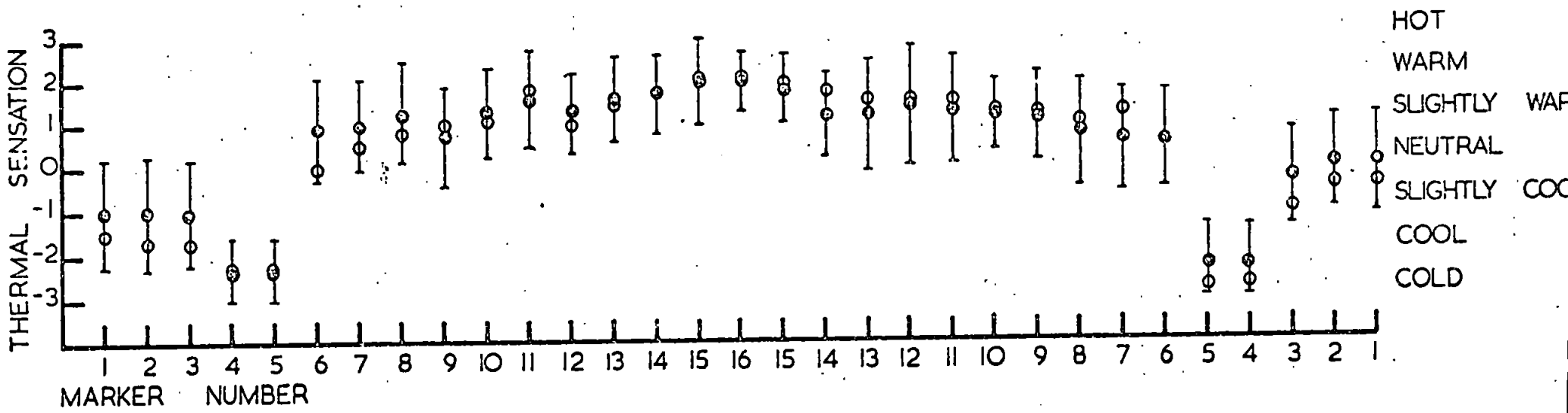


Figure 5.6.7 Median responses of two groups. ⊖ = male, ○ = female.

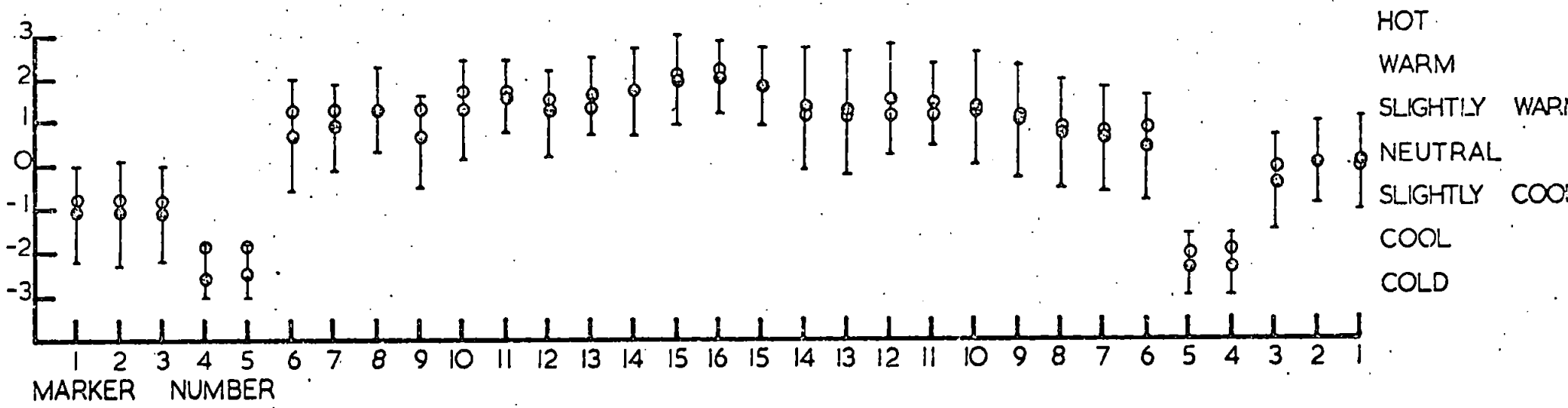


Figure 5.6.8 Median responses of two groups. o = over college age, ⊙ = college age.

The mean vote for the over college age group is 4.6 and for the college age group is 4.4, a mean difference of 0.2.

The mean clo value for the above college age group is 1.06 and for the college age group is 0.95. The mean difference of 0.11 can account for a difference in votes of 0.1.

5.7 Discussion

The results of the present study would indicate that, in predicting the thermal response to a sequence of different environmental conditions, short term past experience should be taken into account.

No significant difference is found between the two age groups (57 college age and 13 over) and between the two sex groups (64 males and 6 females). Clothing insulation is seen to have a small overall effect in the order of 0.3 clo = 0.25 sensation vote although the effect is not evenly spread over the sensation scale for all groups defined with respect to initial sensation.

Any differences due to sex, clothing, age or initial sensation are seen to be small in comparison with the mean confidence limits of plus or minus one sensation vote for the whole group. This is especially the case when ultimately we wish to relate the values back to the verbal scale (5.3.3a) and the values are rounded to the nearest whole vote.

The model described in Section 4 is modified to account for previous sensation by the following two equations:

$$T_{s3} = 0.9\,T_{s1} + 0.45\,T_{s2}$$

$$T_s = T_{s3} + 0.6\,(T_{s3} - T_{s2}) + 0.8$$

where T_{s1} = prediction by physiological model
T_{s2} = previous thermal sensation
and T_s = predicted thermal sensation

The environmental conditions shown in Table 5.4.2 together with the mean height, weight and clothing value of subjects, formed input to the computer program.

Figure 5.7.1 shows the response predicted by the model compared with the results of the survey. The two are in close agreement. The predictions by the model are within one standard error of the median response from the data.

5.8 A Second Validation Study

The model described in Section 4 has been further modified to take account of short term past experience. This adjustment was based on data from a survey of people's responses given along one route in a building. Therefore, it was thought worthwhile to conduct a second survey in another building to see how accurately the model could predict other situations.

The experimental procedure was the same as that described in Section 5.3. Ten subjects from the School of Architecture participated and their personal details were recorded on the

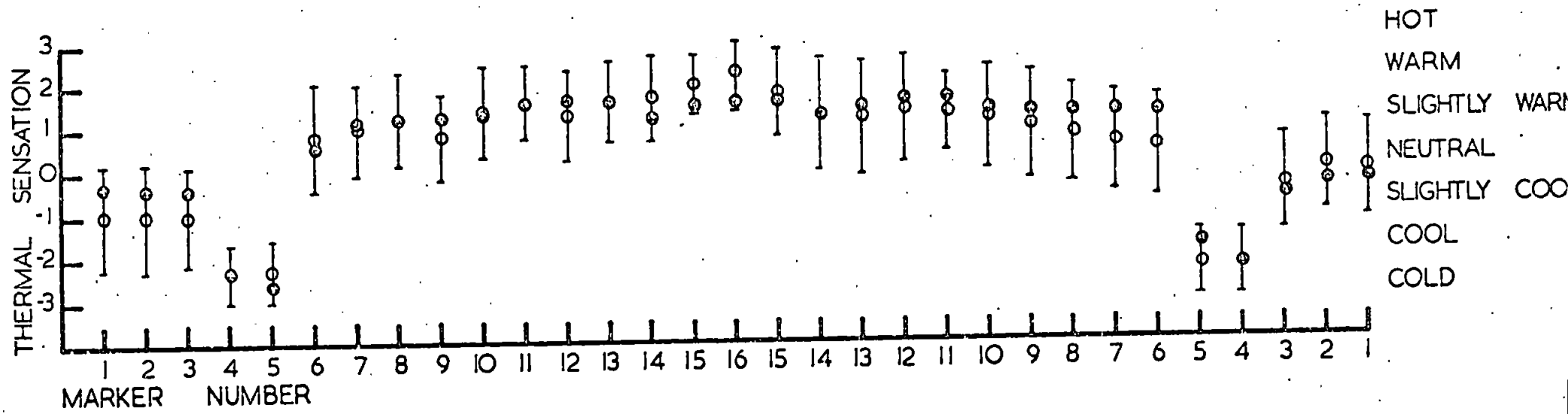


Figure 5.7.1 Comparison of median responses for whole group with predictions by model. ⊙ = model, ○ = data .

standard form shown in Figure 5.3.2. All subjects were college age (range 18 - 28 years). The mean height of the group was 1.8 m and the mean weight was 73 kg. Figures 5.8.1a, b and c show the route through the building, the points at which thermal sensations were stated and the positions at which environmental recordings were taken. The route started in a first floor room, proceeded out, down to the ground floor and around a corridor, down into the basement and back again.

The small group of subjects allowed the survey to be carried out in one afternoon within approximately one hour. Therefore, no corrections to the thermal sensation votes were made. Table 5.8.1 shows the environmental conditions recorded at each point before and after the survey together with the mean values. These mean values were used as input to the computer program for comparison. Thermal sensations only were recorded, using the categories used in Figure 5.3.3a. The median of the responses was taken to represent the average vote at each point. These are shown in Figure 5.8.2.

Comparison of votes at Points 1, 2, 3 and 4 shows an average increase at each point of about one vote on the return journey. On the return journey, the environment at these points is experienced after a relatively cool part of the route, suggesting an effect of previous experience on votes.

The mean clothing insulation value for the group was 0.99. Figure 5.8.3 shows the distribution. The group was

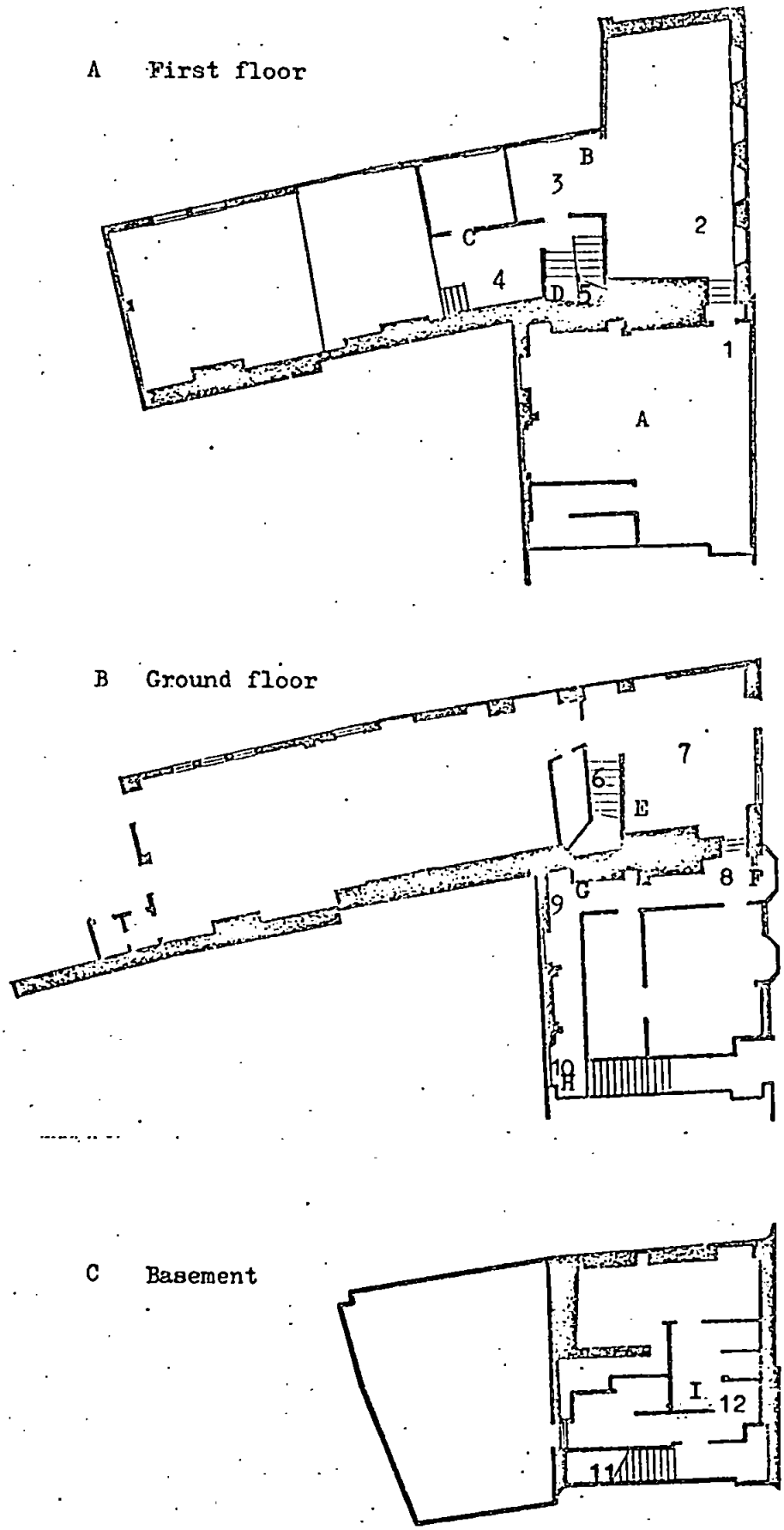


Figure 5.8.1 Building used in second validation study. Numbers denote points at which votes were given. Letters denote points at which recordings were taken.

	A	B	C	D	E	F	G	H	I	
	17.3	14.7	11.8	12	10.8	11.7	11.8	11.8	10.1	max.
Ta	16.8	14.5	11.6	11.8	10.5	11.1	11.3	11.4	9.9	mean C°
	16.25	14.25	11.3	11.5	10.25	10.5	10.7	11	9.7	min.
	17.0	14.2	11.7	12	10.2	11.1	11.1	11.1	10.3	max.
Tr	15.7	14.1	11.7	11.8	10.1	10.8	10.8	11	10.2	mean C°
	14.4	13.9	11.7	11.6	10.0	10.5	10.8	10.5	10	min.
	63	65	70	68	68	72	72	73	74	max.
RH	60	62	69	67	68	70	70	71	69	mean %
	56	58	67	65	68	68	68	68	63	min.
Va	0.102	0.112	0.046	0.097	0.046	0.064	0.076	0.076	0.094	m/s

Measurements of air volocity (Va) were taken on one occasion

Table 5.8.1. Environmental conditions recorded at points along the route

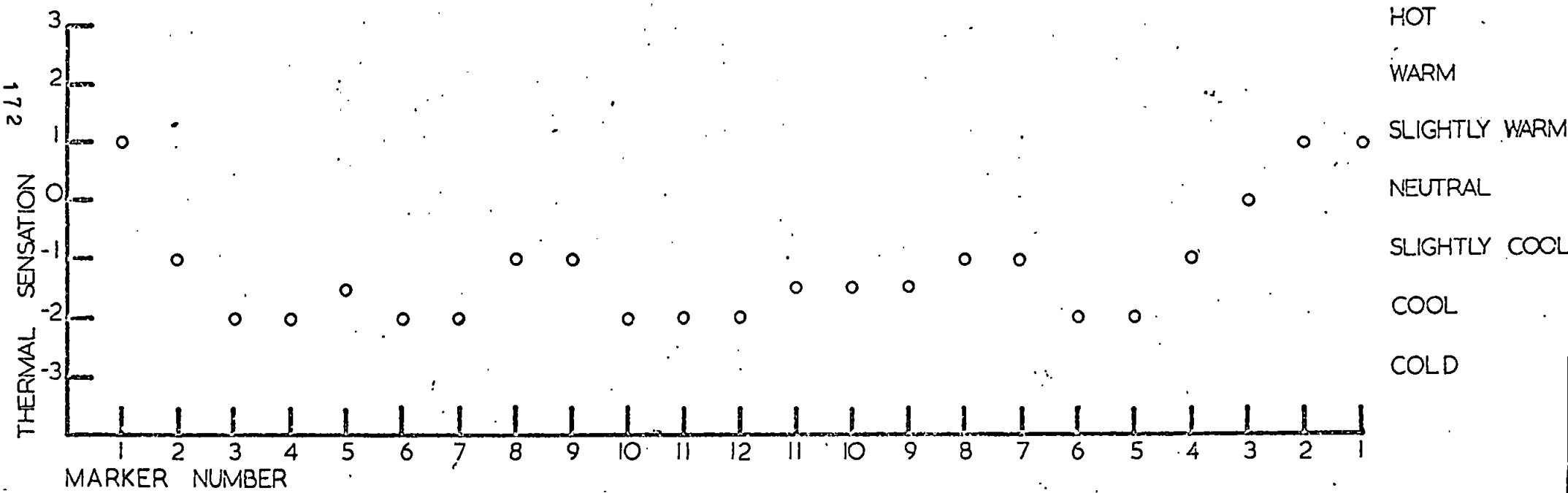


Figure 5.8.2 Median responses of group of 10 subjects in second study.

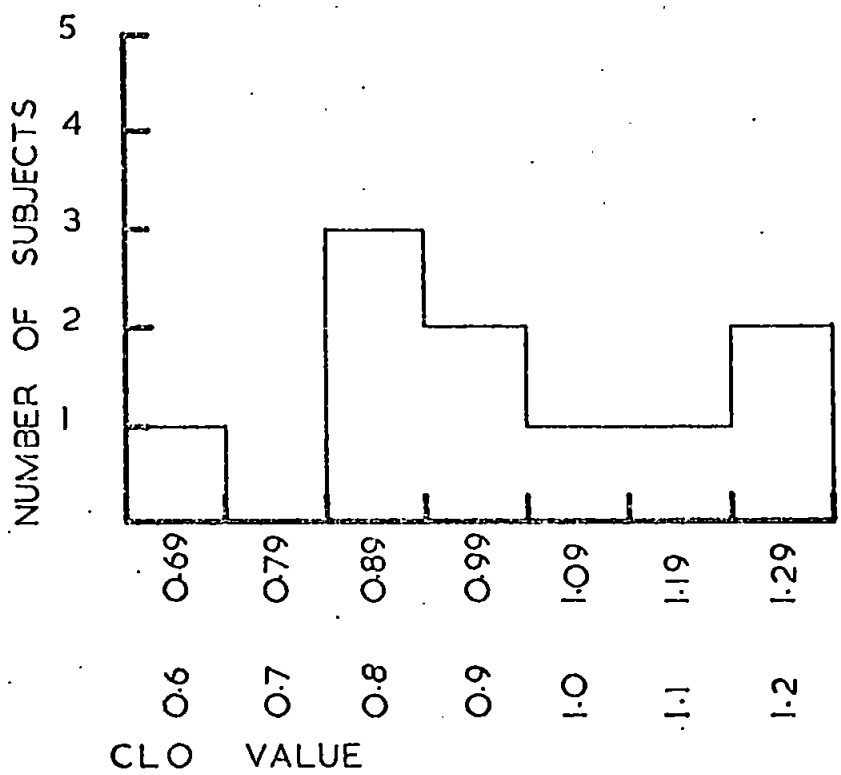


Figure 5.8.3 Distribution of clothing values within group

divided into those above 1 clo (mean 1.19) and those below 1 clo (mean 0.87) for comparison. Figure 5.8.4 shows the results. The difference in mean clothing insulation is 0.32 and the mean difference in votes is 0.5. This is greater than in the first survey (approximately 0.3 clo = 0.25 sensation vote). However, it would be unwise to generalise from this data as the groups were so small (6 and 4).

As with the first survey, considerable differences between individuals were noted. Not only did general levels of votes differ but also subjects varied in their sensitivity to changes. Figure 5.8.5 shows the comparison of two subjects, both very similar in age, physique and wearing similar clothing.

Predictions made by the model are compared with the median responses for the whole group in Figure 5.8.6. As to be expected, the two are not as close as in the first survey. However, the predictions follow the general trend of the data and the two are in reasonably close agreement.

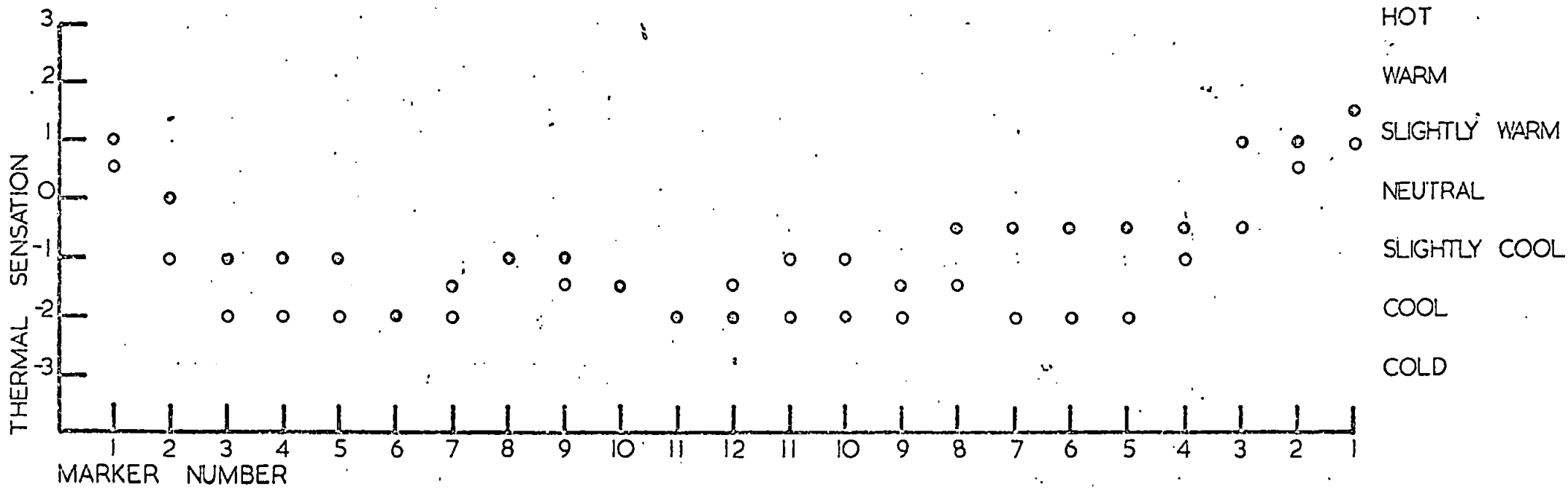


Figure 5.8.4 Comparison of median responses for two groups. o = 1 clo +, o =0.9 clo -.

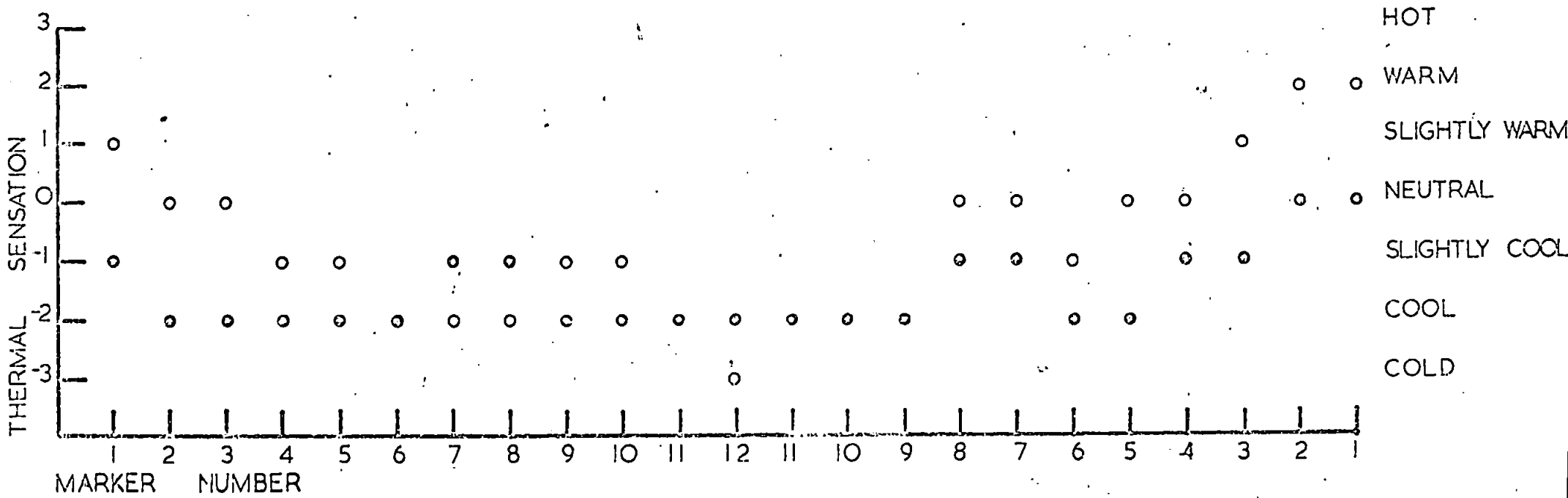


Figure 5.8.5 Comparison of estimates given by two subjects of similar build and clothing.

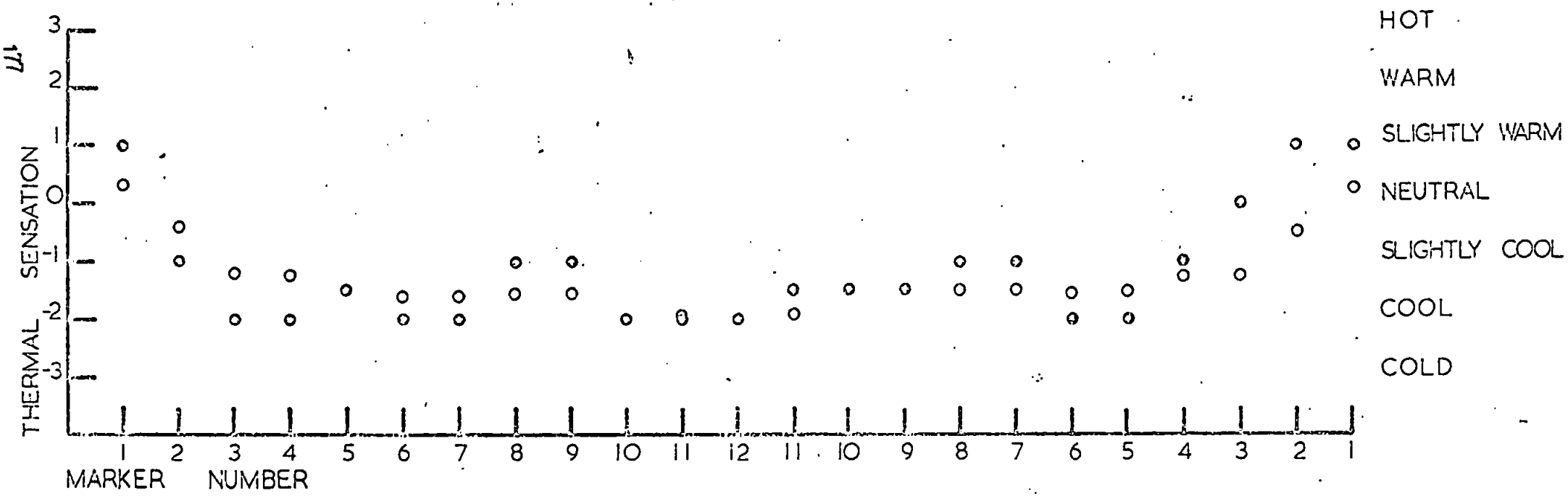


Figure 5.8.6 Comparison of median responses of whole group with predicticns by model.
⊙ = data, o = model.

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Section Six. Towards a Dynamic Model of Human Visual Response

6.1 Introduction

The human visual system has evolved to cope with levels of luminance varying in the order of 1 to 10^{12}, from shadows on a starlit night to snow in full sunlight. The visual system can adapt so that vision is possible under both extremes.

This range is not likely to be met within a building although the often quoted experience of walking into a cinema from a bright street provides us with a close example.

The interior of a building provides the visual system with a different problem from that of the natural range of illumination. Whilst the range within the building will be not nearly so great the changes may occur more rapidly. However, the same mechanisms are at work in an attempt to produce optimum vision under the given conditions.

The word adaptation has been used in vision studies to describe two conditions (ref. 1). The first is 'steady state adaptation' where the eye is given time to reach an equilibrium at a particular adapting level and variations of visual performance are given as a function of that level. The second is 'temporal adaptation' which describes the state where the eye has not reached an equilibrium and performance is given as a function of the time that has elapsed since a change in adaptation level.

In considering the visual response to changes in lighting level as one moves about a building no equilibrium can be assumed and examination of temporal adaptation should prove the more fruitful endeavour.

6.2 Temporal Adaptation

Temporal adaptation has been studied using variations in the threshold level throughout its time course as a measure of changing conditions of visibility. The earliest work on adaptation (refs. 2 and 3) and later work on the photochemistry of vision (ref. 4) has been concerned with the later stages of the development. Other work has centred on the initial stages of adaptation (refs. 5, 6 and 7).

The classical dark adaptation curve illustrating the later stages of the time course is shown in Figure 6.2.1.

This classical dark adaptation curve illustrates the situation where an observer is plunged into darkness and the threshold (L) is defined as the luminance of the test object needed to be just visible above the black background. The falling curves show that as time progresses from the moment of the change of lighting level less and less light is needed on a test object for it to be seen. Beside the fact that the threshold decreases as time progresses the curve exhibits two major features:

1. The course of adaptation is very rapid for the first twenty minutes. Equilibrium is attained after about one hour although evidence has been found suggesting

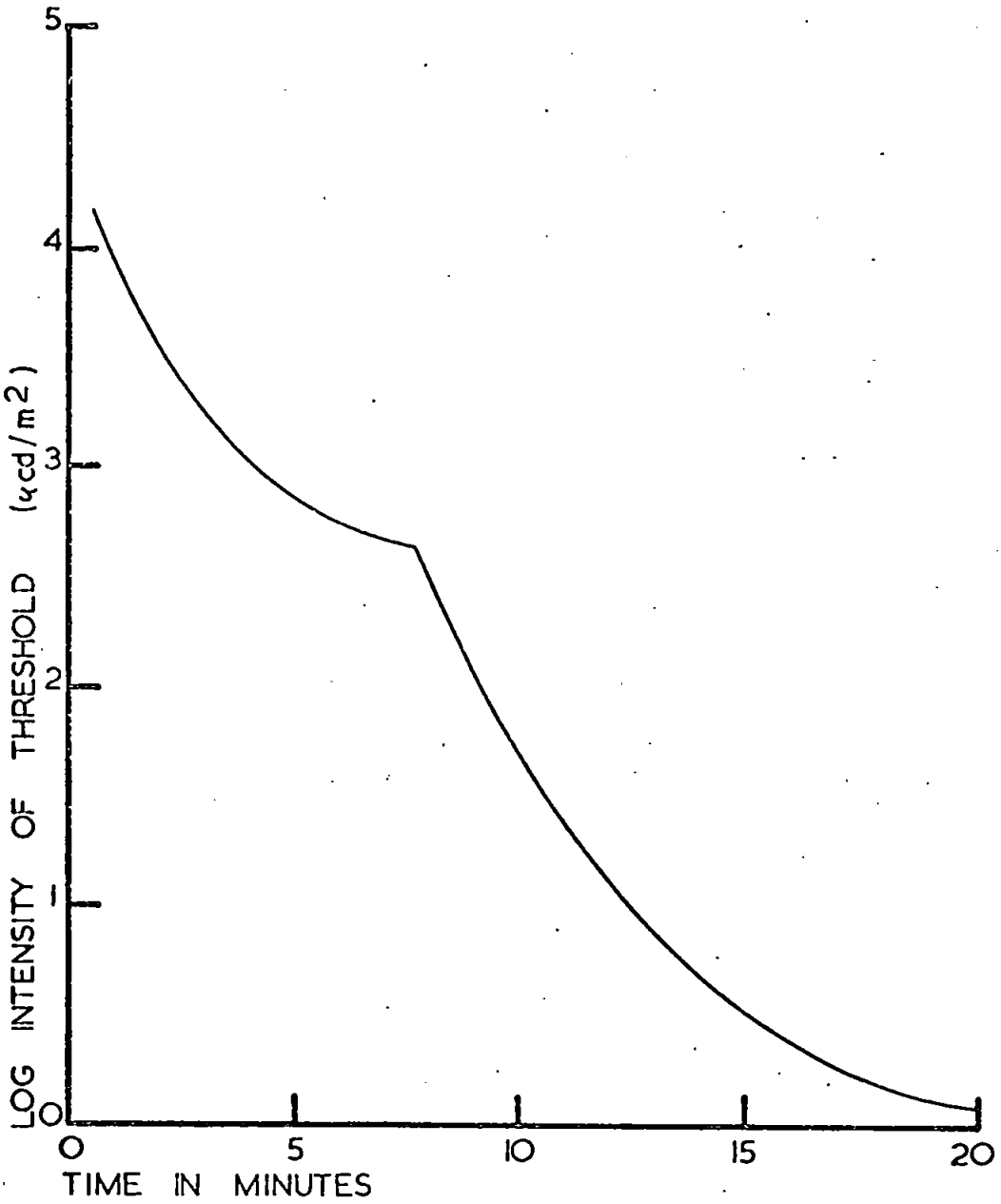

Figure 6.2.1 Classical dark adaptation curve. After Hecht (ref. 9)

that the threshold continues to drop even further for periods up to eight hours (ref. 8).

2. The curve is distinctly broken at the time period of about eight minutes, the change from photopic (light adapted) to scotopic (dark adapted) vision. The physiological basis for this change is a change from cone vision to rod vision.

The two phases of this curve can be examined separately by stimulating the appropriate part of the retina. Figure 6.2.2 shows the distribution of the cones and rods in the eye. There is a marked difference in distribution. The cones are concentrated in the centre of the retina and their density declines rapidly as the distance from the centre increases. The rods begin to appear about 1° from the centre, reaching a maximum density at about 20°.

If an observer is plunged into darkness and a small test flash delivered to the fovea only, then the threshold changes recorded are due to stimulation of the cones only. The change of threshold is shown schematically in Figure 6.2.3. If the small test flash is delivered to an area on the periphery of the retina, where the distribution of cones is sparse, then the threshold changes are due to stimulation of the rods. This change is also shown in Figure 6.2.3. The dark adaptation of the cones is almost complete after about 5 minutes whilst rod adaptation takes about 30 minutes. At first, the cones are more sensitive than the rods but after about 8 minutes the rods are the more sensitive.

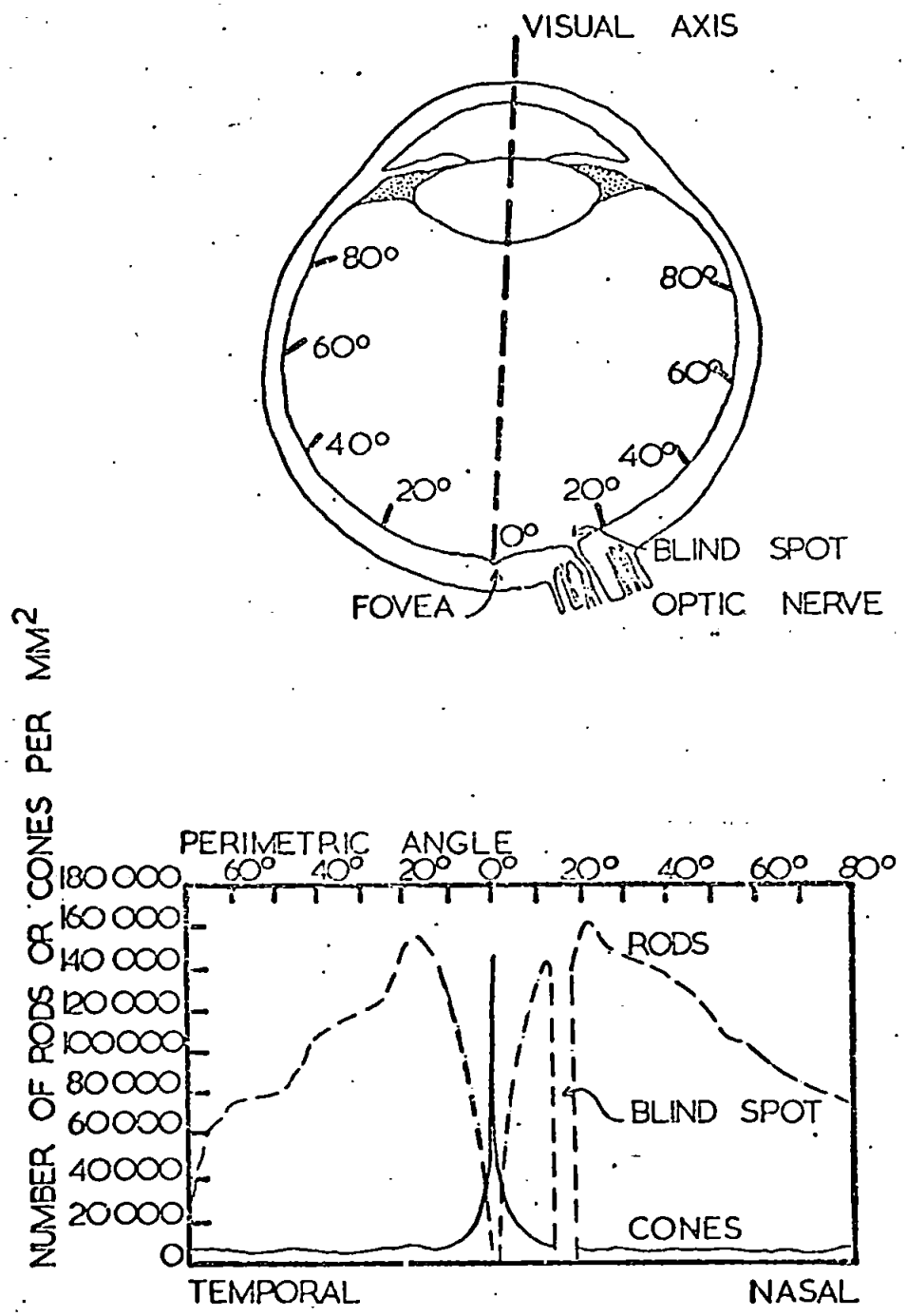

Figure 6.2.2 Schematic horizontal section through the left eye and the distribution of rods and cones.

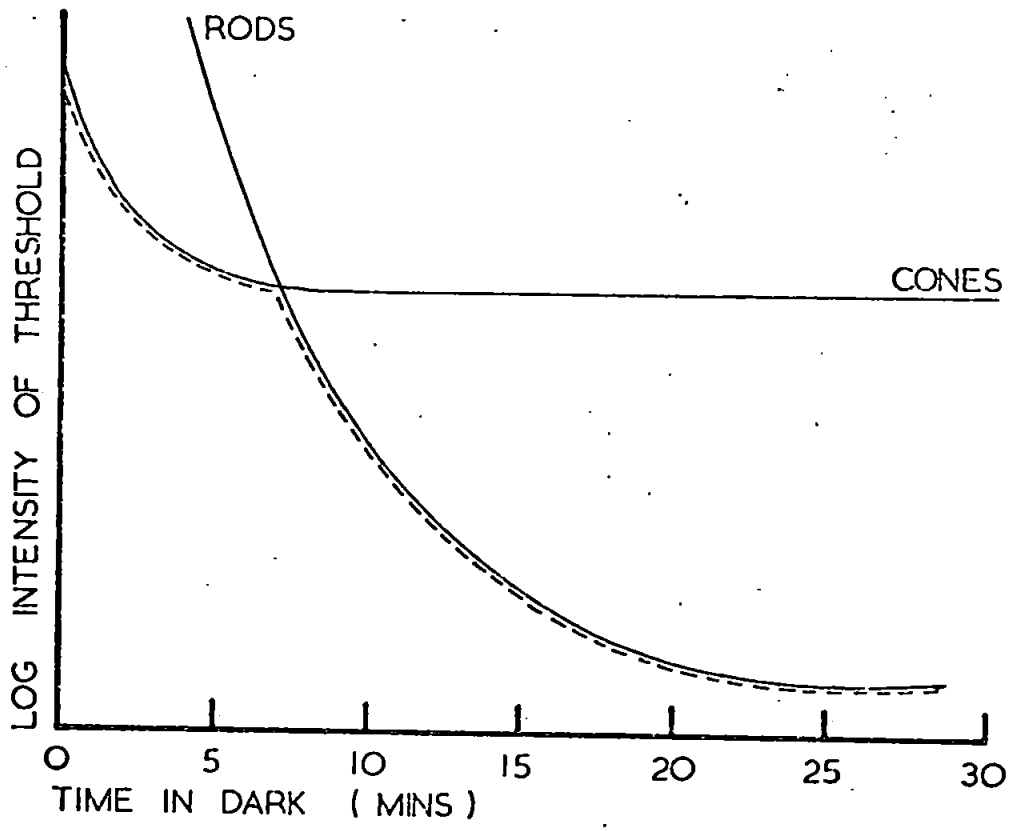

Figure 6.2.3 Changes of threshold in the cones and rods and their combined effect to produce the classical dark adaptation curve.

If instead of a small test flash we now use one large enough to stimulate both the rods and the cones, for the first 8 minutes the cones are more sensitive and the dark adaptation curve will follow the curve of the cones alone, levelling off after about 5 minutes. After about 8 minutes, the rods become more sensitive and the threshold drops again, following the curve of the rods. This composite curve is shown dashed in Figure 6.2.3.

Variation in pre-adaptation moves the whole curve parallel to the time axis so that the photopic phase is extended more and more with the product Lo.to (Lo = pre-adapting luminance, to = exposure time to Lo). This can be seen in Figure 6.2.4, where the solid-line curve illustrates the extreme individual results from 110 subjects studied by Hecht and Mandelbaum (ref. 9). Preliminary adaptation was for 3 minutes with a uniform white field having a luminance of 5000 cd/m^2 and an apparent diameter of 40°. The test patch was 3" diameter viewed with one eye with the natural pupil and was centred 7" from the point of fixation. The dashed-line curves show the range covered by three quarters of a group of 45 subjects studied by Sheard (ref. 10), where preliminary adaptation was for 3 minutes with a uniform white field having a luminance of 500 cd/m^2. The test patch of 20" diameter was viewed with one eye at 10° from the point of fixation. The pupil was artificially dilated and luminance corrected to a constant pupil diameter of 5 mm. The break between the dashed-line photopic and scotopic curves is partly smoothed out due to averaging.

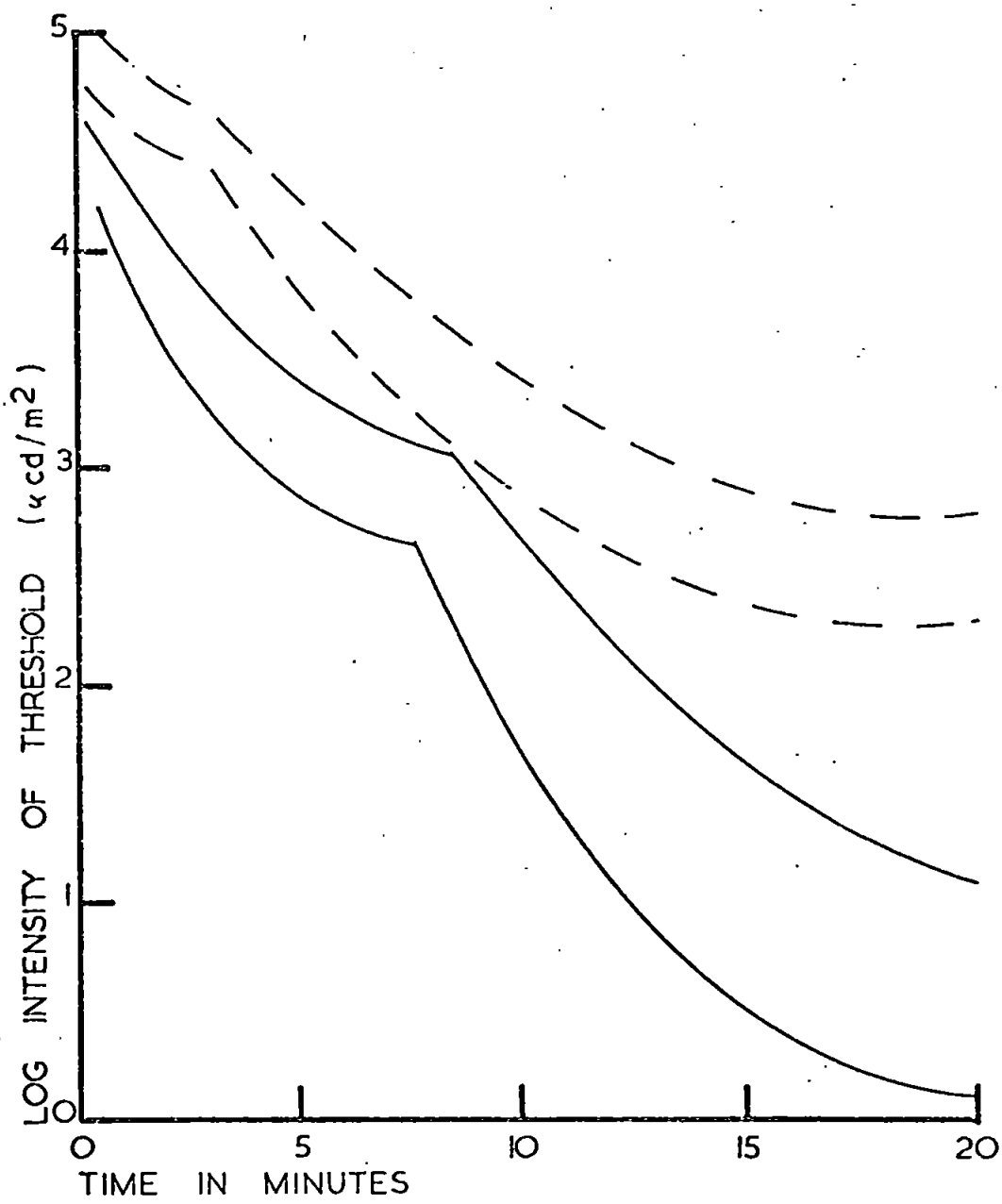

Figure 6.2.4 The effect of varying pre-adaptation time on the changes in threshold

The shape of the curve at the beginning of both the photopic and scotopic stages becomes steeper as preadaptation is reduced. If preadaptation is by a short bright flash then the photopic phase also consists of two parts - an earlier gain of sensitivity more rapidly than normal. Rushton proposes that this is due to a photochemical process (ref. 11).

When Haig (ref. 12) varied preadaptation intensities and durations the rod portion of dark adaptation occurred earlier following shorter or weaker preadaptation. At a given level above final threshold the curve fell more steeply for weaker preadaptation. The difference seemed to depend solely on the product of intensity and duration, as if the quantity of rhodopsin (a photochemical pigment) bleached were the determining factor. This reciprocal relationship has been shown to break down under conditions not studied by Haig (Barlow ref. 1).

When the apparent size of the test is varied the curves shift parallel to the ordinate. Also, as the apparent size of the test is increased the discontinuity between the two phases of the curve diminishes.

6.3 Initial Stages

The course of adaptation discussed so far has typically been measured at intervals of minutes after a change of stimulus and not surprisingly early studies were confined to this magnitude of time scale. Measurements taken at much shorter time intervals had to wait developments in experimental equipment.

In 1947 Crawford (ref. 5) reported on a number of wartime studies of adaptation to brief stimuli, these stimuli simulating gun flashes. He noted that no difference in recovery from a flash was found between positive and negative contrast of object, contrast being defined as:

$$\frac{\text{(Brightness of background)} - \text{(Brightness of object)}}{\text{Brightness of background}}$$

Also, a simple relation exists between recovery of the eye to total darkness and to partial darkness. The curve of the recovery to partial darkness follows that of recovery to complete darkness until the threshold for the finite field brightness is nearly reached, then rapidly flattens out.

The time course of recovery from the simulated flash was about 1.1 seconds and Crawford also studied the fluctuations in the threshold that occur within this brief time course. Figure 6.3.1 shows his results.

These complex threshold curves illustrate the initial stages of both light and dark adaptation (the onset and cessation of a conditioning flash) and are characterised by:

1. The initial rise at the onset and cessation of the conditioning stimulus
2. The rapid drop that flattens abruptly into the regular slow adaptation curve.

Baker (ref. 6) has shown that the rapid fluctuations are not particular to brief flashes but occur whenever adaptation to dark or light begins. He also showed that for

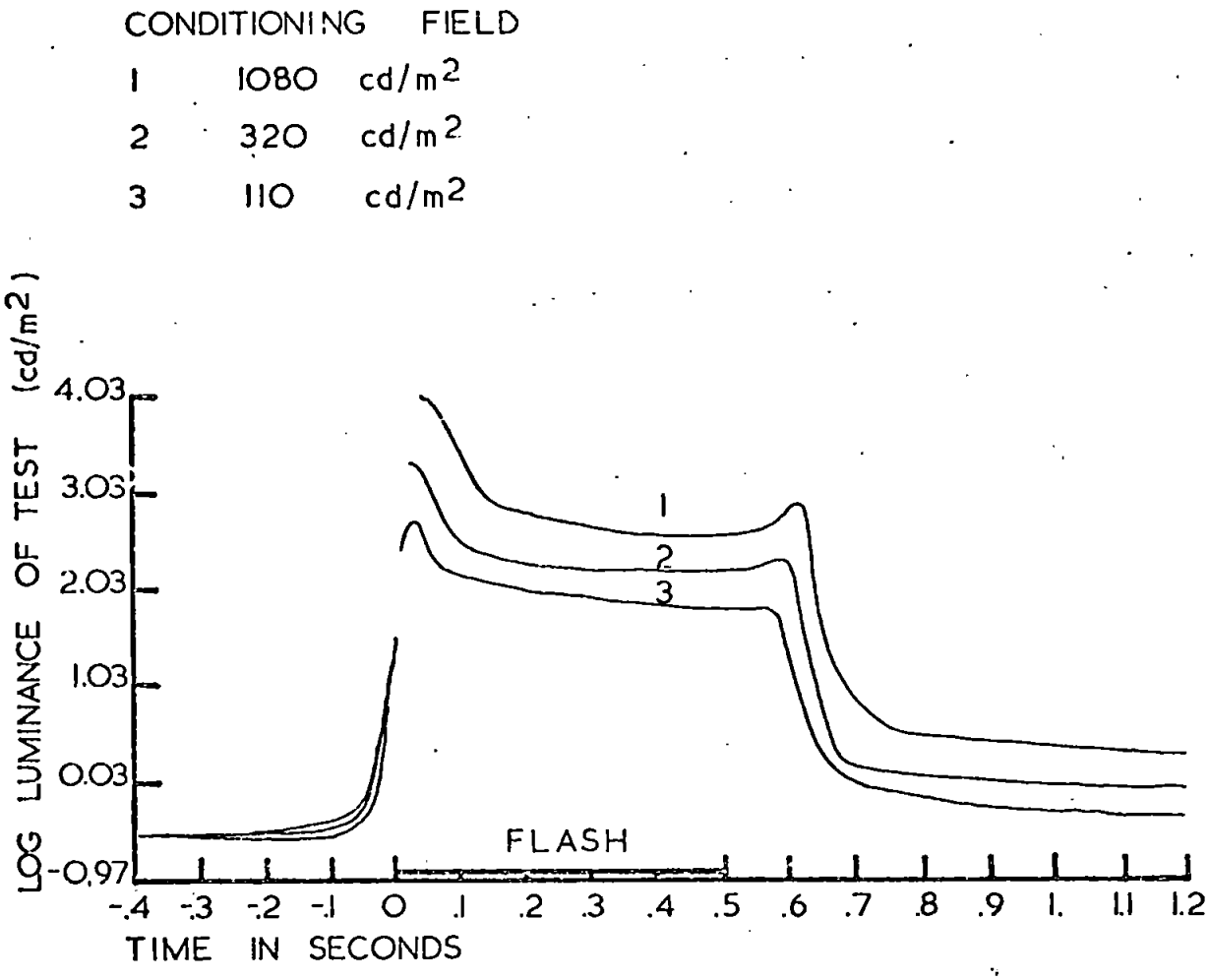

Figure 6.3.1 Crawford's measurements of threshold during brief light adapting flashes. Duration of flash was 0.5 seconds starting at time 0 (ref. 1)

dark adaptation the initial rise is a function of the intensity of the adapting light (Fig. 6.3.2).

Baker distinguishes three phases of the curves shown in Figure 6.3.2. These are illustrated in Figure 6.3.3. To explain the first stage (an initial rise of threshold level), the single visual receptor of the limulus (horse-shoe crab) is suggested as a model of the human visual receptor. The discharge rate of the optic nerve of the limulus depends on the height of a slow potential charge in the receptor. This slow potential results from illumination of the eye and it falls a little at the moment when illumination is terminated. A slightly more intense flash of light is therefore required at this point to raise the potential enough to cause a threshold discharge.

The second phase (a rapid drop) is due to nervous elements beyond the receptor. This explanation also derives from comparison of the human eye with that of the limulus. The limulus preparation, which consisted only of the receptor and attached nerve fibre, displayed no abrupt fall of threshold. The fall of the human threshold must therefore be due to causes higher in the system. Photochemical processes must occur in the limulus eye so these are ruled out.

The third phase of the curve is that of regular dark adaptation. This phase appears flattened out in Figures 6.3.2 and 6.3.3 because of the expanded time scale.

A common feature of Figures 6.3.1, 6.3.2 and 6.3.3 is the apparent anticipatory rise of threshold before the onset

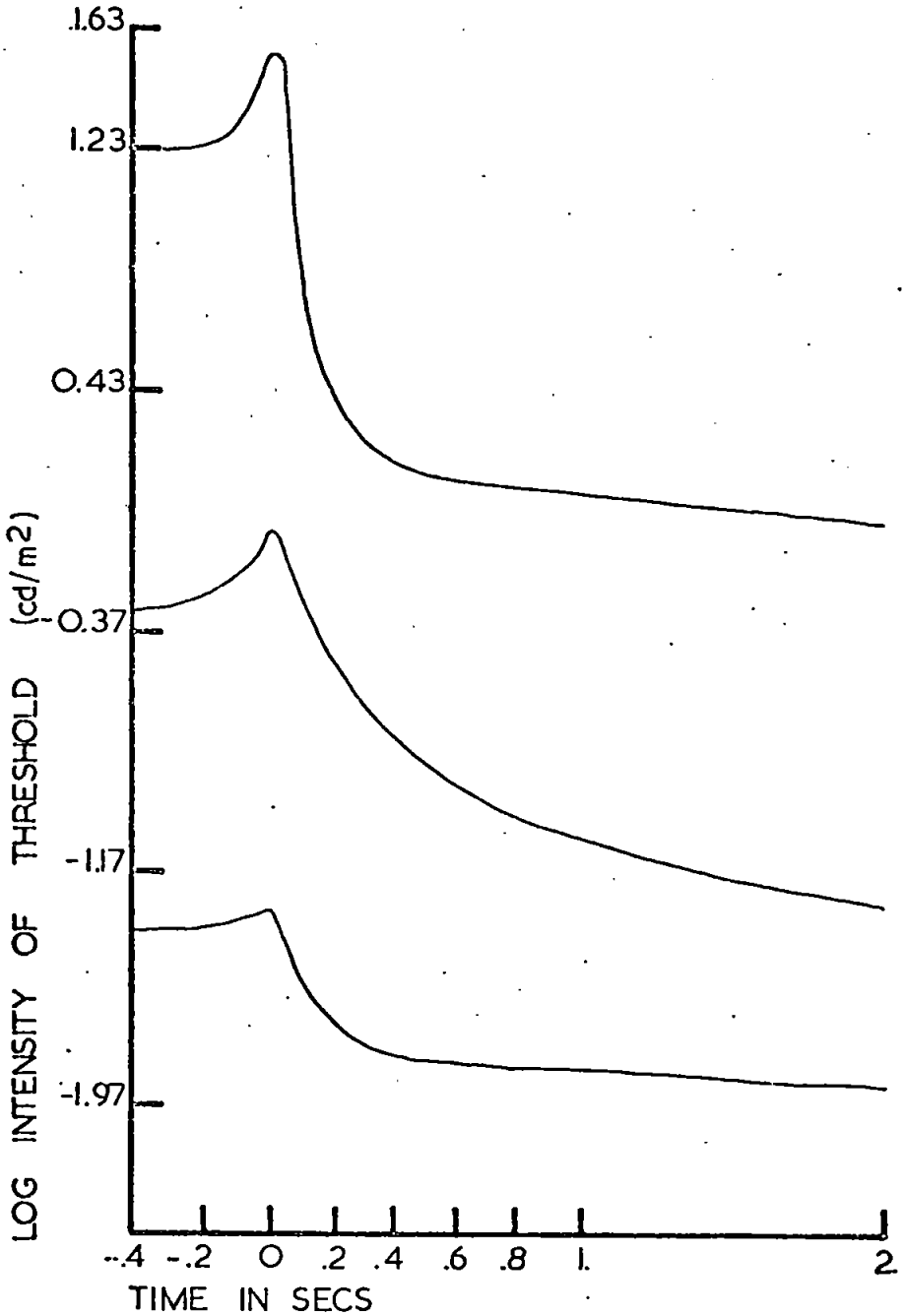

Figure 6.3.2 Early dark adaptation from ref. 13. The adapting field was turned off at time 0.

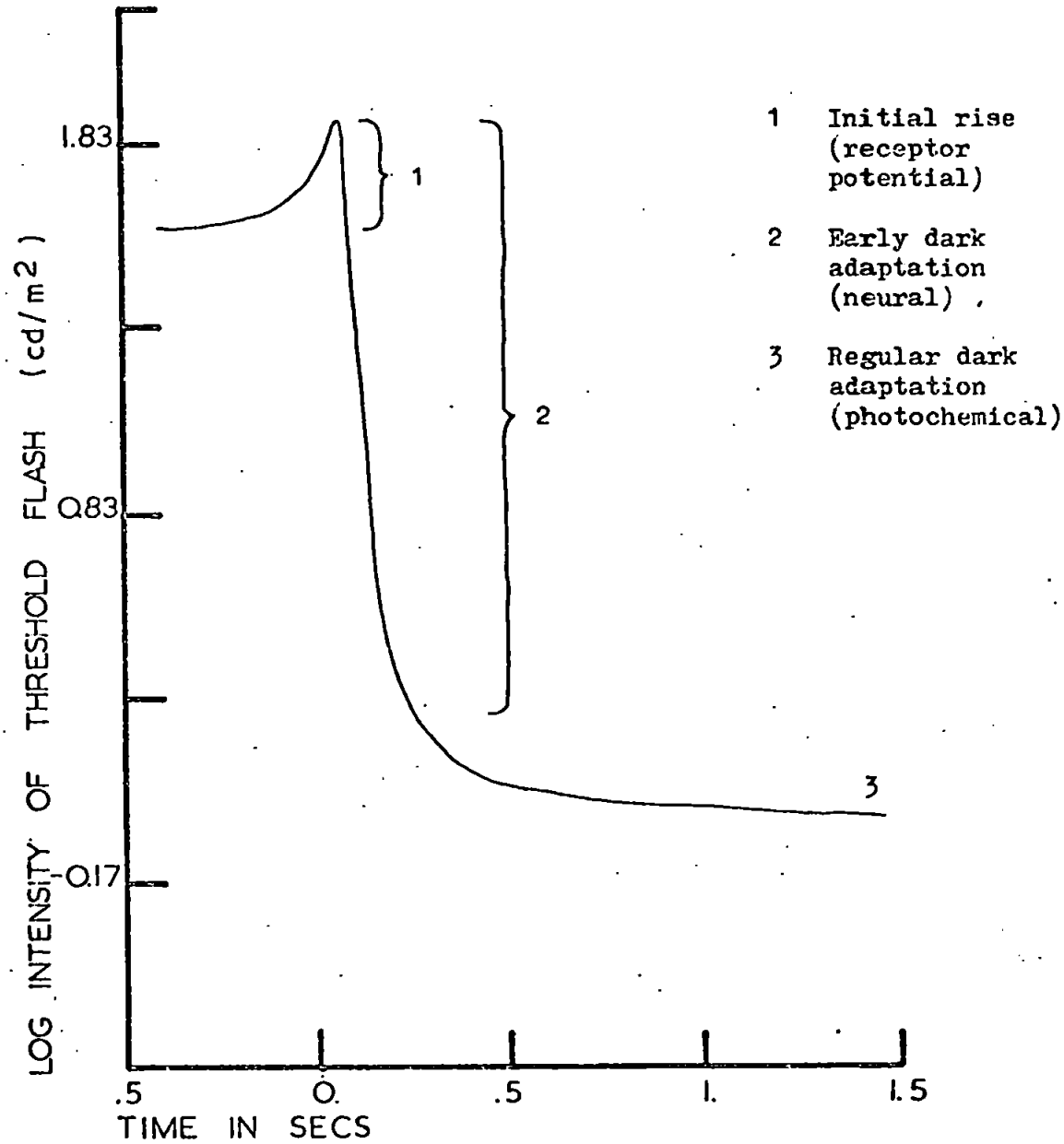

Figure 6.3.3 Summary of suggested early dark adaptation From ref. 13.

of both dark and light adaptation. Baker dismisses this as being 'essentially artificial', resulting from the conditions of measurement (ref. 13).

Crawford offers two explanations. Either the relatively strong conditioning stimulus overtakes the weaker test stimulus on its way from retina to brain and interferes with its transmission, or the process of perception of the test stimulus takes a time of the order of 0.1 seconds so that the impression of a second (large) stimulus within this time interferes with the perception of the first stimulus (ref. 5). Cornsweet states that there is ample physiological evidence that neural activity in the retina begins more slowly when the stimulus is less intense. Therefore, although the test flash may actually be delivered before the adapting light is extinguished, because it is considerably less intense than the adapting light, the neural change resulting from the test flash may occur after the neural effect of the extinction of the adapting light (ref. 14). This phenomenon has also been observed in the study of metacontrast (ref. 15).

The early fluctuations of the threshold level due to a sudden change of luminance have also been studied by Boynton (refs. 16, 17 and 18) who introduced the term 'masking' to describe the elevation of the test threshold due to the simultaneous presence of another stimulus, the effect, he believes, being non photochemical (ref. 7). Boynton defines visibility loss (ϕ) as:

$$= \frac{\text{(increment threshold 0.3 sec after change from B1 to B2)}}{\text{(final increment threshold after steady state adaptation to } B_2\text{)}}$$

B_1 = level to which eye is previously adapted

B_2 = level to which background luminance is changed

This means that visibility loss is defined in terms of what it would become after fully adapting to the new luminance, and for some cases where the change of luminance is upwards, a real increase of visibility may be a loss as defined by the index ϕ.

However, from his experiments Boynton concludes that, provided luminance levels of 1370 cd/m^2 are not exceeded, a value of ϕ depends most importantly on the ratio of change and not on the absolute levels of luminance. This rule breaks down seriously when the change of luminance is to or from a level above 13700 cd/m^2. Although Boynton is concerned with the transient effects of a sudden change or brief stimulus his work is more akin to that of steady state adaptation in that the time interval between change of luminance and test condition is held constant at 0.3 seconds. Therefore, the results cannot be assumed to apply to all time intervals after a change of luminance.

The above studies have been concerned with the investigation of the quantitative a spects of adaptation. Other

studies have been descriptive in nature. For example, in considering the visual experience of a brief stimulus to the visual system Jung puts forward the concept of reciprocal neural mechanisms signalling brightness and darkness (ref. 19). Although the eye has receptors for light only, it has two neuronal systems which signal light increment and light decrement (the B and D systems respectively). Each system receives stimulus not via a single receptor but via a field. A simplified description of the receptive field for each system is the pair of concentric circles shown in Figure 6.3.4.

The B system (on centre) signals light increment when stimulated in the centre of the field. Stimulus to the surround causes inhibition of the light signals from the centre.

The D system (off centre) signals light decrement when stimulated in the centre of the field. Stimulus to the surround inhibits this signal.

The two systems which carry information from the retina to the cortex have a reciprocal relationship. Their relationship to visual experience is shown in Figure 6.3.5.

Flicker studies have also produced modelling studies of visual dynamics. These derive primarily from De Lange who noted the similarity between plottings of his flicker data and the characteristics of a cascade-filter consisting of R-C integrator stages (ref. 20).

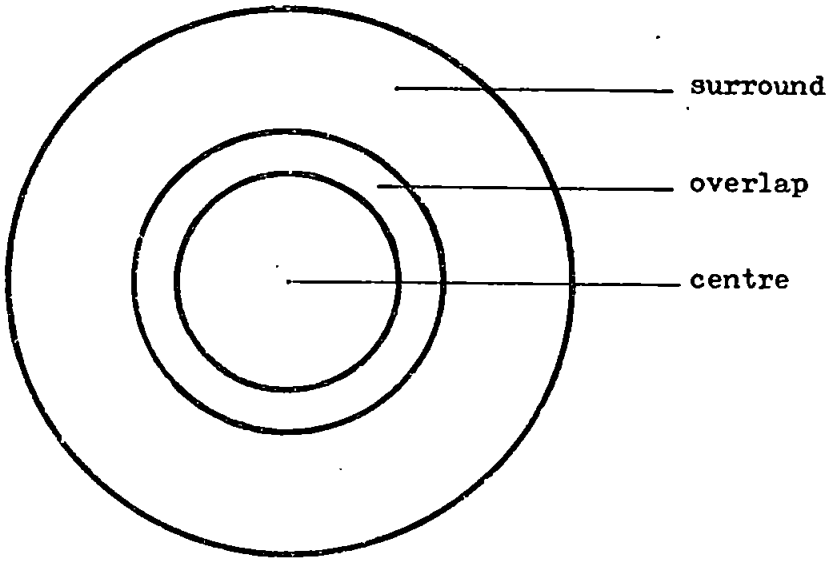

Figure6.3.4 The receptive field from ref. 21

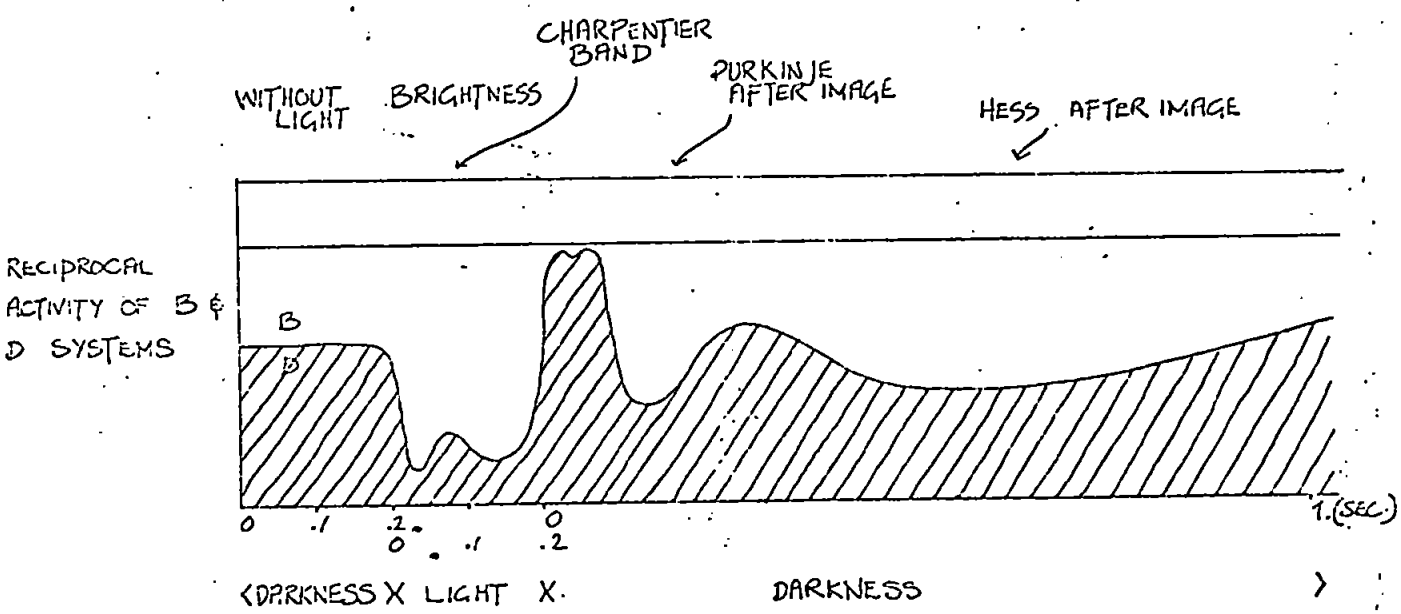

Figure 6.3.5 Relationship of reciprocal B and D systems to visual experience

6.4 Other Studies

Little work has been done in relating the previous temporal adaptation studies to the situation in buildings. Apparent brightness has been explained in terms of general luminance (ref. 22), 'adaptation level' (ref. 23) and spatial interactions (ref. 24). Hopkinson and Collins state that the 'adaptation of the scene' can be measured, taken as the luminance expressed in Foot-Lamberts (the numerical equivalent of illumination) expressed in Lm/ft^2 at the observer's eye (ref. 25). Alternatively, several readings of luminance can be taken with a restricted-angle luminance meter and the adaptation level taken as the average of the values so obtained. It is therefore assumed that the observer is fully adapted to the particular lighting level of the scene. These studies are therefore concerned with steady state adaptation.

Road lighting studies are worth mentioning at this point because it might be assumed that the dynamic situation that exists when, for example, a driver meets oncoming headlights or enters and leaves a tunnel may have stimulated study of temporal adaptation.

Hills (ref. 26) has studied the problem of visibility under night driving conditions and has shown that, using object detection as the criterion for visibility, the visibility of discs can be related to their visual radius by the following equation:

$$\Delta L \sim \{1 + (r_m / r)\}^2$$

where ΔL = the increment of disc luminance above the luminance of its background (cd/m^2)
r_m = a constant for constant background luminance and retinal eccentricity
r = retinal radius of disc (min)

The increment of disc luminance above background luminance for the condition of just visible is therefore given as a function of the area of the object and its distance from the driver (retinal radius) and a constant taking account of the change in summation across the retina with position of the image on the retina.

The model was validated experimentally under two conditions: at night with road lights on (mesopic vision) and at night with road lights off (scotopic vision). Subjects were therefore adapted fully to the test conditions.

The state of adaptation of the driver has been equated with road luminance in the study of discomfort glare (ref. 27).

For tunnel lighting, the CIE recommendations make the following assumptions:

1. At the initial stage of approach, the driver's eyes adapt to the 'outdoor luminance'. This is estimated as a weighted average of luminances of part of the field of view within a solid angle of 2 x 10° in the direction of travel, and at distances of 250m, 150m and 50m from the tunnel entrance for mountainous regions and built-up areas.
2. The initial state of adaptation of the driver's eyes remains constant until he reaches the adaptation point.

3. The distance between the adaptation point and the tunnel entrance, i.e. the 'adaptation distance', is about 25m for tunnel mouths of normal height (ref. 28).

These assumptions are made in determining a value for L_1 (the level of luminance which would give an equivalent state of adaptation to the visual system of the driver). Although the changing state of adaptation is taken into account by considering the state of adaptation at various distances on the approach, the recommendations are not easily applied to the situation of a person walking through a building. Furthermore, not all the problems are solved:

> ".... research is needed into the averaging mechanisms so that they can be taken into account properly, both spatially and temporally, for the determination of L_1 in practice." (ref. 29)

6.5 Methods of Assessment

The curve illustrated in Figure 6.2.1 is plotted through values of the difference between the luminance of a test object and the luminance of the background, for a test object just visible with both eyes. Where the background luminance is zero, this difference is known as the absolute threshold.

For values of luminance of the test greater than threshold this technique cannot be used because the light source of the test affects the adaptation of the eyes. However, the almost complete independence of adaptation of the two eyes makes it possible to use one eye, kept in a state of constant adaptation, as a standard with which to compare variations in adaptation of the other eye. This is the technique of binocular photometry.

In the study of the initial stages of adaptation, Crawford (ref. 5) used lantern slides of various scenes and the time measured between switching off a conditioning light and the observer being able to see a chosen object was taken as an indication of adaptation.

The method of searching for one object (a square), positioned randomly among different objects (circles) was used by Boynton (ref. 30). This method involves the observer in using peripheral vision as well as foveal vision. Boynton (ref. 17) has also used the discrimination of test letters. In both experiments, the time taken to correctly identify the test is taken as a measure of sensitivity of the visual system.

These methods, mentioned above, are typical methods used in laboratory studies and have been useful in attempts to understand the mechanisms of adaptation. Other techniques have been developed in the assessment of the lighting of building interiors.

A similar technique of discrimination to that used by Boynton was used in the study of hospital lighting (ref. 31). Here, observers spent some time adapting to the illumination in an artificially lit room, then walked across a corridor into a daylit ward and viewed either a Landholt ring chart or a Snellen chart (as a measure of acuity). The time taken to perform the task correctly was recorded as a measure of adaptation.

In this study, observers also adapted to a daylit ward, then walked across a corridor into an artificially lit room and adjusted the lighting level until they found it "just

too low", then "preferred" and finally "just too high".

It is worth noting that as observers took time in setting the lighting level of this internal room, they were undoubtedly becoming adapted to the lighting level of this room and not the daylit room. Any errors caused by this problem could have been reduced by the observers setting "just too high" first and "just too low" last. The daylit room was of higher luminance than the internal room and the rate of adaptation to the darker room would be slowed down by encountering the higher luminance values in the second room earlier. Errors could also be reduced by running separate tests for each rating category.

Observers may also assess the level of lighting by judgements of the magnitude of their sensations. One such method is 'direct numeration' in which an observer assigns a number to a sensation, a low number to a feeble sensation and a high number to a strong sensation (ref. 32). The numbers may be freely chosen by the observer.

Lighting levels can also be noted as part of an overall assessment of the lighting of interiors by the method of 'rating scales'. Typically, observers may be given a questionnaire concerning many aspects of the situation to be assessed, of which one is the lighting level. The observer's impression of the lighting may be given using a scale from 1 to 7, where 1 is "too little" and 7 is "too much" (ref. 33). Intermediate numbers may not be assigned verbal categories.

Hopkinson has stated that rating scales are particularly useful in experiments where alterations cannot be made easily to the situation to be judged (ref. 34). Rating scales

relating to warmth and thermal comfort have been discussed in section 2.4 and their use in the present study illustrated in section 5.3.

A simple scale may be one using the phrases given above, just too low/preferred/just too high. To assess the lighting level along a route through a building observers may be given these categories on a slip of paper or they may learn them and, proceeding to walk through the building, they could rate the lighting level at specified intervals according to one of these categories. The use of this scale would however beg the question "just too low for what?".

A study of the use of words for lighting appraisals (ref. 35) compared 14 categories and suggested the following two groups of words: very good/good/favourable/fair/poor/bad, and very good/good/favourable/acceptable/tolerable/poor/bad/very bad. However these scales may only be indirectly linked to the magnitude of lighting level.

The following rating scale is suggested for its simplicity in recording the observer's impressions of the lighting level, independent of a task: very bright/bright/light/satisfactory/dim/dark/very dark.

6.6 Concluding Remarks

Changes in sensitivity of the visual system during adaptation have been studied by recording changes in the threshold. The initial stages of threshold fluctuations, due mainly to neural mechanisms, are confined to a time period of about 1 second after a change of lighting level

(see Figs. 6.3.1, 6.3.2 and 6.3.5). Later changes of threshold are due mainly to photochemical activity in the retina. Figures 6.6.1 and 6.6.2 illustrate recordings of pigment regeneration in the cones and rods respectively where the experimental situation is similar to that producing the curves in Figures 6.2.1 and 6.2.3.

Models based on field studies in both buildings and on roads are of little use for our purpose as in these studies observers are always (presumed) adapted to the experimental conditions.

A model based on the photochemistry of the retina is therefore appropriate. Furthermore, in most cases photopic conditions will prevail (the eye will be light adapted rather than dark adapted) and the photochemistry may be confined to a description of cone pigments.

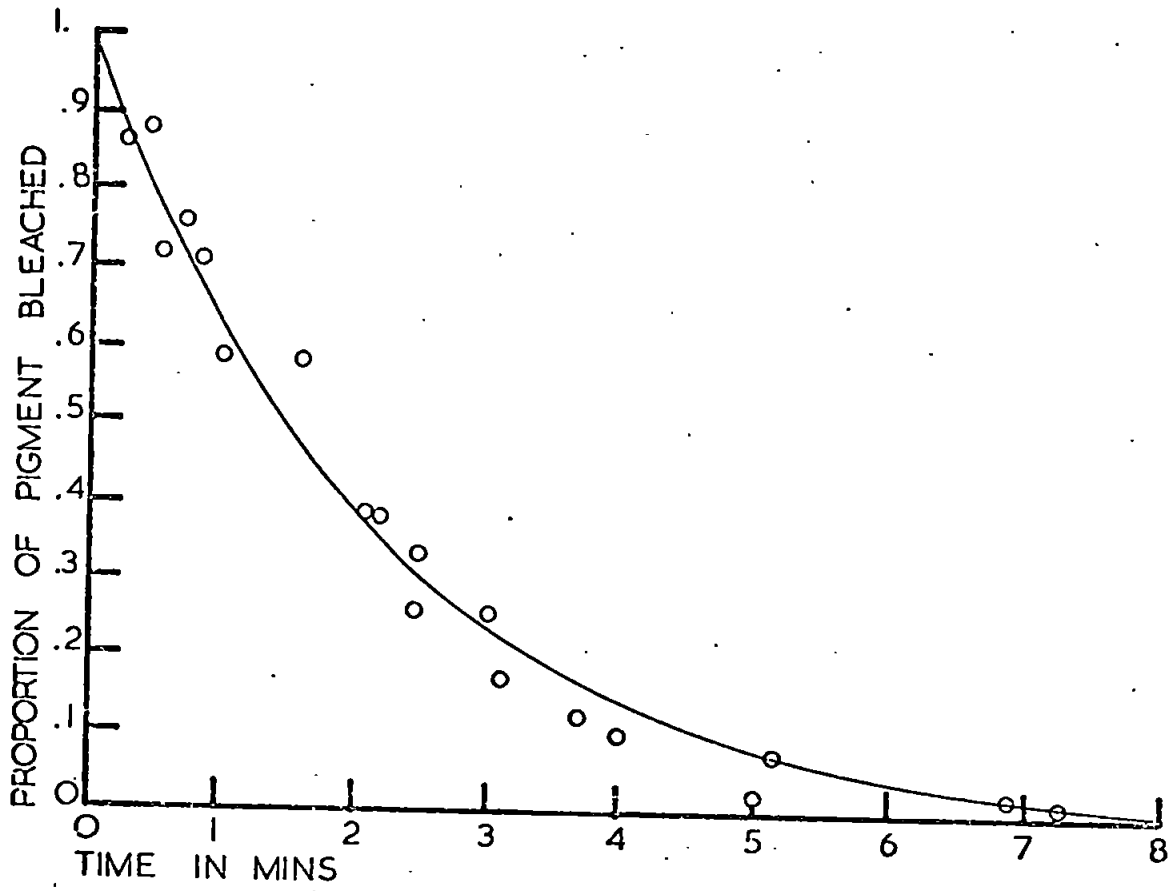

Figure 6.6.1 Regeneration of a cone pigment during dark adaptation (ref. 37)

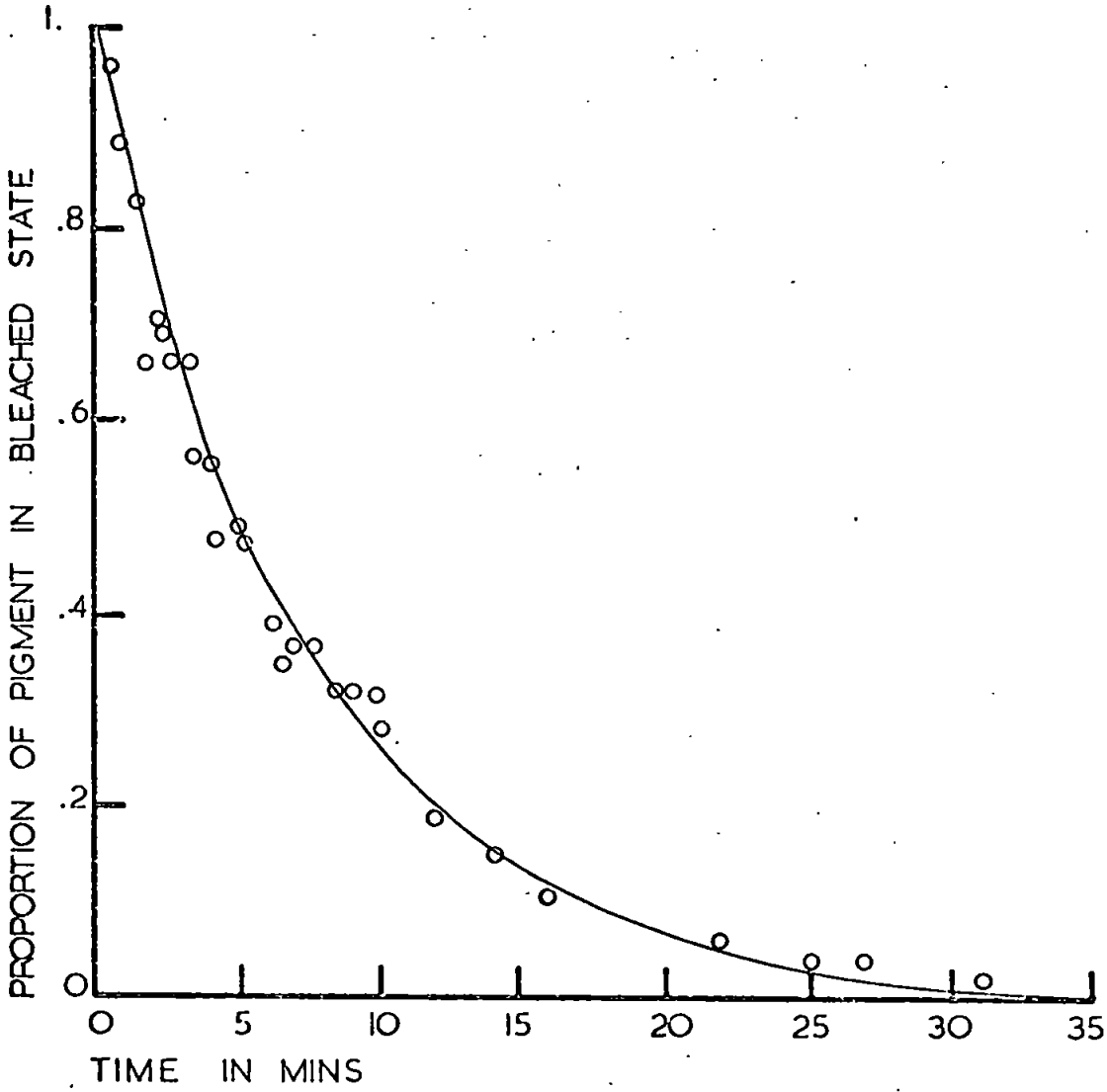

Figure 6.6.2 Regeneration of rhodopsin during dark adaptation (ref 38)

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Section Seven. A Model Based on the Photochemistry of the Cones

7.1 The Model

Figure 7.1.1a illustrates a step-change in luminance as experienced when walking from a dark room into a light room and back into a dark room.

Figure 7.1.1b shows what is assumed to happen to the concentration of pigment in the cones as this step-change occurs. Where the change of luminance is from low to high, bleaching of the pigment takes place. Where the change is from high to low, pigment regenerates due to chemical processes.

Figure 7.1.1c illustrates the change in apparent brightness that may result from the change in luminance shown in 7.1.1a. Where the change of luminance is from low to high, the initial appearance of the room of high luminance is brighter than it will eventually become. Where the change of luminance is from high to low, the room of low luminance will appear darker than it will eventually become.

Comparing Figures b and c, we can see that as pigment bleaches rapidly, apparent brightness decreases rapidly and as pigment regenerates slowly, brightness increases slowly. Also, comparing Figures c and a, we can see that an increase of brightness corresponds to an increase of luminance and a decrease of brightness to a decrease of luminance. Pigment concentration is not independent of luminance but it is a convenient expression of luminance history.

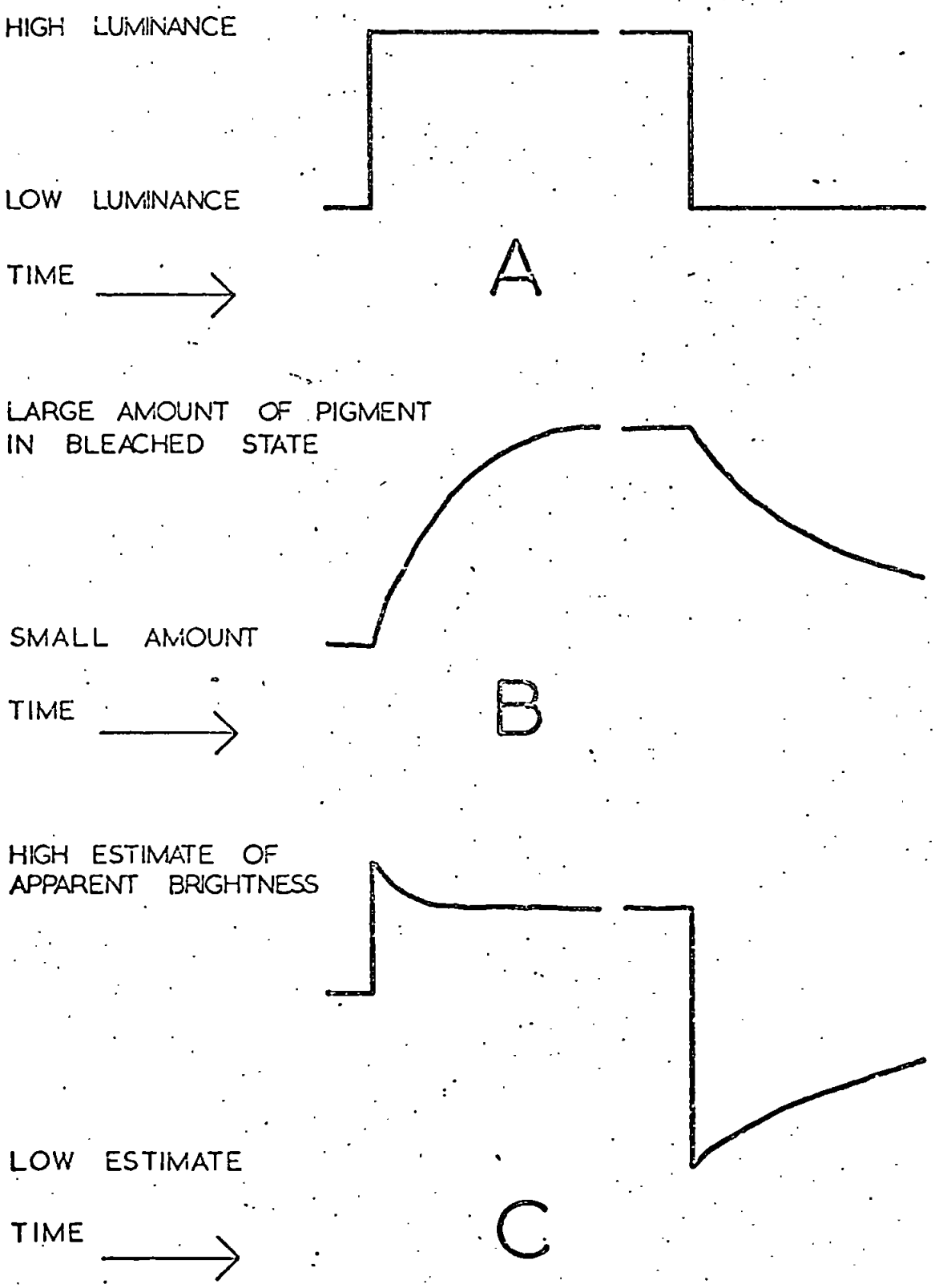

Figure 7.1.1

Step change in luminance with corresponding changes in pigment concentration and apparent brightness.

Therefore, it is proposed that apparent brightness, illustrated by the curves in Figure 7.1.1c, is a function of luminance and the rate of change in pigment concentration as illustrated in Figures 7.1.1a and b respectively.

Cone pigments act under two main influences, bleaching due to light and regeneration due to chemical processes. Rushton proposes that:

1. Pigment is bleached at a rate proportional to quantum catch;
2. Regeneration proceeds at a rate proportional to the fraction of the pigment in the bleached state;
3. Processes 1 and 2 are independent and therefore additive (ref. 1).

From Rushton's theory, Cornsweet derives the following equation:

$$\frac{dX}{dt} = K(1 - X) - AQX \qquad 7.1.1$$

where X = proportion of regenerated pigment in a receptor,
K = probability that an unregenerated molecule will be regenerated in time dt,
A = probability that a quantum incident on a region containing a regenerated molecule will bleach that molecule,
and Q = number of quanta incident during time dt (ref. 2).

Equation 7.1.2 is Cornsweet's solution to Equation 7.1.1.

$$X = \frac{K}{K + AQ} + \frac{AQ}{K + AQ} \cdot e^{-t(K+AQ)} \qquad 7.1.2$$

Cornsweet gives:

$$A = 64 \times 10^{-8}$$

$$K = 0.0077$$

and redefines Q = adapting intensity in trolands.

This solution is valid if $X = 1$ when $t = 0$. In other words, the model is always adapting from the completely dark adapted state to a state Q.

Figure 7.1.2 shows predictions of bleaching action using Equation 7.1.2 for three values of the stimulus Q.

For the case where the model is adapting from any initial value Q_1 to any other value Q_2, the following solution to equation 7.1.1 (see Appendix B) is valid:

$$X = \frac{K}{K + AQ_2} - \frac{KA(Q_1 - Q_2)}{(K+AQ_1)(K+AQ_2)} \cdot e^{-(K+AQ_2)t} \qquad 7.1.3$$

If we let P equal the amount of pigment bleached, then:

$$P = 1 - X$$

and from equation 7.1.3 we can derive the following expression (see Appendix B) for the rate of pigment bleaching with respect to time:

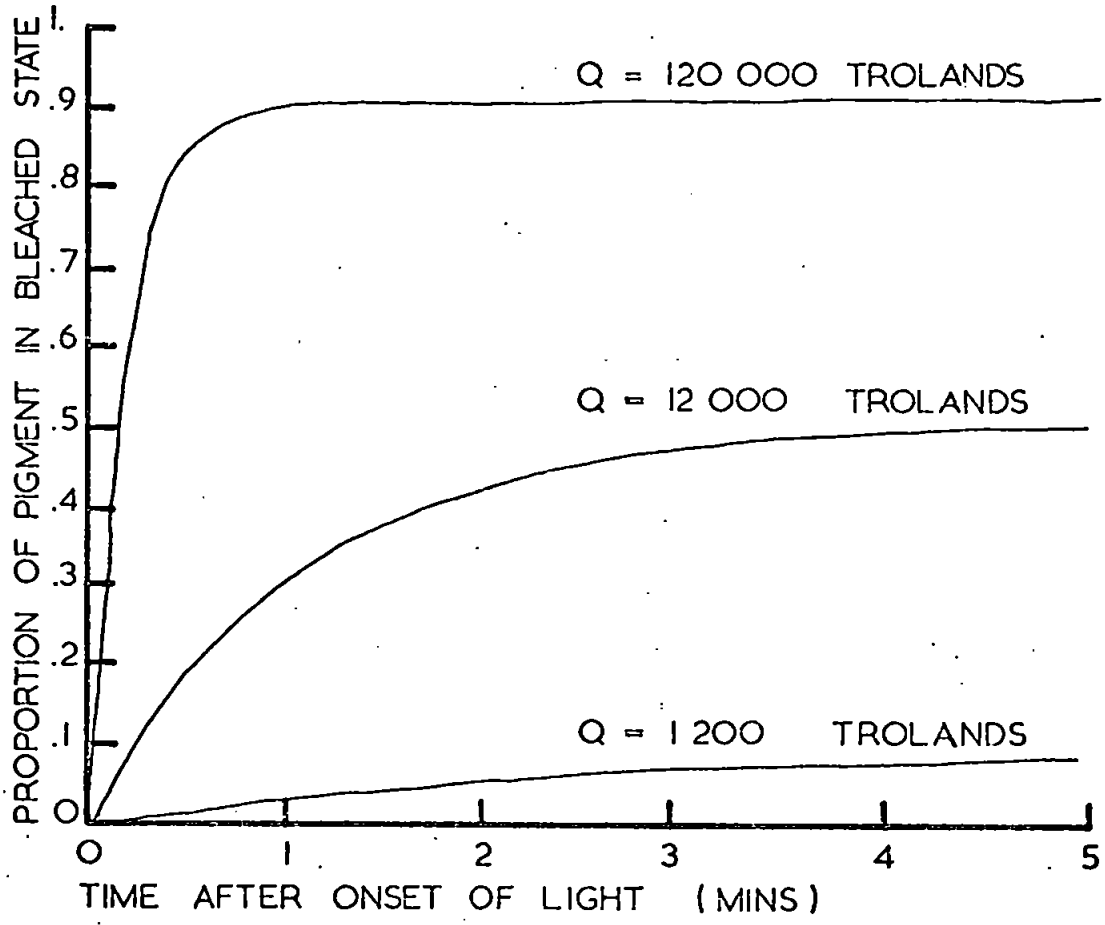

Figure 7.1.2 Predictions of bleaching action of cone pigments using equation 7.1.2 .

$$\frac{dP}{dt} = \frac{-KA(Q_1 - Q_2)}{(K + AQ_1)} \cdot e^{-(K+AQ_2)t} \qquad 7.1.4$$

Where a step-change of stimulus occurs at some value of t, Q_2 takes the value of the new stimulus (this is the prevailing stimulus to which the system will adapt). Q_1, however, must be at some value between the original Q_1 and Q_2 values (unless $t = o$ or t approaches ∞).

Figure 7.1.3 illustrates this, where in 7.1.3a a light stimulus occurs (change from Q_1 to Q_2) and pigment bleaches as in Figure 7.1.3b. When the stimulus changes again (change from Q_2 to Q_3) pigment already bleached is at a level P_1. It can be seen that this value can be less than the final steady state level of bleaching, P_2.

Many values of the prevailing stimulus will cause bleaching or regeneration of pigment to the level P_1. However for each one there is a unique value of t. For example a strong stimulus may bleach to level P_1 in a short time whilst a weaker stimulus will take longer. In Equation 7.1.3 when $t = o$ the model is at an equilibrium determined by Q_1. Therefore when a step-change of stimulus occurs ($t = o$) the new value of Q_1 is defined as the stimulus value which would bleach (or regenerate) to the steady state value P_1. This can be derived from Equation 7.1.3 (see Appendix B) and is as follows:

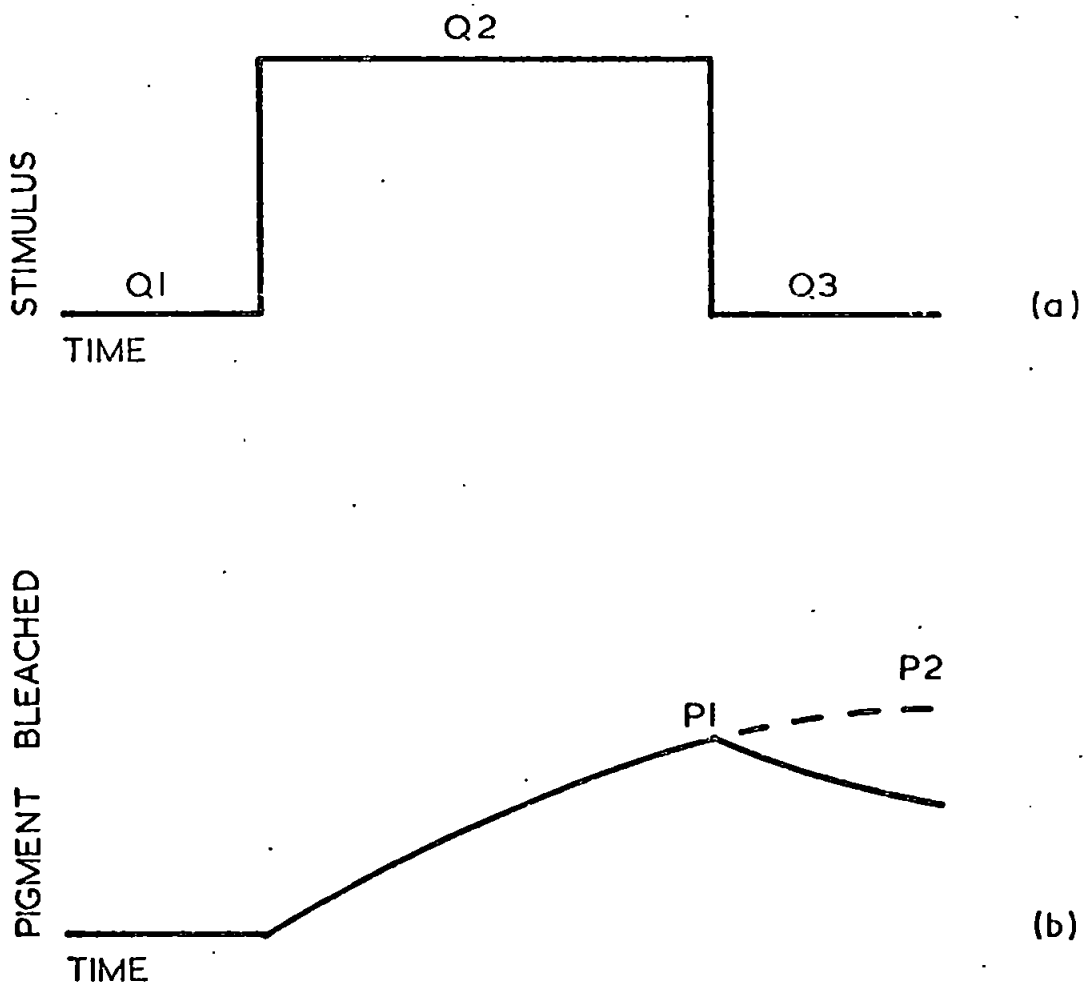

Figure 7.1.3 Bleaching action of cone pigment due to a step change of stimulus.

$$Q_i = \frac{K(1-x)}{XA} \qquad 7.1.5$$

The stimulus Q (and therefore Q_1 and Q_2) is defined by Cornsweet as retinal illuminance (trolands). For our purpose this may be more usefully stated in units of luminance (cd/m^2). Le Grand provides the following equations for the conversion of luminance to retinal illuminance (ref. 3):

Retinal illuminance = $L \times S_e$ (effective trolands)

and

$$S_e = \frac{1}{4} d^2 \left(1 - 0.085 \left(\frac{d^2}{8}\right) + 0.002 \left(\frac{d^4}{48}\right)\right) \qquad 7.1.6$$

where S_e = effective pupil area,
d = pupil diameter (mm),
and L = luminance (cd/m^2).

The diameter of the pupil changes with a change of luminance and the following equation gives approximate values for pupil diameter, as a function of luminance, based on a hyperbolic tangent law suggested by Crawford:

$$d = 5 - 3 \tanh (0.4 \log L) \qquad 7.1.7$$

Undoubtedly, as one walks about a building, one's field of view changes. Often, the walls will form a major element in the field while at other times we may look at the floor, ceiling or a particular feature such as a door, or one may move one's view about the whole room. Even when the direction of one's view is kept parallel to the direction of movement, the field will change.

Therefore, no attempt at restricting the model to viewing only a part of a room has been made. Instead, the average luminance of the room is proposed as the luminance of the field.

Where the surfaces of a room are assumed to be matt, the luminance averaged over all surfaces, in cd/m^2, is given by the following expression:

$$L = \frac{E\rho}{\pi} \qquad 7.1.8$$

where L = the average luminance of all surfaces (cd/m)
E = the average illuminance on all surfaces (lux)
and ρ = the area-weighted average reflectance

The average luminance of a room or part room is proposed as the stimulus. Therefore, Q_2 takes the value of the average luminance of the room or part room, in which the model is situated. Q_1 initially takes the value of the average luminance of the room or part room in which the model was previously situated.

References, Section Seven

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Section Eight. Validation Study

8.1 Field Survey

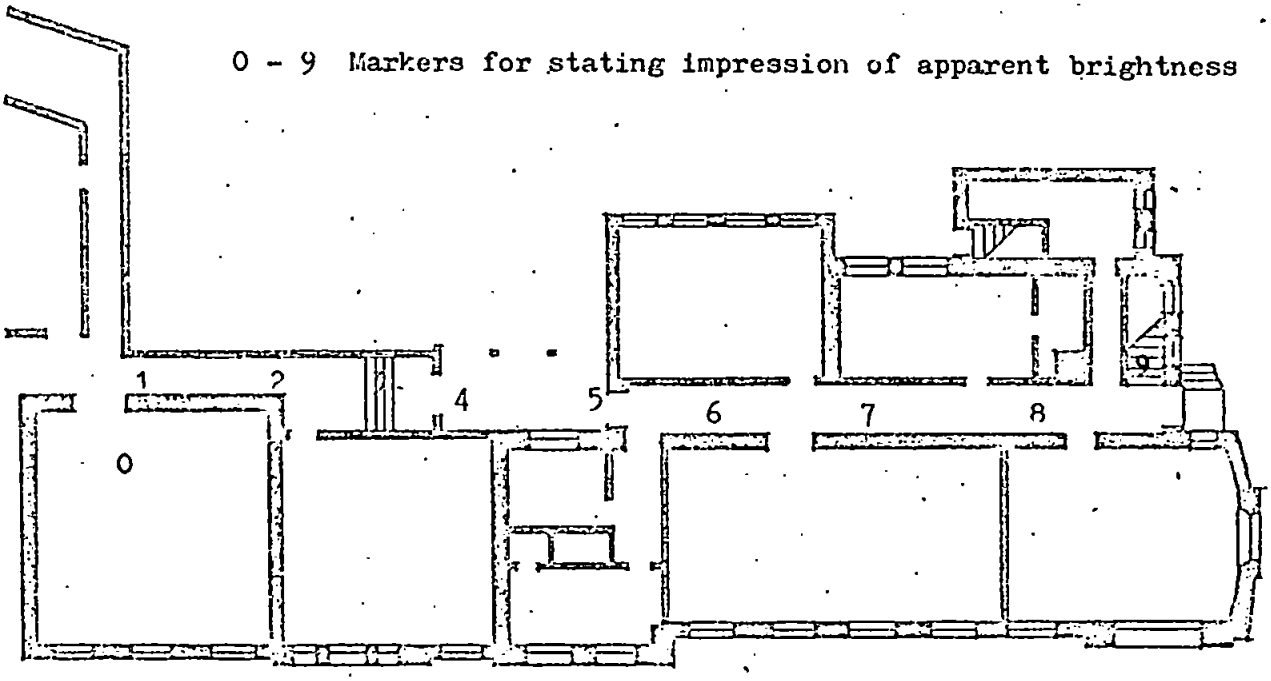
A field survey was conducted, for comparison with predictions by the model, in which ten people participated. The aim of the survey was to elicit their verbal responses to the level of lighting at set points at approximately 5-second intervals along a prescribed route within a building.

The building and route chosen were the same as described in Section 5, except that Point 0 was changed (by the time the survey was conducted, the room containing Point 0 had been altered from its condition in the thermal study). The procedure of the survey was similar to that described in Section 5.

Figure 8.1.1 shows the building in which the survey took place and the points along the route at which a statement of the brightness of the room was made. Subjects were asked to rate the brightness of each room according to the seven point scale shown in Figure 8.1.2, which they carried with them along the route. The subjects started at Point 0 and walked along the route indicated by the numbers 0, 1, 2, 3 etc. to Point 16, then, turning around, retraced the route back to Point 0.

The survey was conducted on two separate days at approximately 22.00 hrs. and lighting was due to artificial light only. The subjects spent some time in the building

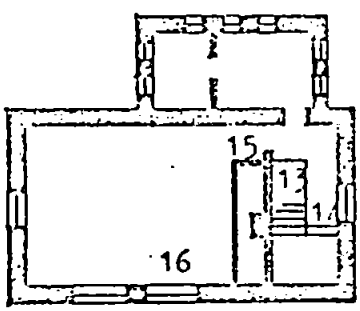
0 - 9 Markers for stating impression of apparent brightness



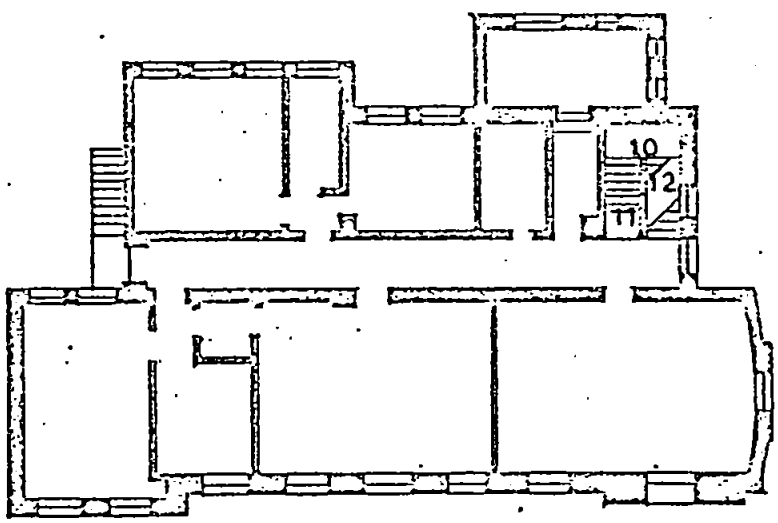
APPROX SCALE 0 2 4 6 8 10 METRES

GROUND FLOOR

10 - 16 Markers for stating impression of apparent brightness



SECOND FLOOR



FIRST FLOOR

Figure 8.1.1 Plans of building used in lighting study

VERY DARK	DARK	DIM	SATISFACTORY	LIGHT	BRIGHT	VERY BRIGHT
1	2	3	4	5	6	7

Figure 8.1.2 Seven-point scale of apparent brightness

before the start of the survey and about 5 minutes in Room 1, the starting point. It was therefore assumed that subjects were light adapted; furthermore, that they were adapted to the luminance of Room 1.

Before walking along the route, each person was asked to rate Room 1. At points along the route, indicated by the numbers (see Figure 8.1.1), a marker was placed and it was at each of these markers that the subject, without stopping, made a verbal statement of his impression of the lighting level. The markers were spaced at approximately 5-second intervals along the route.

Each verbal statement was recorded on a standard form (Figure 8.1.4) by an observer who walked along the route just behind each subject. The numerical values associated with each verbal category, in Figure 8.1.2, formed the basis of a simple statistical analysis. The median was chosen to represent the average of the group with values that are in most cases integer points on the scale. Figure 8.1.5 shows the median response for the group at each point along the route.

8.2 Predictions by the Model

The average luminance of each space along the route was estimated (see Section 9) and together with a description of the route (the geometry of the route is shown in Figure 8.2.1) formed the input to the computer program.

Figure 8.2.1 is an example of the graphical output, from the computer program, of the building and route

You are asked to walk along a prescribed route through the building at a constant speed and to state your impressions of brightness, using a prescribed scale, at five second intervals.

You will be shown the route, and the speed at which to walk will be indicated. The intervals along the route at which you are to state your impressions are marked on the floor. You are not to stop at any of these points but proceed along the whole length of the route without stopping.

The scale by which you will state your impressions is given below. You will also be given a copy to carry with you, but it will help if you memorise the scale before walking through the buildings.

VERY DARK	DARK	DIM	SATISFACTORY	LIGHT	BRIGHT	VERY BRIGHT

Figure 8.1.3 Introduction to survey handed to each subject

DATE _____ NAME _____

VERY BRIGHT	
BRIGHT	
LIGHT	
SATISFACTORY	
DIM	
DARK	
VERY DARK	

TIME TAKEN_____

Figure 8.1.4 Standard form for recording verbal responses to changes in lighting level.

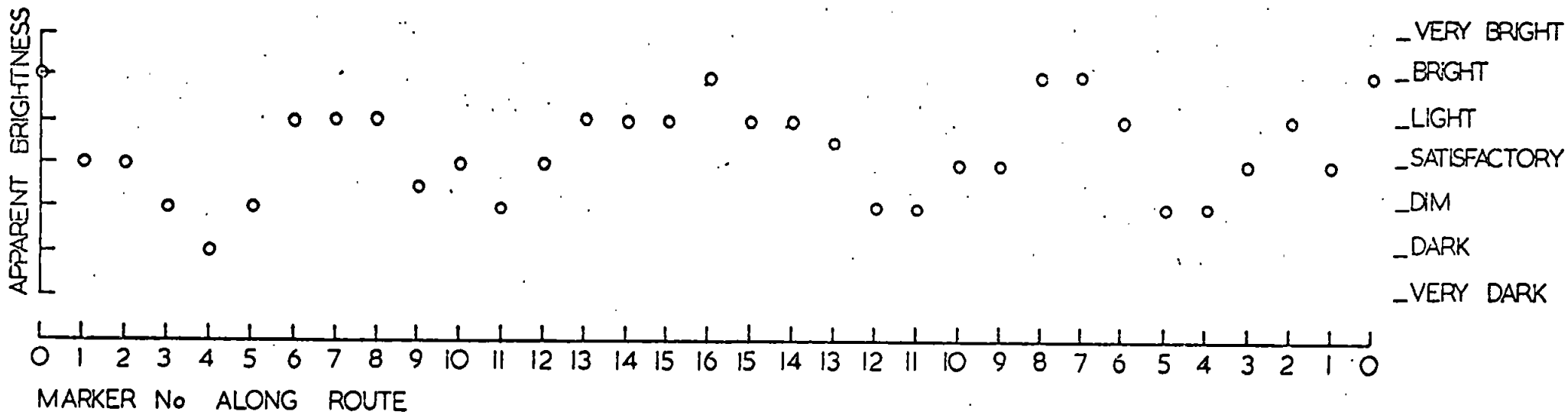


Figure 8.1.5 Median responses given at each point.

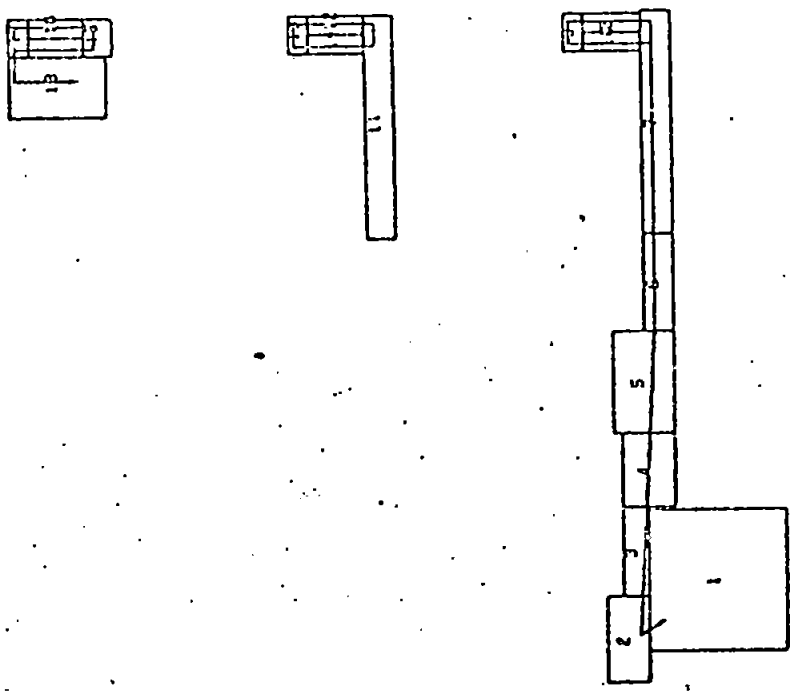


Figure 8.2.1

Description of building and route geometry used in predictions.

geometry. Each rectangle represents a room. The average luminance of each room can be calculated by the program or given as input to the program. Only those rooms through which the route passed are necessarily included in Figure 8.1.1. The three floor levels are plotted separately and the output is originally at 1:500 scale. The single continuous line indicates the route. The program determines in which room the model is at the requested time intervals and selects the luminance of that room as data at that moment.

Table 8.2.1 shows the estimated values of average luminance in each space along the route together with the marker number in that space. We can see that Room 0 has the highest value and, as subjects spent about 5oto 10 minutes in this room before commencing the walk, it is assumed that pigment in the cones is bleached to a level determined by this value of luminance. Therefore, we would expect that on moving to other rooms, with a lower luminance, regeneration of pigment will occur and as a consequence sensitivity of the visual system will increase.

Predictions by the model of pigment concentration at points along the route are illustrated in Figure 8.2.2, showing the gradual regeneration which takes place along the whole length of the route, only interrupted temporarily at points of relatively high luminance.

If pigment regeneration increases the sensitivity of the visual system, we should expect a gradual increase in values of apparent brightness vote along the length of the route,

MARKER NUMBER	LUMINANCE (cd/m^2)
0	90
1	41
2	41
3	15
4	6
5	6
6	72
7	72
8	72
9	17
10	16
11	5
12	3
13	40
14	40
15	58
16	58

Table 8.2.1 Average luminance of each space and marker number.

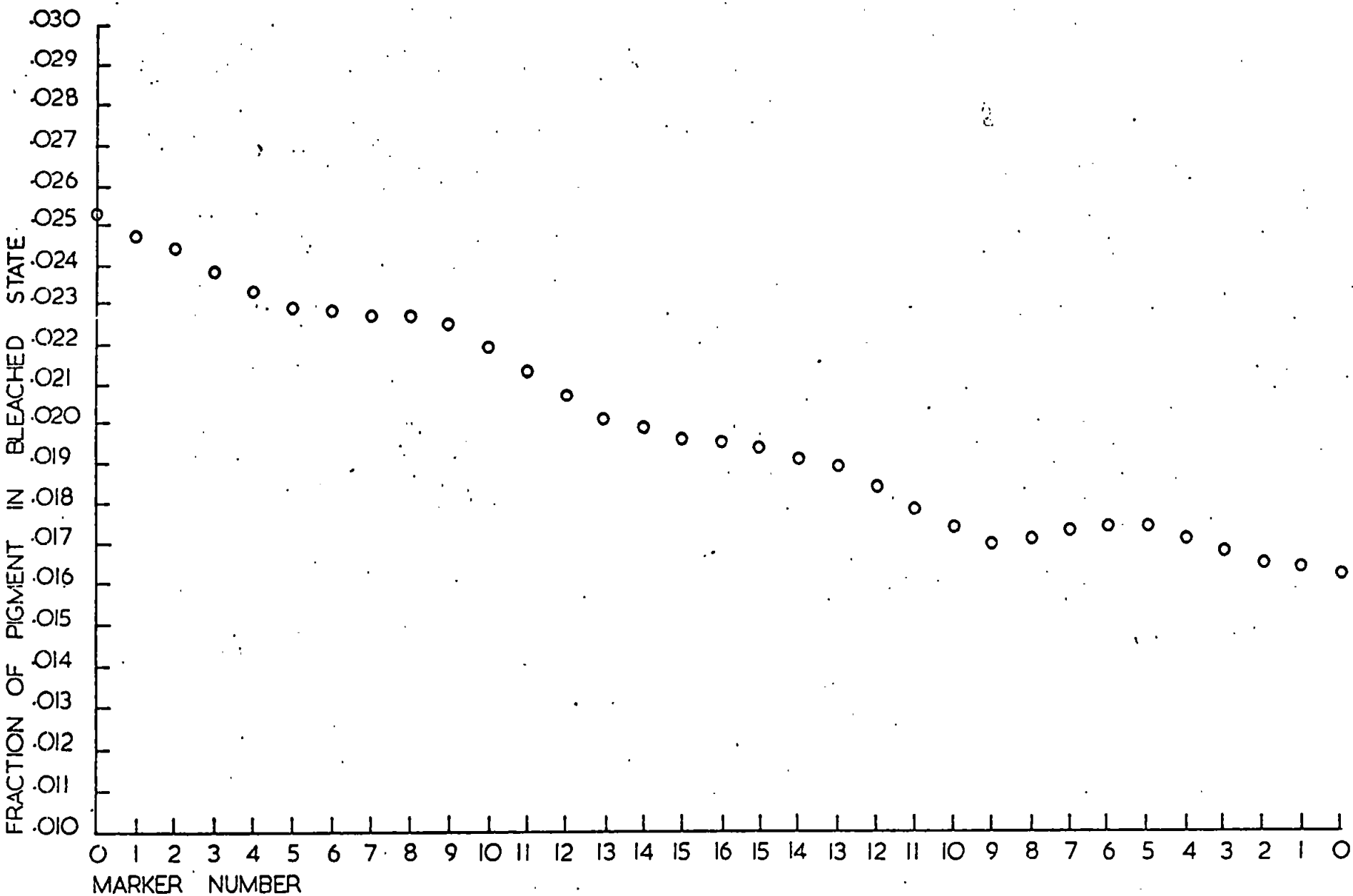


Figure 8.2.2. Predicted regeneration of pigment along the route.

corresponding to the regeneration of pigment. This can be seen in Figure 8.1.4 but is more clear if we join values on this graph corresponding to the same points along the route (remembering that points along the route are symmetrical about Point 16). Figure 8.2.3 illustrates this, where points whose values differ on the outward walk from the return walk are connected and it is clear from this figure that there is an upward trend in subjective estimates.

However, the points at which there is no change of estimate are also representative of people's impressions and when these points are included a simple non-parametric sign test shows this trend to be not significant.

The total number of points (pairs of estimates) considered is 16. If we assume that there is equal likelihood of votes on the return journey being higher than or lower than votes on the outward journey and we assign a plus sign when an estimate is higher and a minus sign when a vote is lower, then the number of plus signs will be 8. The standard error about this value is given by $\sqrt{n \times \frac{1}{2} \times \frac{1}{2}}$ where n = number of pairs of estimates. Therefore, the standard error is 2. At the 5% confidence level, we are concerned with deviations of more than about twice this value. We should expect 95% of samples to be within the range 8 - 4 to 8 + 4. Comparison of all corresponding points along the route shows that on the return journey higher subjective estimates are given at 6 points. This is within the expected range and is therefore not significant.

This suggests that for the conditions experienced in

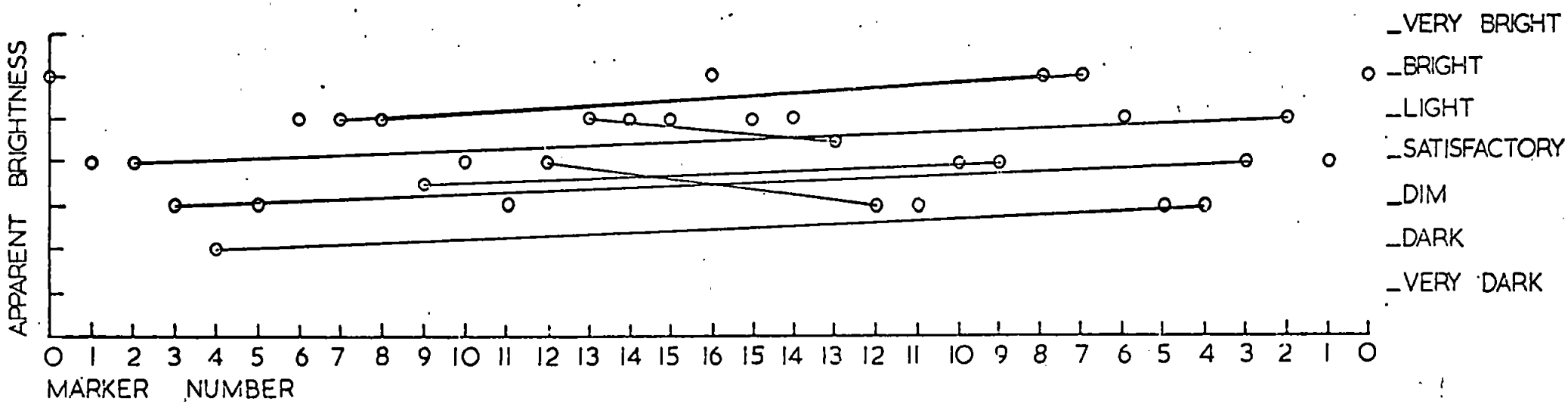


Figure 8.2.3 Upward trend of apparent brightness vote.

the survey, the gradual regeneration of pigment may be ignored and predictions of the subjective estimates may be made based on luminance.

Using Equation 7.1.4 we can compute values for the rate of pigment bleaching at each point along the route. These values are shown plotted in Figure 8.2.4 where the abscissa is log luminance and the ordinate the rate of bleaching (where values are negative this is the rate of regeneration).

Experience tells us that as we move from the bottom left of the figure to the top right the values of the subjective estimates should increase. This is because to the left of the figure are values of low luminance and to the right are values of high luminance. Therefore, we should expect an increase in the value of estimates from left to right. Also, the bottom of the figure corresponds to values of rapid pigment regeneration, associated with a relatively large drop in luminance level. The top of the figure corresponds to values of rapid pigment bleaching associated with a relatively large increase in luminance level. We should therefore expect an increase in the value of votes from the bottom to the top of the figure. This general trend can be seen in the figure.

By definition, loci of equal apparent brightness should run across this general trend. This is seen to be so from Figure 8.2.4, where regression lines have been drawn by eye for each group of estimates. Two points (Numbers 1 and 12) at which 'satisfactory' votes (value 4) were given cause the regression line for this group to be inconsistent if

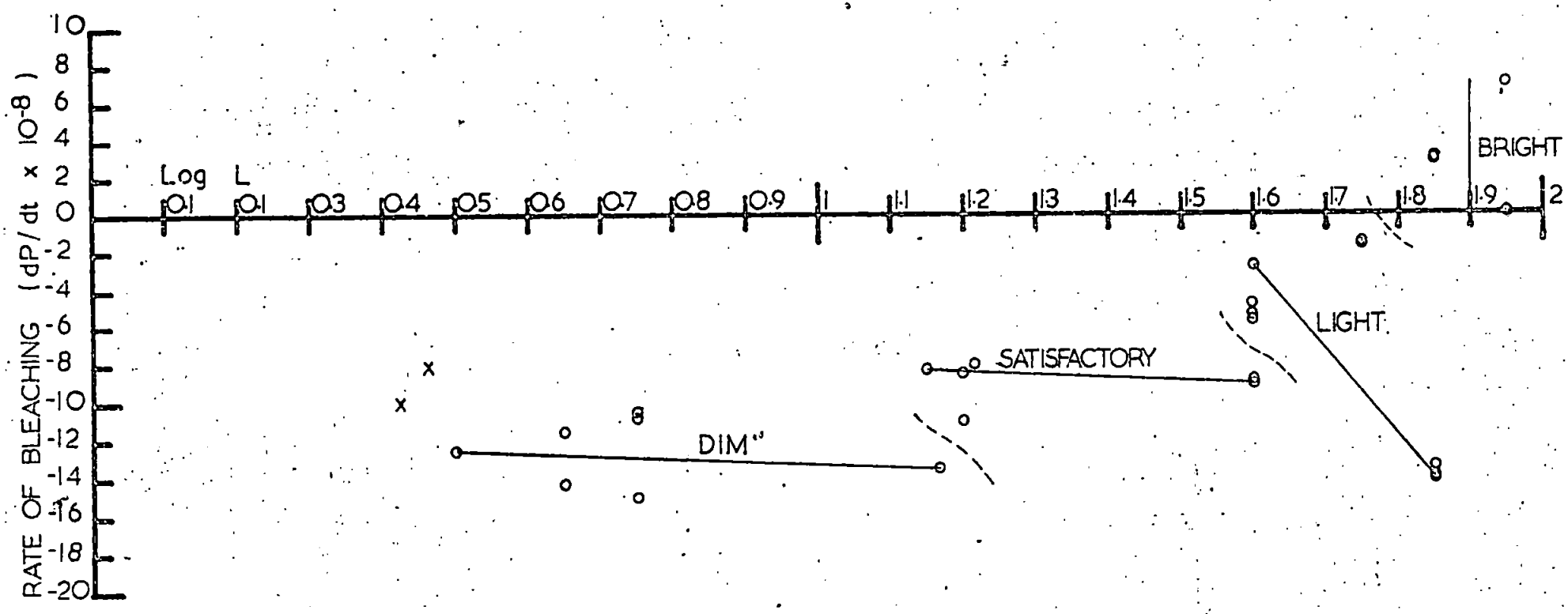


Figure 8.2.4 Plot of log luminance against the rate of bleaching for the votes cast along the route. The dashed lines separate groups of equal apparent brightness votes. The regression lines have been fitted by eye.

included. Examination of these two points shows them to be on the threshold of spaces with a large difference in luminance. It is possible that while the luminance of one space may be relevant on the outward journey, the luminance of the adjacent space is relevant on the return journey. If we plot these two points with the luminance of the adjacent space and the computed rates of bleaching, the two plotted points fall more consistent with the regression line fitted to the 'satisfactory' estimates. The points are shown marked X in Figure 8.2.4.

The disposition of the regression lines accords with our experience. A line approaching the horizontal at values of low luminance and rapid pigment regeneration, that is, a situation where one is plunged into darkness, suggests that differences in luminance are relatively unimportant in the estimate of apparent brightness. When plunged into a dark room, details are indistinguishable. It is only later, as the room appears lighter, that differences may be noticed.

To establish a relationship between the values of luminance and the values of subjective estimate, the mean value of log luminance was established for each group of subjective estimates (Column 1, Table 8.2.2). These means were then expressed as ratios between means of contiguous pairs of estimates. These are shown in Column 2, Table 8.2.2. The mean of these ratios is 1.4. An increment of one vote on the verbal scale therefore corresponds to a mean ratio of 1.4 between two values of log luminance. This is

LOG L (Unsteady state)	RATIOS	LOG L (Steady state)	RATIOS	SUBJECTIVE ESTIMATES
0·77		0·96		3
	1·74		1·95	
1·34		1·88		4
	1·30		1·15	
1·74		2·16		5
	1·10		1·17	
1·88		2·54		6
MEAN	1·4		1·4	

Table 8.2.2 Log luminance ratios for steady state and unsteady state conditions.

based on data collected in the dynamic situation. Steady state values were also determined and may be compared.

8.3 Steady State Data

A model office with furniture to 1/12 scale was used in the experiment. Figure 8.3.1 shows the model and the viewing position. Figure 8.3.2 shows the interior view of the model. The model contained a translucent plastic ceiling and was illuminated from above this by 2×150 watt Atlas 'spot' lights, 4×150 watt 'floodlights' and 8×150 watt 'reflectors', positioned to illuminate the ceiling as evenly as possible. The lamps were connected to a dimmer over which the subjects had control. A total of 7 subjects participated.

The verbal categories shown in Figure 8.1.2 were used by subjects to rate the lighting level of the office. Each subject was asked to set the level of lighting in the office so that it appeared 'dim', 'satisfactory', 'light' etc. The top category on the scale in Figure 8.1.2 was omitted to avoid artificially limiting the top of the scale by the maximum output of the lamps. The bottom category was omitted to keep the scale symmetrical.

Each subject made settings for the whole 5-point scale twice, setting the lighting level for 'dark', then moving up the scale to 'bright' and then back down to 'dark', or first setting for 'bright', then moving down the scale to 'dark' and back up to 'bright'. These two procedures were alternated between subjects.

Figure 8.3.1 Scale model used for the determination of steady state data.

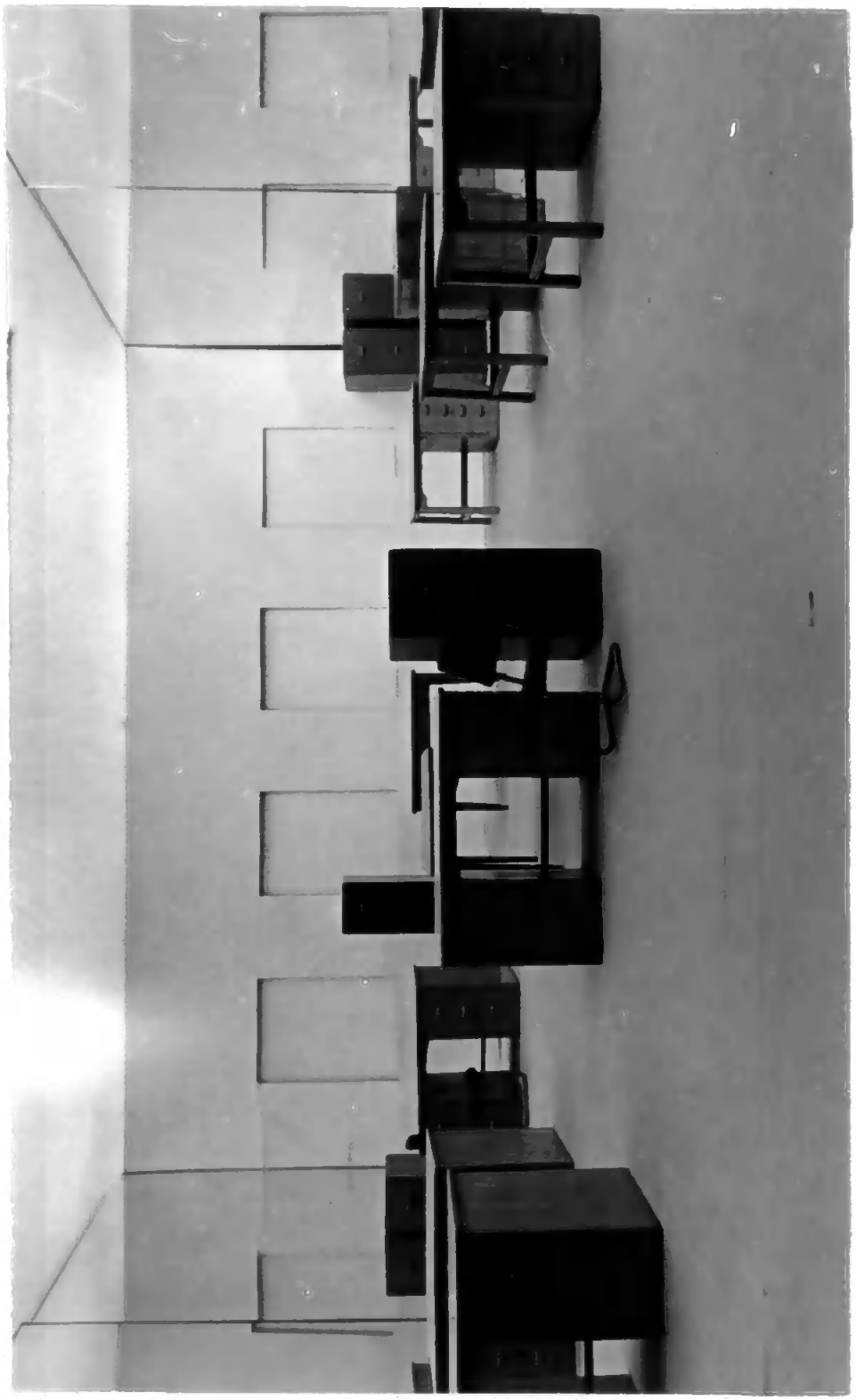


Figure 8.3.2 View inside the model.

At each setting made by a subject, an observer recorded the illuminance in the vertical plane, at the viewing end of the model. The estimated average illuminance on all surfaces in the office was found to be in the ratio 1.14 to measurements taken at this point.

The raw data consisted of 5 pairs (one value determined moving up the scale and one determined moving down for each of the 5 verbal categories) of values of illuminance for each subject.

The geometrical mean of each pair was taken, producing one value of illuminance for each category per subject. The means of illuminance values for each category were then taken, producing one value of illuminance for each category for the whole group. These means of measured illuminance were adjusted (x 1.14) to indicate values of illuminance averaged over all surfaces of the office. The area-weighted average reflectance of the office was estimated at 0.63 and, using Equation 7.1.2, values of luminance in cd/m^2 were determined.

These values were converted to log units and the ratios between these values calculated for comparison with those of the unsteady state conditions. These are shown in Column 4, Table 8.2.2. The two sets of ratios are in reasonable agreement. The mean of the ratios is 1.4 when calculated for both the unsteady state ratios and the steady state ratios.

8.4 Model Predictions Vs Field Survey Data

Predictions may now be made using the value 1.4 determined above and compared with the responses given along the route. Table 8.2.1 shows the estimated values of average luminance in each space along the route together with the marker number in that space. The value of luminance at Point 12 on the outward journey was estimated at 27 (cd/m^2) and the value at Point 1 on the return journey 4 (cd/m^2).

These luminance values were converted to log luminance values and ratios between values at contiguous points established. Each ratio was divided by the value 1.4, determined above, producing a series of values indicating the increase or decrease in subjective estimate between each pair of contiguous points along the route. The initial estimate was given the same value as the survey data (6 = bright) and values were rounded to the nearest half vote.

Figure 8.3.3 shows the comparison between the predictions by the model and the median responses from the survey. The two are in reasonably close agreement. We can therefore make acceptable predictions of the general trend of estimates without consideration of photochemical changes in the eye.

However, more accurate predictions can be made if we include these changes in an expression. The following simple expression was used to predict the values shown in Figure 8.3.4:

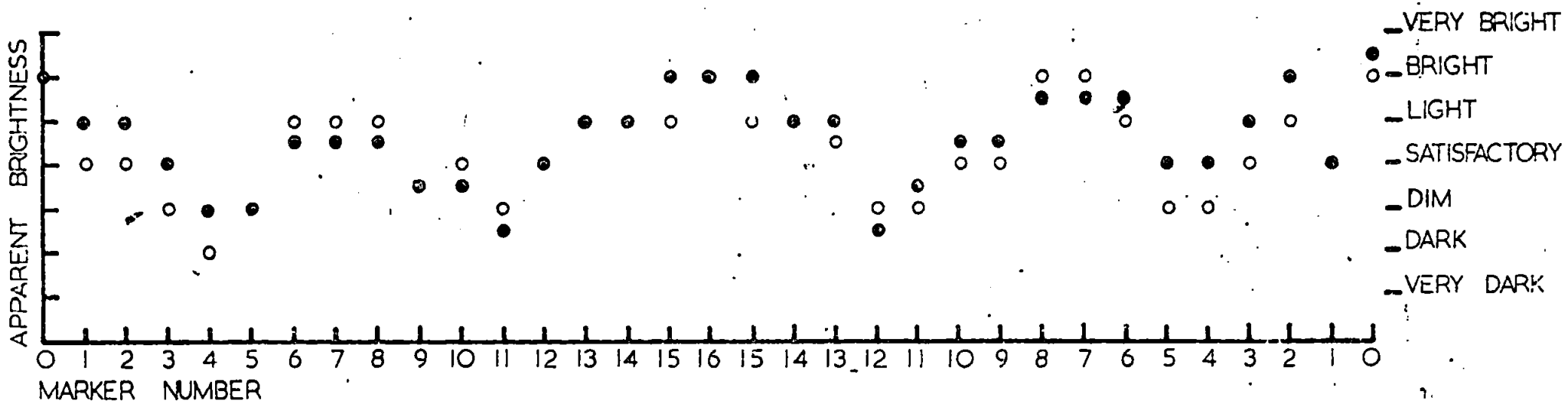


Figure 8.3.3 Comparison of verbal responses of subjects with predictions by the model

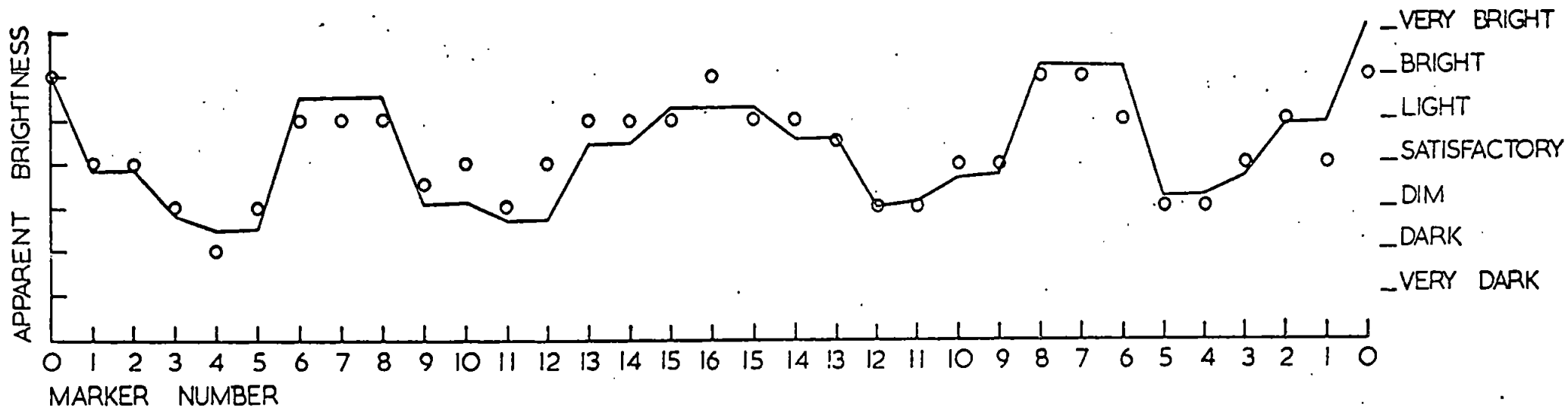


Figure 8.3.4 Comparison of verbal responses of subjects with predictions by the model

$$Z' = Z + 0.045(X'-X) - 16(Y'-Y) \qquad 8.4.1$$

where Z' = prevailing apparent brightness
Z = previous apparent brightness
X' = prevailing luminance (cd/m^2)
X = previous luminance (cd/m^2)
Y' = prevailing fraction of bleached pigment (X antilog 3)
and Y = previous fraction of bleached pigment (X antilog 3)

8.5 Concluding Remarks

Predictions by the photochemical model and comparison of these predictions with the survey data indicates that the gradual changes in people's impressions of the brightness of a sequence of rooms is consistent with changes in predicted pigment concentration in the cones. However, the gradual changes have been shown to be not significant. Furthermore, a close approximation to people's subjective estimates can be made by the simple expression:

$$\text{increase in subjective estimate} = \frac{r}{1.4} \qquad 8.5.1$$

where r = the estimated log luminance ratio of two successive rooms.

A closer approximation can be made when pigment changes are taken into account.

The prediction of average luminance (see Section 9) is shown to be adequate for most cases. However, the discrepancy at Points 1 and 12 suggests that in some cases a more precise description of the visual field may be necessary.

Section Nine. The Indoor Environment

9.1 Introduction

In the previous sections two models have been developed, capable of predicting people's verbal responses to changes in the thermal environment and lighting levels within a building; changes that result from a person walking from one room to another.

The two models may be regarded as producing output and requiring input. The output in each case is the predicted verbal statement of thermal sensation or apparent brightness, the input being a description of the thermal environment and the lighting level, within each room, respectively. This section is concerned with the input to the models.

9.2 The Thermal Environment

The model of human thermal response is written as a series of FORTRAN subroutines (see Appendix C). The inputs to the model required to describe the thermal environment of a room are ambient air temperature (Ta) °C, mean radiant temperature (Tr) °C and relative humidity (RH) as a percentage. Any computer program which generates values for these variables and makes them accessible to FORTRAN subroutines can be used. The following is based on information contained in the IHVE Guide (ref. 1) but has not been validated further.

In predicting the values of these three variables within a building it is useful to consider the building at two periods in the year; Winter, when the building is subjected to cooling by the environment and Summer, when the building is subjected to heating by the environment.

9.3 Winter Conditions

In the British Isles, most buildings for human habitation have some form of internal heating in Winter. In the early stages of a design the thermostat setting or desired temperature (Ta) to the rooms of a building, together with a description of the type of heating (convective or radiant), is a convenient and readily understood description. This brief description assumes that the desired temperature is attained and maintained.

The IHVE Guide (ref. 1) gives values for air temperature (Ta) corresponding to values of environmental temperature (Te) for both convective and radiant heating, in three types of building. Table 9.3.1 gives average values computed from these tables.

The Guide also gives an expression for the approximation of environmental temperature:

$$T_e = \tfrac{2}{3} T_r + \tfrac{1}{3} T_a \qquad (^{\circ}C) \qquad 9.3.1$$

Te	15°C		18°C		21°C	
Heating type	CON.	RAD.	CON.	RAD.	CON.	RAD.
Factory	16.3	12	19.2	14.9	22.3	17.4
Open office	16.3	13.2	19.5	15.9	22	18.5
Private office	16.4	14	19.2	16.9	22.4	19.7

Table 9.3.1 Values in boxes are Ta (°C).

Substituting the values of Ta and Te from Table 9.3.1 into Equation 9.3.1 we produce Table 9.3.2 giving values of Tr.

Comparing Tables 9.3.1 and 9.3.2, it is clear that irrespective of building type and environmental temperature Tr is consistently higher than Ta with radiant heating and lower than Ta with convective heating. The average value by which Tr is lower than Ta is 1.9°C. The average value by which Tr is higher than Ta is 3.2°C. Therefore, we will presume that for Winter conditions, where a design temperature Ta is stated, Tr will take a value 3°C higher than Ta when radiant heating is used and 2°C lower when convective heating is used.

In a well ventilated building the vapour pressure of the air is equal to that outside. In crowded buildings and in Winter, when the windows are closed for days on end, the indoor vapour pressure may rise 7 mm Hg or more above the outdoor level (ref. 2).

Relative humidity is a convenient expression of the moisture content of air and may be used to describe the outdoor conditions. Internal relative humidity may be calculated as follows;

$$vp_o = \frac{RH_o \times pss_o}{100} \qquad \text{(mm Hg)}$$

Te	15°C		18°C		21°C	
Heating type	CON.	RAD.	CON.	RAD.	CON.	RAD.
Factory	14.4	16.5	17.4	19.5	20.3	22.8
Open office	14.4	15.9	17.3	19.1	20.5	22.2
Private office	14.4	15.5	17.4	18.5	20.3	21.6

Table 9.3.2 Values in boxes are Tr (°C).

where vp_o = outside vapour pressure (mm Hg)
pss_o = saturated vapour pressure at outside temperature (mm Hg)
and RH_o = outside relative humidity

For a crowded building or Winter conditions,

$$vp_i = vp_o + 7 \quad (mm\ Hg) \qquad 9.3.2$$

where vp_i = indoor vapour pressure (mm Hg)

Indoor relative humidity is,

$$RH_i = \frac{100.\ vp_i}{pss_i}$$

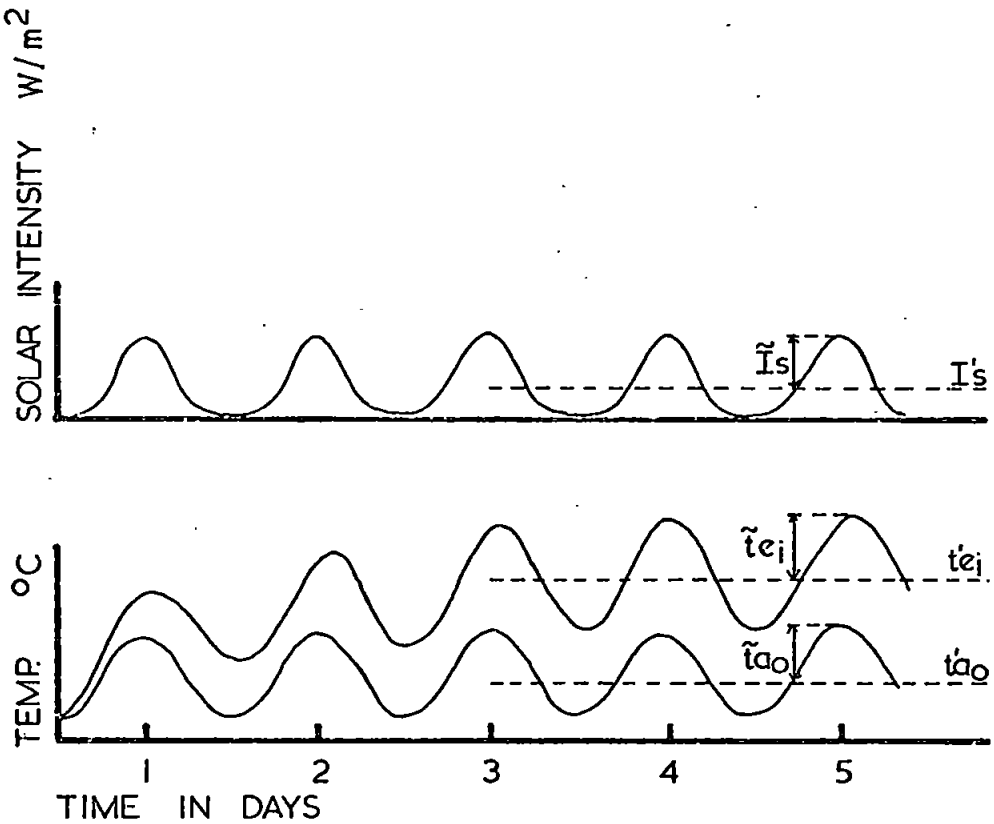
where RH_i = indoor relative humidity
and pss_i = saturated vapour pressure at inside temperature (mm Hg)

9.4 Summer Conditions

This section does not apply to a naturally ventilated building and assumes that the ventilation rate is constant night and day.

Summer conditions are characterised by transient thermal conditions due mainly to solar heat gain. The peak daily temperature as well as the daily mean temperature may therefore be usefully calculated.

Summertime temperatures may be calculated using the admittance procedure (ref. 3) outlined in the IHVE Guide.



I's = Daily mean solar intensity, $\tilde{I}s$ = swing in solar intensity about daily mean, t'ei = daily mean environmental temp. indoors, $\tilde{t}ei$ = swing in environmental temp. about daily mean, t'ao = daily mean outdoor air temp., $\tilde{t}ao$ = swing about daily mean.

Figure 9.4.1 Cyclic heat gains in summer heat wave conditions.

Figure 9.4.1 shows the theoretical heat input and the resulting temperature swings in outside air and inside environmental temperatures.

The method involves, firstly, calculation of the daily mean heat gains and the resulting daily mean indoor temperature. Secondly, the swing in heat gains and the resulting swing in indoor temperature is calculated.

The daily mean heat gain is the sum of the mean solar and mean casual gains (casual gains are heat inputs to the building from lighting, occupants, electrical equipment etc. and are presumed to occur cyclically).

$$Q't = Q's + Q'c \qquad \text{(watts)}$$

where $Q't$ = daily mean heat gain (watts)
$Q's$ = daily mean solar heat gain (watts)
$Q'c$ = daily mean casual heat gain (watts)

The daily mean indoor temperature is given by,

$$t'ei = t'ao + \frac{Q't}{\sum AU + Cv}$$

where $t'ei$ = daily mean indoor environmental temperature (°C)
$t'ao$ = daily mean outdoor air temperature (°C)
$\sum AU$ = sum of products of areas of exposed surfaces and the appropriate U values (w/°C)
and Cv = ventilation loss (w/°C)

The swing in structural heat gains may be neglected in most instances in the United Kingdom and the swing (mean to peak) in heat gain given by,

$$\tilde{Q}_t = \tilde{Q}_s + \tilde{Q}_c + \tilde{Q}_a \qquad \text{(watts)}$$

where $\tilde{Q}_t$ = total swing in heat input (watts)
$\tilde{Q}_s$ = swing in solar heat gain (watts)
$\tilde{Q}_c$ = swing in casual heat gain (watts)
$\tilde{Q}_a$ = swing in air to air gain (watts)

The admittance (Y) of a surface is a measure of its ability to smooth out temperature variations. The swing in environmental temperature is given by,

$$\tilde{t}_{ei} = \frac{\tilde{Q}_t}{\sum AY + C_v}$$

where $\tilde{t}_{ei}$ = swing in indoor environmental temperature (^oC)
and $\sum AY$ = sum of the products of the areas of exposed surfaces and the appropriate admittance values

The instantaneous indoor environmental temperature is given by,

$$t_{ei} = t'_{ei} + \tilde{t}_{ei}$$

From Equation 9.3.1, where ta = tr, ta = tei. Also, where ta = tr, tr = tei.

Relative humidity may be calculated in the same manner as for the Winter conditions except that Equation 9.3.2 becomes,

$$vpi = vpo \qquad (mm\ Hg)$$

9.5 Estimation of Lighting Levels

In Section 8, input to the model for prediction of apparent brightness (FORTRAN Program included in Appendix C) was defined as the average luminance of a room, given by,

$$L = \frac{E\rho}{\pi}$$

where L = average luminance of all surfaces (cd/m^2)
E = average illuminance on all surfaces (lux)
ρ = area-weighted average reflectance

This section is concerned with the calculation of the value E.

The calculation of the illuminance (E) averaged over all surfaces of an empty room is described by Sumpner (ref. 4).

9.6 Single Enclosures

For a room lit only by an artificial light,

light flux entering the room = $\phi L \times L.O.R.$ (lumens) 9.6.1

where ϕL = light flux from the lamp (lumens)

$L.O.R. = \dfrac{\text{light flux from the luminaire}}{\text{light flux from the lamp}}$

Let

E = average illuminance on all surfaces (lux)

and let

A = area of each surface (m^2)

Then

light flux striking all surfaces = $E \times \sum A$ (lumens) 9.6.2

Any light striking a surface is either reflected, absorbed or transmitted. Restated,

$$\rho + \tau + \alpha = 1. \qquad 9.6.3$$

where ρ = reflectance of surface
τ = transmittance of surface
and α = absorbtance of surface

Therefore,

flux absorbed and transmitted by all surfaces $= E \times \sum A(\alpha + \tau)$

But from 9.6.3;

$$\alpha + \tau = 1. - \rho$$

Therefore;

flux absorbed and transmitted by all surfaces $= E \times \sum A(1. - \rho)$

In the steady state condition;

$$\phi L \times L.O.R. = E \times \sum A(1. - \rho)$$

Therefore;

$$E = \frac{\phi L \times L.O.R}{\sum A(1. - \rho)} \quad \text{(lux)} \quad 9.6.4$$

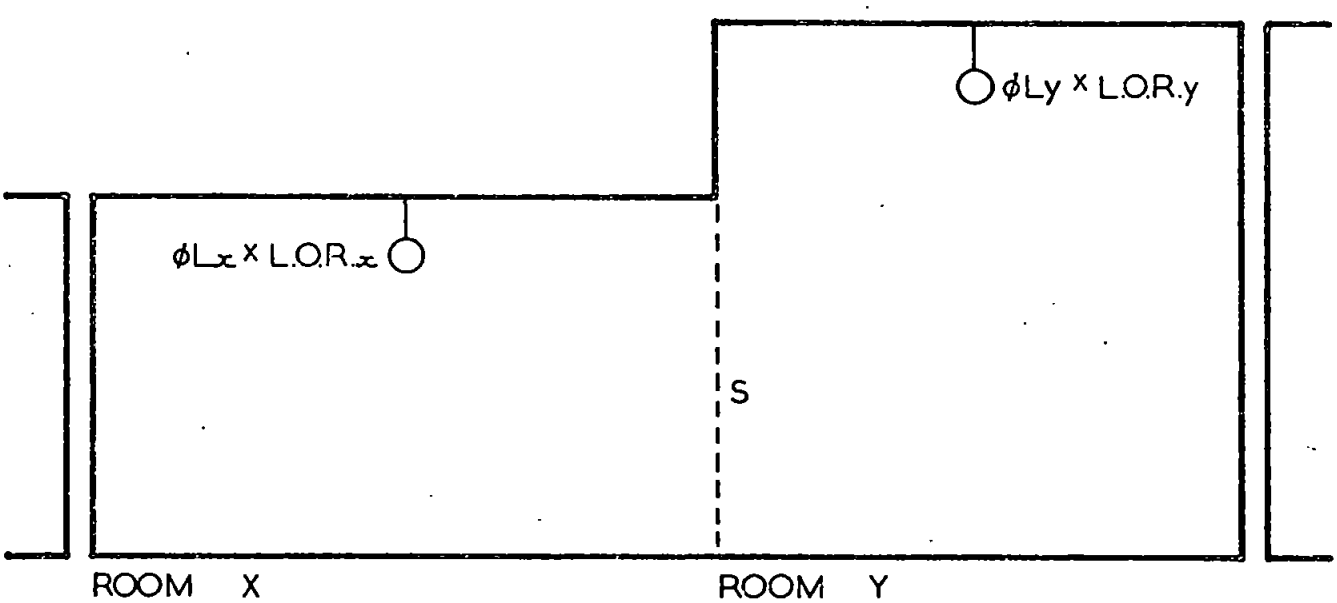


Figure 9.7.1 Section through two rooms, X and Y, borrowing light

9.7 Borrowed Light

In estimating the illuminance of rooms in the field survey, two complications arose.

Firstly, rooms were not empty. Here a simple solution was adopted. Major items, such as filing cabinets and desks, were regarded as an extension of the room surface and accounted for in the calculation. Minor items were ignored.

Secondly, the rooms are not separate enclosures and rooms therefore 'borrow' light from each other. Some rooms are irregular shapes, with a clearly irregular lighting distribution. Both these cases were treated in the same manner. The average illuminance for each separate enclosure (room or part room) is calculated using Equation 9.6.4. The amount of 'borrowed' light is then estimated and added. Figure 9.7.1 illustrates a simple example.

Two rooms, X and Y, are shown joined. Consider the case where Room X borrows light from Room Y. The dividing plane, S, between the two rooms (shown dotted) is assumed to be a surface with transmittance equal to unity (where the two rooms are separated by glass, the appropriate value for the transmittance of glass is used). Light flux falling on this imaginary plane from Room Y is therefore transmitted to Room X.

From Equation 9.6.2;

light flux striking all surfaces of Room Y $= E_Y \times \Sigma A_Y$ (lumens)

Therefore,

light flux striking Surface S = $E_Y \times A_S$ (lumens)

and

light flux transmitted to Room X = $E_Y \times A_S(\tau)_S$ (lumens)

For Room X,

light flux entering room from light source = $\phi L_X \times L.O.R_X$ (lumens)

and

light flux entering room from Surface S = $E_Y \times A_S(\tau)_S$ (lumens)

Therefore, from Equation 9.6.4, the average illuminance, Ex, is given by,

$$E_X = \frac{\phi L_X \times L.O.R._X + E_Y \times A_S(\tau)_S}{\sum A(1-\rho)_X} \quad \text{(lux)} \quad 9.6.5$$

where the reflectance ρ of the surface S is equal to $1-(\tau+\alpha)_s$. When this surface is imaginary $\rho = 0$.

Similarly, for Room Y;

light flux entering room from light source $= \phi L_y \times L.O.R._y$ (lumens)

and

light flux entering room from Surface S $= E_x \times A_s(\tau)_s$ (lumens)

Therefore, from Equation 9.6.4, the average illuminance, Ey, is given by,

$$E_y = \frac{\phi L_y \times L.O.R._y + E_x \times A_s(\tau)_s}{\sum A(1-\rho)_y} \quad \text{(lux)} \quad 9.6.6$$

where the reflectance ρ of the surface S is equal to $1-(\tau+\alpha)_s$. When this surface is imaginary, $\rho = 0$.

9.8 Daylight

For a daylit room,

$$\text{flux entering room} = \frac{\tau . A_g . S \times E_{sky}}{100}$$

where τ = transmittance of glass,
A_g = area of glass (m^2),
S = daylight factor on outside of glass,
E_{sky} = sky illuminance (lux).

Equation 9.6.4 may therefore be rewritten,

$$E = \frac{\tau . A_g S}{\sum A(1-\rho)} \cdot \frac{E_{sky}}{100} \qquad \text{(lux)}$$

The daylight factor is defined as,

$$df = \frac{E \times 100}{E_{sky}}$$

where df = daylight factor.

Where rooms borrow light, as for example Rooms X and Y in Figure 9.7.1, Equations 9.6.5 and 9.6.6 may be rewritten,

$$E_x = \frac{(\tau . A_q . S)_x \times E_{sky} + (E_Y \, A_s (\tau)_s) \times 100}{\sum A (1 - \rho)_x} \qquad \text{(lux)}$$

and,

$$E_y = \frac{(\tau . A_q . S)_y \times E_{sky} + (E_x \, A_s (\tau)_s) \times 100}{\sum A (1 - \rho)_y} \qquad \text{(lux)}$$

References, Section Nine

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10 Future Studies

This pilot study has shown that we can make reasonable approximations to people's sequential experiences of the lighting and the thermal environment within buildings. However, it would be a mistake to regard the two models of human response as definitive, rather they should be regarded as starting points.

For example, it has been shown that, when lit by two lamps of different Colour Discrimination Index, two identical rooms are judged equally satisfactory in visual appearance when the interior lit by the lamp having the smaller colour gamut is set to a higher illuminance (ref. 1).

The empirical relationship between the illuminance ratio of the two rooms to the colour rendering properties of the lamps of the two rooms is,

$$\text{Illuminance ratio} = 1{\cdot}06 - 1{\cdot}08\log(\text{gamut area ratio})$$

The illuminance ratio may be converted to a log luminance ratio and the correction added to the estimate of the change in apparent brightness, as given by equation 8.5.1 .

The model predicting people's thermal sensations was validated against conditions during the winter months. Recent work (ref. 2) has shown however that comfort temperatures in buildings are related to the indoor temperatures and the mean monthly outdoor temperature. This suggests

that the temperature corresponding to the mid point on the scale of warmth (neutral / comfortable) is likely to vary over the seasons of the year. Whether the whole seven - point scale can be simply moved up and down with the variations in climatic conditions poses an interesting question.

Clearly, the two models developed are not the whole story, as all our senses play some part in the total experience of architecture. Present day design techniques for the acoustics of buildings ignore the sequential experience. Therefore, this would seem an area in which to do further work.

Most of us are familiar with the experience of walking into a fully occupied, often smoke filled, lecture room or pub from a well ventilated corridor. The experience serves to remind us that odours play a part in our experience of buildings, and that they are particularly noticeable when suddenly changed.

The age old belief that red rooms are warmer than blue rooms presents a problem of the interaction of the senses. Some recent work (ref. 3) has shown that people do prefer a lower ambient temperature in red rooms than in blue rooms, but the effect is so small as to be hardly of practical significance. Nevertheless, the question of the interaction of the senses is an interesting one and in the context of the sequential experience deserves further attention.

This study has been mainly concerned with the sequential experience of

the interiors of buildings. An interesting study is that of the interface between inside and outside. This is a special case of the sequential experience; one that is often an abrupt experience. Here, there are special problems associated with the cooling effects of winds, the effects of changes in wind speed and direction on balance (ref. 4) and direct radiation from the sun.

It is hoped that this thesis has made a modest step towards combining our previously separate concerns for the environmental aspects and sequential experiences of architecture.

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APPENDIX A

Nomenclature:

Equations 3.2.2 - 3.2.9

ρ	Density of the tissue)
c	Specific heat of tissue) ρc = 1cal/cc°C
T	Temperature (°C)
T_s	Temperature, surface layer (°C)
T_1	Temperature, middle layer (°C)
T_2	Temperature, core layer (°C)
T_B	Average body temperature (°C)
T_A	Ambient temperature (°C)
t	Time (hrs)
K	Specific thermal conductivity of wet tissue (kcal/m/hr/°C X 1.163 = w/m/°C)
$\alpha k+$	Thermal conductivity coefficient of proportional control for $\Delta T_B > 0$ = 00.147/°C
$\alpha k-$	Thermal conductivity coefficient of proportional control for $\Delta T_B < 0$ = 00.066/°C
γk	Thermal conductivity coefficient of rate control (sec/°C)
X	Distance from surface (cm)
ΔX_s	Thickness of surface layer = 0.8 cm
ΔX_1	Thickness of middle layer = 1.6 cm
ΔX_2	Thickness of core layer = 3.2 cm
ΔX_{s1}	$\frac{1}{2}(\Delta X_s + \Delta X_1)$ (cm)
ΔX_{12}	$\frac{1}{2}(\Delta X_1 + \Delta X_2)$ (cm)
M	Metabolic rate per unit area (kcal/m²/hr X 1.163 = w/m²)
αm	Metabolic rate coefficient of proportional control $T_B < 0$ (kcal/m²/hr/°C X 1.163 = w/m²/°C)

R	Heat loss (radiation) per unit area (kcal/m^2/hr X 1.163 = w/m^2)
V	Heat loss (vaporisation) per unit area (kcal/m^2/hr X 1.163 = w/m^2)
α_V	Vaporisation coefficient of proportional control (kcal/m^2/hr/^{o}C X 1.163 = w/m^2/^{o}C)
λ_V	Vaporisation coefficient of 4th power proportional control (kcal/m^2/hr/^{o}C X 1.163 = w/m^2/^{o}C)
h	Heat transfer coefficient (skin/air)(kcal/m^2/hr/^{o}C X 1.163 = w/m^2/^{o}C)
h_R	Heat transfer coefficient of radiation (kcal/m^2/hr/^{o}C X 1.163 = w/m^2/^{o}C)
h_c	Heat transfer coefficient of convection (kcal/m^2/hr/^{o}C X 1.163 = w/m^2/^{o}C)
v	Velocity of air at skin surface (cm/sec)
E	Exercise (kcal/m^2/hr X 1.163 = w/m^2)
δ_E	Increase in vaporisation coefficient due to violent exercise

Equations 3.2.10 - 3.2.21

Parameters:

HC	Head core
HS	Head skin
EC	Extremities core
ES	Extremities skin
TC	Trunk core
TM	Trunk muscle
TS	Trunk skin
CB	Central blood

C	Thermal capacitance (kcal/^{o}C X 1.163 = watt-hours ^{o}C)
T	Temperature (^{o}C)
t	Time (hrs)

MBF	Muscle blood flow (l/hr)
E	Exercise (kcal/hr X 1.163 = watts)
T_A	Ambient temperature (^oC)
$\overline{T}_S$	Average skin temperature (^oC)
α	Dimension less fraction accounting for counter-current heat exchange
ρc	Product of density and specific heat of blood (kcal/^oC X 1.163 = watt-hours/^oC)
ΔM	Shivering metabolism (kcal/hr X 1.163 = watts)
E_{VR}	Respiratory heat loss (kcal/hr X 1.163 = watts)
M_o	Basal metabolism (kcal/hr X 1.163 = watts)
E_{V_o}	Insensible evaporative heat loss (kcal/hr X 1.163 = watts)
E_V	Evaporative heat loss (kcal/hr X 1.163 = watts)
SBF	Skin blood flow (l/hr)
$A_{HS}.h_o$	Product of area and environmental heat coefficient (kcal/hr/^oC X 1.163 = w/^oC)
K	Thermal conductance between layers (kcal/hr/^oC X 1.163 = w/^oC)
$\overline{T}_M$	Average muscle temperature (^oC)

Equations 3.2.22 and 3.2.23

C	Specific heat of tissue
T	Temperature of tissue (^oC)
r	Radial distance from axis of cylinder (cm)
h_m	Rate of tissue heat generation due to metabolism (watts)
Q_c	Product of mass flow rate and specific heat of blood entering the capilliary beds per unit volume
T_a	Temperature of blood in artery (^oC)

h_a	Proportionality constant of heat transfer between the arteries and tissue per unit volume
h_v	Proportionality constant of heat transfer between the veins and tissue per unit volume
T_v	Temperature of blood in vein (^oC)
K	Thermal conductivity ($w/m/^oC$)

Equations 3.2.24 - 3.2.39

BC(N)	Convective heat transfer between central blood and N (kcal/hr X 1.163 = watts)
BF(N)	Total effective blood flow to N (l/hr)
T(N)	Temperature of N (^oC)
TD(N)	Conductive heat transfer between N and N + 1 (kcal/hr x 1.163 = watts)
TC(N)	Thermal conductance between N and N + 1 (kcal/hr/^oC X 1.163 = w/^oC)
HF(N)	Rate of flow into or from N (kcal/hr X 1.163 = watts
Q(N)	Total metabolic heat production in N (kcal/hr X 1.163 = watts)
E(N)	Total evaporative heat loss from N (kcal/hr X 1.163 = watts)
H(I)	Total environmental heat transfer coefficient for element I (kcal/hr/^oC X 1.163 = w/^oC)
TAIR	Effective environmental temperature (^oC)
F(N)	Rate of change of temperature in N (^oC/hr)
ERROR(N)	Output from thermoreceptors in compartment N (^oC)
TSET(N)	Set point for receptors in N (^oC)
RATE(N)	Dynamic sensitivity of receptors in N (hr)
COLD(N)	Output from cold receptors (^oC)
WARM(N)	Output from warm receptors (^oC)
WARMS	Integrated output from warm receptors (^oC)
COLDS	Integrated output from cold receptors (^oC)
SKINR(I)	Fraction of all skin receptors in element I (N.D.)

SWEAT	Total efferent sweat command (kcal/hr X 1.163 = watts)
DILAT	Total efferent skin vasodilation command (l/hr)
STRIC	Total efferent skin vasoconstriction command (N.D.)
CHILL	Total efferent shivering command (kcal/hr X 1.163 = watts)
CSW	Sweating from head core coefficient (kcal/hr/ C X 1.163 = w/^{o}C)
SSW	Sweating from skin coefficient (kcal/hr/ C X 1.163 = w/^{o}C)
PSW	Sweating from skin and head core coefficient (kcal/hr/ C X 1.163 = w/^{o}C)
CDIL	Vasodilation from head core coefficient (l/hr/^{o}C)
SDIL	Vasodilation from skin coefficient (l/hr/^{o}C)
PDIL	Vasodilation from skin and head core coefficient (l/hr/^{o}C)
CCON	Vasoconstriction from head core (l/hr/^{o}C)
SCON	Vasoconstriction from skin (l/hr/^{o}C)
PCON	Vasoconstriction from skin and head core (l/hr/^{o}C)
CCHIL	Shivering from head core (kcal/hr/^{o}C X 1.163 = w/^{o}C)
SCHIL	Shivering from skin (kcal/hr/^{o}C X 1.163 = w/^{o}C)
PCHIL	Shivering from skin and head core (kcal/hr/^{o}C X 1.163 = w/^{o}C)

Equations 3.3.3 - 3.3.7

HFCR	Heat flow from core to skin shell (w/m^{2})
HFSK	Heat flow from skin to environment (w/m^{2})
RM	Shivering metabolism (MR) (w/m^{2})
ERES	Respired evaporative heat loss (w/m^{2})

CRES	Respired convective heat loss (w/m^2)
WK	Work rate (w/m^2)
SKBF	Skin blood flow ($l/hr/m^2$)
TCR	Core temperature (^oC)
TSK	Skin temperature (^oC)
DRY	Dry heat exchange (w/m^2)
EV	Total evaporative heat loss (w/m^2)
REGSW	Sweating ($g/hr/m^2$)
SKSIG	Receptor signals from skin (^oC)
CRSIG	Receptor signals from core (^oC)
DILAT	Vasodilation ($l/hr/m^2$)
STRIC	Vasoconstriction ($l/hr/m^2$)
COLDS	Cold signal from receptors in skin (^oC)
COLDC	Cold signal from receptors in core (^oC)

Equations 3.3.8 - 3.3.12

M_{sk}	Metabolic heat loss through skin surface (w/m^2)
T_{sk}	Skin temperature (^oC)
T_{oh}	Humid operative temperature (^oC)
T_o	Operative temperature (^oC)
w	Skin wettedness
T_{dew}	Linear dew temperature (^oC)
h	Combined heat transfer coefficient ($w/m^2/^oC$)
h_c	Convective heat transfer coefficient ($w/m^2/^oC$)
F_d	Burton thermal efficiency factor (dry heat loss) (N.D.)
F_{pd}	Nishi permeation efficiency factor (evaporative heat loss) (N.D.)

T_{SOH}	Standard operative humid temperature (°C)
$SET*$	Standard effective temperature (°C)
T_S	Thermal sensation

Equations 3.4.1 - 3.4.4

M	Metabolic rate (kcal/hr X 1.163 watts)
$\bar{T}_S$	Mean skin temperature (°C)
A_{DU}	Area of body determined by Dubois formula (m^2)
Y	Thermal sensation
L	Thermal load (kcal/m^2/hr X 1.163 = w/m^2)

APPENDIX B

Derivation of Equation 7.1.3

$$\frac{dX}{dt} = K(1 - X) - AQX$$

$$= K - KX - AQX$$

$$= K - X(K + AQ)$$

Therefore $$\frac{dX}{K - X(K + AQ)} = dt$$

However,

$$\frac{d}{dt}.(K - X(K + AQ)) = -(K + AQ)$$

If we multiply both sides by $-(K + AQ)$ we get

$$\frac{-(K + AQ)dX}{K - X(K + AQ)} = -(K + AQ)dt$$

So on integration we get

$$\log_e(K - X(K + AQ)) = -(K + AQ)t + B$$

where B is the constant of integration.

Rewriting we get

$$K - X(K + AQ) = B.e^{-(K + AQ)t} \qquad (1)$$

But when $t = 0$,

$$X = \frac{K}{K + AQ_1}$$

where Q_1 = the initial retinal illuminance in trolands to which the eye is adapted.

and when $t = \infty$,

$$X = \frac{K}{K + AQ_2}$$

where Q_2 = the prevailing retinal illuminance in trolands to which the eye is adapted.

To find B, consider X when $t = 0$,

$$B = \frac{K - K(K + AQ_2)}{K + AQ_1}$$

$$B = \frac{K(K + AQ_1 - K + AQ_2)}{K + AQ_1}$$

$$B = \frac{KA(Q_1 - Q_2)}{K + AQ_1}$$

Substituting for B in equation (1) and putting $Q = Q_2$ because Q_2 is the prevailing retinal illuminance in trolands, we get

$$K - X(K + AQ_2) = \frac{KA(Q_1 - Q_2)}{(K + AQ_1)} . e^{-(K + AQ_2)t}$$

Therefore

$$X = \frac{K}{K + AQ_2} - \frac{KA(Q_1 - Q_2)}{(K + AQ_1)(K + AQ_2)} . e^{-(K + AQ_2)t}$$

Derivation of equation 7.1.4

$$X = \frac{K}{K + AQ_2} - \frac{KA(Q_1 - Q_2)}{(K + AQ_1)(K + AQ_2)} . e^{-(K + AQ_2)t}$$

Let $P = 1 - X$

Then,

$$1 - P = \frac{K}{K + AQ_2} - \frac{KA(Q_1 - Q_2)}{(K + AQ_1)(K + AQ_2)} . e^{-(K + AQ_2)t}$$

and

$$P = 1 - \frac{K}{K + AQ_2} + \frac{KA(Q_1 - Q_2)}{(K + AQ_1)(K + AQ_2)} . e^{-(K + AQ_2)t}$$

Differentiating we get

$$\frac{dP}{dt} = \frac{KA(Q_1 - Q_2)}{(K + AQ_1)(K + AQ_2)} . -(K + AQ_2)e^{-(K + AQ_2)t}$$

Therefore

$$\frac{dP}{dt} = \frac{KA(Q_1 - Q_2)}{(K + AQ_1)} . e^{-(K + AQ_2)t}$$

Derivation of Equation 7.1.5

$$X = \frac{K}{K + AQ_2} - \frac{KA(Q_1 - Q_2)}{(K + AQ_1)(K + AQ_2)} \cdot e^{-(K + AQ_2)t}$$

From equation 7.1.3, when $t = \infty$,

$$X = \frac{K}{K + AQ_2}$$

$$K = X(K + AQ_2)$$

$$\frac{K}{X} = K + AQ_2$$

$$\frac{K(1 - X)}{X} = AQ_2$$

Therefore

$$\frac{K(1 - X)}{XA} = Q_2$$

As Q_1 = the steady state value to which the system is adapted at $t = 0$, when a step change occurs $Q_1 = Q_2$ as derived above and Q_2 takes a new value.

APPENDIX C

```
      MASTER EDIT
C           MASTER EDIT ALLOWS CONSTRUCTION AND
C           EDITING OF DATA FOR THE MODELS.
C           EACH EDITING FACILITY IS CALLED BY A
C           COMMAND NUMBER. CONTROL REMAINS WITH
C           THE FACILITY UNTIL TERMINATED. EACH MODEL
C           MAY BE CALLED SEPARATELY TO OPERATE ON
C           THE SAME BUILDING DATA. THE ROUTE MAY
C           BE CHANGED AND DATA UNCHANGED OR VICE
C           VERSA BEFORE A MODEL IS RUN.
C           ALLOW 20 SPACES MAX
C           ALLOW 6 POINTS ON ROUTE
      REAL LMEN(20),ILLOT(20),ILLMA(20),ILLMN(20)
      INTEGER TS(2)
      INTEGER SCALE
C           PLOTTER BUFFER AREA
      DIMENSION IBUF(1000)
      DIMENSION IFNO(2)
      COMMON WAIT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLMN,ILLMT,DFINT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLM1,LUMEN,S(120),G(5,140)
      COMMON D(10,120),U(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARM(20)
C           INITIALISE PLOTTER
      CALL PLOTS (IBUF(1),1000,7)
C           SET SCALE
      CALL FACTOR (0.1)
C           DRAW SCREENS
      FF = 1.
      CALL SCREEN (FF)
      NMAX = 0
 100  DELETE = 0.
 101  CONTINUE
C           READ IN EDIT COMMAND
      READ (1,900) IN
      GOTO (1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,
     1      16,17,18,19,20),IN
C           SPACE
    1 CALL SS (7,NMAX)
      GOTO 100
C           GAP
    2 CALL SG (TS,DELETE,N,YY,FF)
      GOTO 100
C           WINDOW
    3 CALL SW (TS,DELETE,N,YY,FF)
      GOTO 100
C           DOOR
    4 CALL SD (TS,DELETE,N,YY,FF)
      GOTO 100
C           REFLECTANCE
    5 CALL SR (IFLAG)
      GOTO 100
C           PLOT
    6 CALL SP (FF,SCALE,YY,N)
      GOTO 100
C           ERASE
    7 CALL SE (DELETE)
      GOTO 101
C           LUMINAIRES
    8 CALL SL
      GOTO 100
```

```
C              HIDDEN OBSTRUCTION
    9   CALL SF (DELETE)
        GOTO 100
C              SKY ILLUMINANCE
   10   CALL SK (ILSKY)
        GOTO 100
C              TRANSMITTANCE
   11   CALL ST (TRANS)
        GOTO 100
C              ROUTE
   12   CALL ROUTES (ITOTL,N,FF,YY)
        GOTO 100
C              ROOM ILLUMINANCE
   13   CALL SI (IFLAG)
        GOTO 100
C              PHOTIC MODEL
   14   CALL PHOTIC (IFLAG,ITOTL,H,YY,FF,N,SCALE)
        GOTO 100
C              PERSPECTIVE
   15   CALL VISIO
        GOTO 100
C              THERMAL MODEL
   16   CALL THERMIL (ITOTL,N,FF,SCALE,YY,H)
        GOTO 100
C              SCALE FACTOR
   17   CALL SCALES (FF,SCALE)
        GOTO 100
C              THERMAL CHARACTERISTICS
   18   CALL SH
        GOTO 100
   19   CALL SHB (H,FF)
        GOTO 100
   20   CONTINUE
C              CLOSE PLOTTER
        CALL PLOT (0.0,0.0,999)
C              IF ANY DATA IS TO BE SAVED,
C              INSERT ROUTINES HERE.
  900   FORMAT(I2)
        STOP
        END
```

```
      SUBROUTINE SS (N,NMAX)
C          SUBROUTINE SS DEALS WITH INPUT OF SPACES
C               EACH SPACE IS DEFINED BY COORDS OF THE
C               BOTTOM LEFT HAND AND TOP RIGHT HAND CORNERS
C               AND A ROOM HEIGHT.
C               N IS SPACE REF. NUMBER
      INTEGER T,N
      REAL LUMEN(20),ILLHT(20),ILLMA(20),ILLMN(20)
      COMMON WAIT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLMD,ILLHT,DFINT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      READ  (1,150) N
C               DEFAULT FLOOR LEVEL
      Z1 = 0.
   10 READ  (1,130) X1,Y1
      READ  (1,130) X2,Y2
      READ  (1,120) T
      IF(T.EQ.0) GOTO 15
C               FLOOR LEVEL
      READ  (1,140) Z1
   15 CONTINUE
      READ  (1,140) Z2
      Z2 = Z2+Z1
      CALL INPUTS (X1,X2,Y1,Y2,Z1,Z2,N)
      CALL PLOTS (X1,X2,Y1,Y2)
      CALL NUMBER  (X1,Y1,X2,Y2,N)
      N = N+1
      READ  (1,120) T
      IF(T.EQ.0) GOTO 10
      N = N-1
      IF(NMAX.GT.N) GOTO 20
      NMAX = N
   20 N = NMAX
      RETURN
  120 FORMAT(I1)
  130 FORMAT(2F4.0)
  140 FORMAT(F3.0)
  150 FORMAT(I2)
      END
```

```
      SUBROUTINE INPUTS (X1,X2,Y1,Y2,Z1,Z2,N)
C           SUBROUTINE INPUTS STORES THE COORD
C           DATA DEFINING EACH SPACE (BOTTOM
C           LEFT HAND AND TOP RIGHT OF A RIGHT
C           PARALLELAPIPED) SEQUENTIALLY IN S.
C           N IS SPACE REF. NUMBER.
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON WAIT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLMN,ILLMT,DFIMT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      K = (N-1)*6+1
      S(K  ) = X1
      S(K+1) = Y1
      S(K+2) = Z1
      S(K+3) = X2
      S(K+4) = Y2
      S(K+5) = Z2
      RETURN
      END
```

```
      SUBROUTINE AREAS (X1,X2,Y1,Y2,Z1,Z2,N)
C          SUBROUTINE AREAS CALCULATES AND STORES
C          THE AREA OF EACH SURFACE OF EACH SPACE
C          IF DOORS ARE TO BE GIVEN REFLECTANCE
C          VALUES,DOOR AREAS MUST BE SUBTRACTED.
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON WAIT(30),DIST(30),TIME(50),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(50)
      COMMON ILLIN,ILLMT,DFIMT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),H(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      AREA(1,N) = (X2-X1)*(Z2-Z1)-(AGLAS(1,N)+AGAPS(1,N))
      AREA(2,N) = (Y2-Y1)*(Z2-Z1)-(AGLAS(2,N)+AGAPS(2,N))
      AREA(3,N) = (X2-X1)*(Z2-Z1)-(AGLAS(3,N)+AGAPS(3,N))
      AREA(4,N) = (Y2-Y1)*(Z2-Z1)-(AGLAS(4,N)+AGAPS(4,N))
      AREA(5,N) = (X2-X1)*(Y2-Y1)
      AREA(6,N) = AREA(5,N)
      RETURN
      END
```

```
      SUBROUTINE SG (TS,DELETE,HH,Y,FF)
C             SUBROUTINE SG ALLOWS INPUT OF GAPS. A
C             GAP IS DEFINED BY TWO DIAGONALLY OPPOSITE
C             CORNERS OF A RECTANGLE.
      INTEGER T,J
      INTEGER TS(2)
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      DIMENSION IFNO(2)
      COMMON WAIT(50),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLAB,ILLMT,DFIMT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      Z1 = 0.
      DO 30 IR = 1,5
   10 READ  (1,130)X1,Y1
      READ  (1,130)X2,Y2
      READ  (1,120) I
      IF(I.EQ.0) GOTO 15
C             ALPHA MODE
C             FLOOR LEVEL
      READ  (1,140) Z1
      ZZ1 = Z1
   15 CONTINUE
      READ  (1,140) Z2
      IF(DELETE.EQ.1.) Z1=ZZ1
      Z2 = Z2+Z1
C             TEST WHETHER LINE HORIZ OR VERTICAL
      IF(X1.EQ.X2) GOTO 20
C             LINE IS HORIZONTAL
      IFLAG = 1
      GOTO 25
C             LINE IS VERTICAL
   20 IFLAG = 2
   25 CONTINUE
      CALL INCLUS (IFLAG,X1,Y1,X2,Y2,Z1,Z2,TS,2,IFNO)
C             ALL GAPS OF SPACE TS MUST BE DELETED
      IF(DELETE .EQ. 0.) GOTO 27
      X1 = 0.
      X2 = 0.
      Y1 = 0.
      Y2 = 0.
      Z1 = 0.
      Z2 = 0.
C             IF ONLY 4 GAPS PER SPACE ARE ALLOWED
C             IR BECOMES IFNO AND IS DETERMINED BY
C             INCLUS
   27 CALL INPUTG (X1,X2,Y1,Y2,Z1,Z2,TS(1),IR,TS,2)
      CALL AREAG2 (X1,Y1,Z1,X2,Y2,Z2,TS(1),IFNO(1),DELETE)
      CALL INPUTG (X1,X2,Y1,Y2,Z1,Z2,TS(2),IR,TS,1)
      CALL AREAG2 (X1,Y1,Z1,X2,Y2,Z2,TS(2),IFNO(2),DELETE)
      KK = (TS(1)-1)*6+1
      CALL ORIGIN (S(KK+2),HH,Y,FF)
      CALL SYMBOL (X1,Y1,1.4,3,0.0,-1)
      CALL PLOT (X2,Y2,2)
      CALL SYMBOL (X2,Y2,1.4,3,0.0,-1)
      READ  (1,120) T
      IF(T.EQ.1) GOTO 40
   30 CONTINUE
   40 RETURN
  100 FORMAT(4F10.2)
```

```
120   FORMAT(I1)
130   FORMAT(2F4.0)
140   FORMAT(F3.0)
      END
```

```
      SUBROUTINE INPUTG (X1,X2,Y1,Y2,Z1,Z2,N,IR,TS,I)
C          SUBROUTINE INPUTG STORES THE COORD
C               DATA OF EACH GAP SEQUENTIALLY IN R
C               THE MAX VALUE OF IR DETERMINES THE
C               MAX NUMBER OF GAPS PER SPACE. N IS
C               THE SPACE-REF NUMBER WHICH CONTAINS
C               THE GAP. EACH GAP IS FLAGGED BY THE
C               ADJACENT-SPACE REF NUMBER.
      INTEGER TS(2)
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON WALT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLMN,ILLMT,DEPT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATN(20),ARH(20)
      K = (I-1)*7+1
      G(IR,K+1) = X1
      G(IR,K+2) = Y1
      G(IR,K+3) = Z1
      G(IR,K+4) = X2
      G(IR,K+5) = Y2
      G(IR,K+6) = Z2
      G(IR,K  ) = TS(I)
      RETURN
      END
```

```
      SUBROUTINE AREAG2 (X1,Y1,Z1,X2,Y2,Z2,N,IFNO,DELETE)
C           SUBROUTINE AREAG2 CALCULATES AND STORES
C           THE AREA OF GAP )J EACH FACE OF EACH SPACE
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON WAIT(30),DIST(30),TIME(50),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(50)
      COMMON ILLTR,ILLHT,DFIHT(20),AREA(6,20)
      COMMON AGLAS(4,20),AG2(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      IF(X1.EQ.X2) GOTO 10
      IF(DELETE.EQ.0.) GOTO 5
      AG2(IFNO,N) = AG2(IFNO,N)-ABS((Z1-Z2)*(X1-X2))
      GOTO 20
    5 AG2(IFNO,N) = AG2(IFNO,N)+ABS((Z1-Z2)*(X1-X2))
      GOTO 20
   10 IF(DELETE.EQ.0.) GOTO 15
      AG2(IFNO,N) = AG2(IFNO,N)-ABS((Z1-Z2)*(Y1-Y2))
      GOTO 20
   15 AG2(IFNO,N) = AG2(IFNO,N)+ABS((Z1-Z2)*(Y1-Y2))
   20 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SW (TS,DELETE,HH,Y,FF)
C           SUBROUTINE SW ALLOWS INPUT OF WINDOWS.
C           A WINDOW IS DEFINED BY  TWO DIAGONALLY
C           OPPOSITE CORNERS OF A RECTANGLE. AREA
C           OF GLASS IS CALCULATED.
      INTEGER TS(2)
      INTEGER T,H
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      DIMENSION IFNO(2)
      COMMON WALT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLMN,ILLMT,DFINT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON STGIA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),U(10,120),REFS(6,20)
      COMMON ATA(20),ATB(20),ARH(20)
      Z1 = 0.
      DO 30 IR = 1,10
   10 READ  (1,130) X1,Y1
      READ  (1,130) X2,Y2
      READ  (1,120) H
      IF(H.EQ.0) GOTO 15
C           CALL HEIGHT
      READ  (1,140) Z1
      ZZ1 = Z1
   15 CONTINUE
      READ  (1,140) Z2
      IF(DELETE.EQ.1.) Z1=ZZ1
      Z2 = Z2+Z1
C           TEST WHETHER LINE IS HORIZ OR VERTICAL
      IF(X1.EQ.X2) GOTO 20
C           LINE IS HORIZONTAL
      IFLAG = 1
      GOTO 25
C           LINE IS VERTICAL
   20 IFLAG = 2
   25 CONTINUE
      II = 1
      CALL INCLUS (IFLAG,X1,Y1,X2,Y2,Z1,Z2,TS,II,IFNO)
C           ALL WINDOWS OF SPACE TS MUST BE DELETED
      IF(DELETE.EQ. 0.) GOTO 27
      X1 = 0.
      X2 = 0.
      Y1 = 0.
      Y2 = 0.
      Z1 = 0.
      Z2 = 0.
   27 CALL INPUTW (X1,X2,Y1,Y2,Z1,Z2,TS(1),IR)
      CALL AREAG1 (X1,Y1,Z1,X2,Y2,Z2,TS(1),IFNO(1),DELETE)
      KK = (TS(1)-1)*6+1
      CALL ORIGIN (S(KK+2),HH,Y,FF)
      CALL SYMBOL (X1,Y1,1.4,3,0.0,-1)
      CALL PLOT (X2,Y2,2)
      CALL SYMBOL (X2,Y2,1.4,3,0.0,-1)
      READ (1,120) T
      IF(T.EQ.1) GOTO 40
   30 CONTINUE
   40 RETURN
  100 FORMAT(4F10.2)
  120 FORMAT(I1)
  130 FORMAT(2F4.0)
  140 FORMAT(F3.0)
      END
```

```
      SUBROUTINE INPUTW (X1,X2,Y1,Y2,Z1,Z2,N,IR)
C           SUBROUTINE INPUTW STORES THE COORD
C           DATA OF EACH WINDOW
C           THE MAX VALUE OF IR DETERMINES THE
C           MAX NUMBER OF WINDOWS PER SPACE
C           N IS SPACE REF NUMBER
      REAL LMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON WALL(30),DIST(30),TIME(50),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(50)
      COMMON ILLMN,ILLMT,DFINT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      K = (N-1)*6+1
      W(IR,K  ) = X1
      W(IR,K+1) = Y1
      W(IR,K+2) = Z1
      W(IR,K+3) = X2
      W(IR,K+4) = Y2
      W(IR,K+5) = Z2
      RETURN
      END
```

```
      SUBROUTINE AREAG1 (X1,Y1,Z1,X2,Y2,Z2,N,IFNO,DELETE)
C          SUBROUTINE AREAG1 CALCULATES AND STORES
C          THE AREA OF GLASS ON EACH FACE OF EACH SPACE
      REAL LUMEN(20),ILLHT(20),ILLMA(20),ILLMN(20)
      COMMON WAIT(30),DIST(30),TIME(50),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(50)
      COMMON ILLIN,ILLOT,DFIDT(20),AREA(6,20)
      COMMON AG1(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),H(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      IF(X1.EQ.X2) GOTO 10
      IF(DELETE.EQ.0) GOTO 5
      AG1(IFNO,N) = AG1(IFNO,N)-ABS((Z1-Z2)*(X1-X2))
      GOTO 20
    5 AG1(IFNO,N) = AG1(IFNO,N)+ABS((Z1-Z2)*(X1-X2))
      GOTO 20
   10 IF(DELETE.EQ.0.) GOTO 15
      AG1(IFNO,N) = AG1(IFNO,N)-ABS((Z1-Z2)*(Y1-Y2))
      GOTO 20
   15 AG1(IFNO,N) = AG1(IFNO,N)+ABS((Z1-Z2)*(Y1-Y2))
   20 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SD (TS,DELETE,HH,Y,FF)
C           SUBROUTINE SD ALLOWS INPUT OF DOORS. A
C           DOOR IS DEFINED BY TWO DIAGONALLY OPPOSITE
C           CORNERS OF A RECTANGLE.
      INTEGER TS(2)
      INTEGER T,H
      REAL LUMEN(20),ILLHT(20),ILLMA(20),ILLMN(20)
      DIMENSION IFNO(2)
      COMMON WAIT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLMN,ILLHT,DFIHT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      Z1 = 0.
      DO 30 IR = 1,10
      READ  (1,130) X1,Y1
      READ  (1,130) X2,Y2
      READ  (1,120) I
      IF(H.EQ.0) GOTO 15
C           FLOOR LEVEL
      READ  (1,140) Z1
      ZZ1 = Z1
   15 CONTINUE
      READ  (1,140) Z2
      IF(DELETE.EQ.1.) Z1=ZZ1
      Z2 = Z2+Z1
C           TEST WHETHER LINE IS HORIZ OR VERTICAL
      IF(X1.EQ.X2) GOTO 20
C           LINE IS HORIZONTAL
      IFLAG = 1
      GOTO 25
C           LINE IS VERTICAL
   20 IFLAG = 2
   25 CONTINUE
      CALL INCLUS (IFLAG,X1,Y1,X2,Y2,Z1,Z2,TS,2,IFNO)
C           ALL DOORS OF SPACE TS MUST BE DELETED
      IF(DELETE.EQ.0.) GOTO 27
      X1 = 0.
      X2 = 0.
      Y1 = 0.
      Y2 = 0.
      Z1 = 0.
      Z2 = 0.
   27 CALL INPUTD (X1,X2,Y1,Y2,Z1,Z2,TS(1),IR)
      CALL INPUTD (X1,X2,Y1,Y2,Z1,Z2,TS(2),IR)
      KK = (TS(1)-1)*6+1
      CALL ORIGIN (S(KK+2),HH,Y,FF)
      CALL SYMBOL (X1,Y1,1.4,3,0.0,-1)
      CALL PLOT (X2,Y2,2)
      CALL SYMBOL (X2,Y2,1.4,3,0.0,-1)
      READ  (1,120) T
      IF(T.EQ.1) GOTO 40
   30 CONTINUE
   40 RETURN
  100 FORMAT(4F10.2)
  120 FORMAT(I1)
  130 FORMAT(2F4.0)
  140 FORMAT(F3.0)
      END
```

```
      SUBROUTINE INPUTD (X1,X2,Y1,Y2,Z1,Z2,N,IR)
C             SUBROUTINE INPUTD STORES THE COORD
C             DATA OF EACH DOOR
C             THE MAX VALUE OF IR DETERMINES THE
C             MAX NUMBER OF DOORS PER SPACE
C             N IS SPACE REF NUMBER.
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON MAIT(50),DIST(50),TIME(59),SIDE1(50)
      COMMON SIDE2(50),SIDE3(50),XYZ(90),MODE(59)
      COMMON ILLMA,ILLMT,DFINT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,12),J(10,120),REFS(6,20)
      K = (N-1)*5+1
      D(IR,K  ) = X1
      D(IR,K+1) = Y1
      D(IR,K+2) = Z1
      D(IR,K+3) = X2
      D(IR,K+4) = Y2
      D(IR,K+5) = Z2
      RETURN
      END
```

```
      SUBROUTINE INCLUS (IFLAG,X1,Y1,X2,Y2,Z1,Z2,TS,II,IFNO)
C           SUBROUTINE INCLUS TESTS THE FACES OF
C           EACH SPACE FOR INCLUSION OF THE LINE
C           X1,Y1 - X2,Y2. II IS SET TO EQUAL 1 IF
C           LINE REPRESENTS A WINDOW (INCLUDED IN
C           ONLY ONE SPACE) OR 2 IF LINE REPRESENTS
C           A GAP OR DOOR. IF WALL THICKNESSES ARE
C           TO BE ALLOWED THE LINE MUST BE CHECKED
C           FOR INCLUSION WITHIN A TOLLERANCE.
      INTEGER TS(2)
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      DIMENSION IFNO(2)
      COMMON WALT(30),DIST(30),TIME(50),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(50)
      COMMON ILLMP,ILLMT,DFINT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      GOTO (10,30),IFLAG
C           TEST AGAINST ALL HORIZONTAL FACES
   10 N = 0
      I = 0
   15 N = N+1
      K = (N-1)*6+1
      IF(Z1.LT.S(K+2).OR.Z2.GT.S(K+5)) GOTO 15
      IF(Y1.NE.S(K+1)) GOTO 25
      B = (X1+X2)/2
      C = ((S(K+3)+S(K))/2)
      A = ABS(B-C)
      B = ABS(X1-X2)/2
      C = ABS(S(K+3)-S(K))/2
      IF(A+B.GT.C) GOTO 25
      I = I+1
      TS(I) = N
      IFNO(I) = 3
      IF((.EQ.II) GOTO 100
   25 IF(Y1.NE.S(K+4)) GOTO 15
      B = (X1+X2)/2
      C = ((S(K+3)+S(K))/2)
      A = ABS(B-C)
      B = ABS(X1-X2)/2
      C = ABS(S(K+3)-S(K))/2
      IF(A+B.GT.C) GOTO 15
C           TS STORES SPACE REF NUMBER
      I = I+1
      TS(I) = N
      IFNO(I) = 1
      IF(I.EQ.II) GOTO 100
      GOTO 15
C           TEST AGAINST VERTICAL FACES
   30 N = 0
      I = 0
   35 N = N+1
      K = (N-1)*6+1
      IF(Z1.LT.S(K+2).OR.Z2.GT.S(K+5)) GOTO 35
      IF(X1.NE.S(K+3)) GOTO 45
      B = (Y1+Y2)/2
      C = ((S(K+4)+S(K+1))/2)
      A = ABS(B-C)
      B = ABS(Y1-Y2)/2
      C = ABS(S(K+4)-S(K+1))/2
      IF(A+B.GT.C) GOTO 45
```

```
C             TS STORES SPACE REF. NUMBER
      I = I+1
      TS(I) = 4
      IFIO(I) = 2
      IF(I.EQ.II) GOTO 100
   45 IF(X1.NE.S(K)) GOTO 35
      B = (Y1+Y2)/2
      C = ((S(K+4)+S(K+1))/2)
      A = ABS(B-C)
      B = ABS(Y1-Y2)/2
      C = ABS(S(K+4)-S(K+1))/2
      IF(A+B.GT.C) GOTO 35
C             TS STORES SPACE REF. NUMBER
      I = I+1
      TS(I) = 8
      IFIO(I) = 4
      IF(I.EQ. II) GOTO 100
      GOTO 35
  100 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SR (IFLAG)
C     SUBROUTINE SR ALLOWS INPUT OF REFLECTANCE
C           VALUES FOR ROOM SURFACES.
      INTEGER T
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON WALT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLMN,ILLMT,DFLMT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(11,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      IFLAG = 0
   10 READ  (1,110) N,R1,R2,R3,R4,RF,RC
      CALL REFCT (R1,R2,R3,R4,RF,RC,N)
      READ  (1,120) T
      IF(T.EQ.0) GOTO 10
      RETURN
  110 FORMAT(I2,5F3.1)
  120 FORMAT(I1)
      END
```

```
      SUBROUTINE REFLCT (R1,R2,R3,R4,RF,RC,N)
C           SUBROUTINE REFLCT STORES THE REFLECTANCE
C           OF EACH INTERNAL SURFACE OF SPACE N.
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON DIST(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),NODE(59)
      COMMON ILLIN,ILLOT,DEFIT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON STGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON P(10,120),H(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      REFS(1,N) = R1
      REFS(2,N) = R2
      REFS(3,N) = R3
      REFS(4,N) = R4
      REFS(5,N) = RF
      REFS(6,N) = RC
      RETURN
      END
```

```
      SUBROUTINE SP (FF,SCALE,Y,H)
C           SUBROUTINE SP PLOTS, ON THE CALCOMP
C           GRAPH PLOTTER, NUMBERED SPACES, TOGETHER
C           WITH WINDOWS DOORS AND GAPS, AS DEFINED
C           BY SUBROUTINES SS,SW,SD AND SG RESPECTIVELY
      INTEGER SCALE
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON WAIT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLMA,ILLMT,DEFIT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
C           NEW PAGE
      POINT = SCALE*0.25
      CALL PLOT (POINT,0.0,-3)
      H = 100.0
      SS = (-1.)
      CALL ORIGIN (SS,H,Y,FF)
      CALL SCREEN (FF)
      N = 0
   10 N = N+1
      K = (N-1)*6+1
      CALL ORIGIN (S(K+2),H,Y,FF)
      CALL PLOT (S(K),S(K+1),3)
      CALL PLOT (S(K+3),S(K+1),2)
      CALL PLOT (S(K+3),S(K+4),2)
      CALL PLOT (S(K),S(K+4),2)
      CALL PLOT (S(K),S(K+1),2)
      CALL NUMBR (S(K),S(K+1),S(K+3),S(K+4),N)
      I = S(K+6)
      IF(I.GT.0) GOTO 10
      H = 100.0
      DO 30 I = 1,N
      K = (I-1)*7+1
      KK= (I-1)*6+1
      CALL ORIGIN (S(KK+2),H,Y,FF)
      DO 20 IR = 1,5
      IF(G(IR,K+1).LE.0) GOTO 20
C           PLOT GAPS
      CALL SYMBOL (G(IR,K+1),G(IR,K+2),1.4,3,0.0,-1)
      CALL PLOT (G(IR,K+4),G(IR,K+5),2)
      CALL SYMBOL (G(IR,K+4),G(IR,K+5),1.4,3,0.0,-1)
   20 CONTINUE
      K = (I-1)*6+1
      DO 25 IR = 1,10
      IF(D(IR,K).LE.0) GOTO 22
C           PLOT DOORS
      CALL SYMBOL (D(IR,K),D(IR,K+1),1.4,3,0.0,-1)
      CALL PLOT (D(IR,K+3),D(IR,K+4),2)
      CALL SYMBOL (D(IR,K+3),D(IR,K+4),1.4,3,0.0,-1)
   22 CONTINUE
      IF(W(IR,K).LE.0) GOTO 25
C           PLOT WINDOWS
      CALL SYMBOL (W(IR,K),W(IR,K+1),1.4,3,0.0,-1)
      CALL PLOT (W(IR,K+3),W(IR,K+4),2)
      CALL SYMBOL (W(IR,K+3),W(IR,K+4),1.4,3,0.0,-1)
   25 CONTINUE
   30 CONTINUE
      RETURN
  100 FORMAT(4F10.2)
      END
```

```
      SUBROUTINE ORIGIN (S,H,Y,F)
C           SUBROUTINE ORIGIN RESETS THE ORIGIN ON
C           THE CALCOMP PLOTTER TO THE APPROPRIATE
C           PAGE, DETERMINED BY THE FLOOR LEVEL S.
      Y = (-Y)
      CALL FACTOR (1.)
      CALL PLOT (0.0,Y,-3)
      IF(S.LE.0.) GOTO 20
      IF(S.LE.H)  GOTO 10
      Y = 19.0
      GOTO 30
   10 Y = 9.5
      H = S
      GOTO 30
   20 Y = 0.0
   30 CALL PLOT (0.0,Y,-3)
      CALL FACTOR (F)
      RETURN
      END
```

```
      SUBROUTINE SCREEN (F)
C           SUBROUTINE SCREEN PLOTS A SERIES OF THREE
C           PAGE OUTLINES VERTICALLY ON THE CALCOMP
C           PLOTTER
      CALL FACTOR (1.)
      DO 10 I = 1,3
      CALL PLOT (0.0,0.5,-3)
      CALL PLOT (0.0,9.0,3)
      CALL PLOT (0.0,9.0,2)
      CALL PLOT (9.0,9.0,2)
      CALL PLOT (9.0,0.0,2)
      CALL PLOT (0.0,0.0,-2)
   10 CONTINUE
      CALL PLOT (0.0,-28.5,-3)
      CALL FACTOR (F)
      RETURN
      END
```

```
      SUBROUTINE NUMBR (X1,Y1,X2,Y2,I)
C             SUBROUTINE NUMBR WRITES THE SPACE
C             NUMBER IN THE CENTRE OF EACH SPACE
C             I IS SPACE REF. NUMBER
C             ESTABLISH CENTRE
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON WAIT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLIN,ILLMT,OFILT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATB(20),ARH(20)
      X = (X1+X2)/2-0.3
      Y = (Y1+Y2)/2
C             SET IN ALPHA MODE
C     *
C     *
C             MOVE ALPHA CURSOR TO X,Y
C     *
C     *
C             WRITE N
      FPI = I
      CALL NUMBER (X,Y,0.7,FPI,0.0,-1)
C     *
C     *
C             RETURN GRAPHICS CURSOR
      RETURN
 250  FORMAT(I2,2F10.2)
      END
```

```
      SUBROUTINE SK (ILSKY)
C             SKY ILLUMINANCE
      READ  (1,210) ILSKY
      RETURN
 210  FORMAT(F7.0)
      END
```

```
      SUBROUTINE ST (TRANS)
C             TRANSMITTANCE OF GLASS
      READ  (1,220) TRANS
      RETURN
 220  FORMAT(F3.2)
      END
```

```
      SUBROUTINE SX (DELETE)
C             SUBROUTINE SX FLAGS DELETE FOR OTHER
C             ROUTINES.
      DELETE = 1.
      RETURN
      END
```

```
      SUBROUTINE PPLOTS (X1,X2,Y1,Y2)
C             SUBROUTINE PPLOTS PLOTS SPACES IN PLAN
      CALL PLOT (X1,Y1,3)
      CALL PLOT (X2,Y1,2)
      CALL PLOT (X2,Y2,2)
      CALL PLOT (X1,Y2,2)
      CALL PLOT (X1,Y1,2)
 100  FORMAT(4F10.2)
      RETURN
      END
```

```
      SUBROUTINE SL
C           SUBROUTINE SL ALLOWS DESCRIPTION OF
C           LUMINAIRES. INPUT REQUIRED IS ROOM NUMBER,
C           NUMBER OF LUMINAIRES, DESIGN LUMENS PER
C           LUMINAIRE, AND LIGHT OUTPUT RATIO PER
C           LUMINAIRE.
      REAL LUMENS,LORTO
      INTEGER T
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON NAME(30),DIST(5),TIME(50),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(50)
      COMMON ILLM,ILLMT,DEFMT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATB(20),ARM(20)
 10   READ  (1,160) T,NUMBR,LUMENS,LORTO
      LUMEN(T) = LUMEN(T)+LUMENS*NUMBR*LORTO/100.
      READ  (1,120) T
      IF(T .EQ. 0) GOTO 10
      RETURN
 160  FORMAT(2I2,F5.0,F3.0)
 120  FORMAT(I1)
      END
```

```
      SUBROUTINE SF (DELETE)
C             SUBROUTINE SF ALLOWS DESCRIPTION OF
C             OBSTRUCTIONS TO WINDOWS. INPUT REQUIRED
C             IS ROOM NUMBER, FACE NUMBER (EACH ROOM
C             HAS FOUR FACES 1,2,3,4; N,E,S,W RESPECTIVELY)
C             T IS USED TO TERMINATE COMMAND.
      INTEGER T
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON WAIT(30),DIST(3),TIME(50),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(50)
      COMMON ILLMA,ILLMT,OFFMT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATP(20),ARH(20)
C             IF DELETE,ZERO ARRAY
      IF(DELETE .EQ. 1.) GOTO 20
C             ROOM NUMBER
   10 READ  (1,150) N
      IN = (N-1)*3+1
      F(IN) = N
C             FACE NUMBER AND ANGLE
      READ  (1,200) F(IN+1),F(IN+2)
      READ  (1,120) T
      IF(T .EQ. 0) GOTO 10
      GOTO 30
   20 DO 30 IN = 1,60
      F(IN)=0.
   30 CONTINUE
      RETURN
  120 FORMAT(I1)
  150 FORMAT(I2)
  200 FORMAT(F2.0,F3.0)
      END
```

```
      SUBROUTINE DAYFO (I,DFOUT)
C           SUBROUTINE DAYFO APPROXIMATES THE DAYLIGHT
C           FACTOR (DFOUT) ON THE OUTSIDE SURFACE OF
C           A WINDOW FOR VARIOUS ANGLES OF OBSTRUCTION
C           ABOVE THE HORIZONTAL. I IS ANGLE OF
C           OBSTRUCTION (RANGE 10-80 DEG. IN STEPS
C           OF 10).
      I=I/10
      GOTO (1,2,3,4,5,6,7,8),I
    1 DFOUT = .4
      RETURN
    2 DFOUT = .36
      RETURN
    3 DFOUT = .3
      RETURN
    4 DFOUT = .25
      RETURN
    5 DFOUT = .19
      RETURN
    6 DFOUT = .15
      RETURN
    7 DFOUT = .12
      RETURN
    8 DFOUT = .1
      RETURN
      END
```

```
      SUBROUTINE ROUTES (ITOTL,I,FF,YY)
C           SUBROUTINE ROUTES ALLOWS INPUT OF A
C           ROUTE. THE ROUTE IS A SERIES OF STRAIGHT
C           LINES CONNECTING POINTS IN SPACE. THE
C           POINTS MUST BE DEFINED BY THEIR 3-D
C           CARTESIAN COORDS (UNITS ARE METRES).
C           A MODE OF TRAVEL BETWEEN EACH PAIR OF
C           POINTS MUST BE DEFINED
      REAL LMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON WAIT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLMN,ILLMT,DFINT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),V(10,120),REFS(6,20)
      COMMON ATA(20),ATN(20),ARH(20)
      H = 100.0
      KWAIT = 0
      KOUNT = 0
   10 KOUNT = KOUNT+1
      N = 3*KOUNT-2
      WRITE (3,1200)
      READ  (1,1210)XYZ(N),XYZ(N+1),XYZ(N+2),MODE(KOUNT+KWAIT)
      CALL VPSPC (1,XYZ(N),XYZ(N+1),XYZ(N+2),ISP)
      WRITE (3,999) ISP
  999 FORMAT(I3)
      CALL ORIGIN (S((ISP*6-5)+2),H,YY,FF)
      IF(KOUNT.GE.1) GOTO 15
      CALL PLOT (XYZ(N),XYZ(N+1),3)
      GOTO 17
   15 CALL PLOT (X,Y,3)
      CALL PLOT (XYZ(N),XYZ(N+1),2)
   17 X = XYZ(N)
      Y = XYZ(N+1)
      IF(MODE(KOUNT+KWAIT).NE.1.AND.MODE(KOUNT+KWAIT).NE.2) GOTO 20
      CALL SYMBOL (XYZ(N),XYZ(N+1),1.4,11,0.0,-1)
      KWAIT = KWAIT+1
      X = XYZ(N)
      Y = XYZ(N+1)
      WRITE (3,1220)
      READ  (1,1230) WAIT(KOUNT),MODE(KOUNT+KWAIT)
C           IF MODE = 10 STOP INPUT
   20 IF(MODE(KOUNT+KWAIT) .NE. 10) GOTO 10
      ITOTL = KOUNT-1
      CALL MOVE (ITOTL)
      RETURN
 1200 FORMAT(12H INPUT X Y Z MODE)
 1210 FORMAT(3F4.1,I2)
 1220 FORMAT(36H TIME IN MINS AND MODE TO NEXT POINT)
 1230 FORMAT(F4.2,I2)
      END
```

```
      SUBROUTINE SI (IFLAG)
C           SUBROUTINE SI IS AN ALTERNATIVE TO
C           SPECIFYING REFLECTANCES OF SURFACES,
C           LUMINAIRE AND DAYLIGHT DATA. THE ROUTINE
C           ALLOWS DIRECT STATEMENT OF AVERAGE
C           LUMINANCE FOR ANY SPACE
      INTEGER T
      REAL LUMEN(20),ILLHT(20),ILLMA(20),ILLMN(20)
      COMMON WAIT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),NODE(59)
      COMMON ILLIN,ILLMT,DFILT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(5,20)
      COMMON ATA(20),ATR(20),ARH(20)
      IFLAG = 1
      READ  (1,210) N
      DO 10 I = 1,N
      READ  (1,220) ILLHT(I)
   10 CONTINUE
  210 FORMAT(I2)
  220 FORMAT(F5.1)
      RETURN
      END
```

```
      SUBROUTINE PRDTIC (IFLAG,ITOTL,N,YY,FF,N,SCALE)
C           SUBROUTINE PRDTIC CONTROLS THE PREDICTION
C           OF AVERAGE INTERNAL ILLUMINANCE FOR EACH
C           SPACE AND THE PREDICTION OF BRIGHTNESS
      DIMENSION AREF(20)
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON WATT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLIN,ILLMT,DFIMT(20),AREA(6,20)
C           FOR EACH INTERVAL ALONG THE ROUTE.
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      IF(IFLAG.EQ.1) GOTO 100
      N = 0
   20 N = N+1
      K = (N-1)*6+1
      CALL AREAS (N)
      IF(S(K+6).NE.0) GOTO 20
      CALL SIGMX (N,AREF)
      DO 30 I = 1,N
      ILLIN(I)= LUMEN(I)/SIGMA(I)
   30 CONTINUE
      DO 50 I = 1,N
      ILLMN(I)= 0
      DO 40 II= 1,4
      N1 = (I-1)*6+1
      IF(F(N1).NE.I) GOTO 35
      IF(F(N1+1).NE.II) GOTO 35
      CALL DAYFO (F(N1+2),DFOUT)
      GOTO 38
   35 DFOUT = 0.44
   38 ILLMN(I) = ILLIN(I)+(TRANS*AGLAS(II,I)*DFOUT/SIGMA(I))
     1*(ILSKY/100)
   40 CONTINUE
      DFIMT(I) = (ILLMN(I)*100)./ILSKY
   50 CONTINUE
      DO 60 I = 1,N
      ILLMT(I)= ILLMN(I)+ILLMA(I)
      ILLMT(I) = ILLMT(I)*AREF(I)/3.1415927
   60 CONTINUE
C           INITIALISE VARIABLES
  100 TIME = 0.
      RINC = 1.
      KWAIT= 0.
      KSEC = 0.
      KINC = 0.
      ISTI = 0
      CALL SP (FF,SCALE,YY,N)
C           PRINT OUT INTERVAL (SECS)
      WRITE (5,1270)
      READ   (1,1280) INC
      WRITE (5,1285)
      READ   (1,1290) IV
      X = XYZ(1)
      Y = XYZ(2)
      Z = XYZ(3)
      CALL VPSPC (N,X,Y,Z,ISPACE)
      Q1 = ILLMT(ISPACE)
      CALL TROLRD (Q1)
      DO 200 KOUNT = 1,ITOTL
      KK = KOUNT+KWAIT
```

```
      MODEK = MODE(KK)
      IF(MODEK.NE.1.AND.MODEK.NE.2) GOTO 210
      I = WAIT(KOUNT)*60
      INCT = INC
      IF(I.LT.INCT) INCT=I
      CALL VPSPC (N,X,Y,Z,ISPACE)
      Q2 = ILLMT(ISPACE)
      CALL TROLNB (Q2)
      KN = (ISPACE-1)*6+1
      CALL ORIGIN (S(KN+2),N,YY,FF)
      CALL SYMBOL (X,Y,1.0,11,0.0,-1)
      DO 220 KT = 1,I,INCT
      CALL CONES (Q1,Q2,INCT,PGMNT)
C            PGMNT IS FRACTION OF PIGMENT BLEACHED
      WRITE (3,250) X,Y,PGMNT,ILLMT(ISPACE)
      CALL VERBLB (ILLMT(ISPACE),PGMNT,IV,ISW)
      PGMNT = 1-PGMNT
      Q1 = (0.0077-0.0077*PGMNT)/(64.E-08*PGMNT)
 220  CONTINUE
      KWAIT = KWAIT+1
      KK = KOUNT+KWAIT
 210  TIMEK = TIME(KK)
      KTIM = TIMEK+0.5
      MODEK = MODE(KK)
      IF(MODEK.EQ.10) GOTO 200
      CALL VRIABL (KOUNT,X0,X1,Y0,Y1,Z0,Z1,XABS0,XABS1,
     1             YABS0,YABS1,ZABS0,ZABS1)
      INCT = INC
      IF(KTIM.LT.INCT) INCT=KTIM
      DO 200 K = 1,KTIM,INCT
      CALL INTRVL (X0,X1,KOUNT,KTIM,K,Y0,Y1,Z0,Z1,X,Y,Z)
      CALL VPSPC  (N,X,Y,Z,ISPACE)
      Q2 = ILLMT(ISPACE)
      CALL TROLNB (Q2)
      CALL CONES  (Q1,Q2,INCT,PGMNT)
C            PGMNT IS FRACTION OF PIGMENT BLEACHED
      KN = (ISPACE-1)*6+1
      CALL ORIGIN (S(KN+2),N,YY,FF)
      CALL SYMBOL (X,Y,1.0,11,0.0,-1)
      WRITE (3,250) X,Y,PGMNT,ILLMT(ISPACE)
      CALL VERBLB (ILLMT(ISPACE),PGMNT,IV,ISW)
      PGMNT = 1.-PGMNT
      Q1 = (0.0077-0.0077*PGMNT)/(64.E-08*PGMNT)
 200  CONTINUE
      RETURN
 250  FORMAT(4F10.4)
 1270 FORMAT(19H P/O PERIOD IN SECS)
 1280 FORMAT(I2)
 1285 FORMAT(5H VOTE)
 1290 FORMAT(I1)
      END
```

```
      SUBROUTINE TROLND (TROLM)
C           SUBROUTINE TROLND CALCULATES THE RETINAL
C           ILLUMINATION LEVEL (IN EFFECTIVE TROLANDS)
C           FOR A LUMINANCE TROLM.
C           CHANGES OF PUPIL AREA DUE TO THE STILES-
C           CRAWFORD EFFECT AND LUMINANCE ARE TAKEN
C           INTO ACCOUNT.
      DPUPL = 5.0-3.0*TANH(0.4*ALOG(TROLM))
      APUPL = 0.7854*DPUPL**2.*(1.-0.085*(DPUPL**2.
     1        /3.)+0.002*(DPUPL**4./48))
      TROLM = TROLM*APUPL
      RETURN
      END
```

```
      SUBROUTINE CONES (Q1,Q2,INCT,PGINT)
C           SUBROUTINE CONES CALCULATES THE FRACTION
C           OF PIGMENT WITHIN THE CONES, IN THE
C           BLEACHED STATE, AFTER TIME INCREMENT
C           INCT, WHERE THE RETINAL ILLUMINANCE TO
C           WHICH THE CONES ARE ADAPTED IS Q1 (IN
C           TROLANDS) AND THE RETINAL ILLUMINANCE
C           TO WHICH THE CONES ARE ADAPTING IS Q2
C           (IN TROLANDS).
      DO 10 ITIME = 1,INCT
      TIMES = ITIME
      PGINT = 1.-(0.0077/(0.0077+64.E-08*Q2))*
     1          (0.0077*64.E-03*(Q1-Q2)/
     1          ((0.0077+64.E-03*Q1)*(0.0077+64.E-03*
     1          Q2)))*EXP(-TIMES*(0.0077+64.E-08*Q2))
   10 CONTINUE
      DPDT = (-0.0077*64.E-03*(Q1-Q2)/(0.0077+64.E-08*Q1))
     1*EXP(-TIMES*(0.0077+64.E-03*Q2))
      WRITE (3,100) DPDT
  100 FORMAT(1H ,39 DPDT = ,F10.8)
      RETURN
      END
```

```
      SUBROUTINE SIGMX (N,AREF)
C           SUBROUTINE SIGMX CALCULATES THE SUM OF
C           ALL SURFACES TIMES RESPECTIVE REFLECTANCES
C           FOR EACH ROOM. N IS THE TOTAL NUMBER
C           OF ROOMS.
      DIMENSION AREF(20)
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON WATT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLMA,ILLMT,DEIMT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      DO 5 M = 1,N
      SIGMA(M)=0.
      AREF(M) = 0.
    5 CONTINUE
      DO 20 M = 1,N
      DO 10 I = 1,6
      SIGMA(M)= SIGMA(M)+(AREA(I,M)*(1.-REFS(I,M)))
      AREF(M) = AREF(M)+AREA(I,M)*REFS(I,M)
   10 CONTINUE
   20 CONTINUE
      DO 40 M = 1,N
      DO 30 I = 1,4
      SIGMA(M) = SIGMA(M)+(AGLAS(I,M)*0.9)
      AREF(M) = AREF(M)+(AGLAS(I,M)*0.1)
   30 CONTINUE
   40 CONTINUE
      DO 50 M = 1,N
      AREAT = 0.
      DO 60 I = 1,6
      AREAT = AREAT+AREA(I,M)
   60 CONTINUE
      DO 70 I = 1,4
      AREAT = AREAT+AGLAS(I,M)
   70 CONTINUE
      AREF(M) = AREF(M)/AREAT
   50 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE VERBLB (X1,Y1,IV,ISW)
      IF(ISW .NE. 0) GOTO 101
      ISW = 1
      X = X1
      Y = Y1
      Z = IV
      X = ALOG10(X)
  101 CONTINUE
      X1= ALOG10(X1)
      A = 10.**X
      B = 10.**X1
      IF(A.LT.B) GOTO 110
      IF(A.GT.B) GOTO 210
      GOTO 150
  210 B = B+B/10.
      IF(A.GT.B) GOTO 275
      GOTO 150
  275 R = X/X1
      Z1 = R/1.4
      GOTO 310
  110 B = B-B/10.
      IF(A.LT.B) GOTO 175
  150 Z1 = Z
      GOTO 310
  175 R = X1/X
      Z1 = R/1.4
  310 CONTINUE
C     Z1 = Z*(16*(Y1-Y)-0.0425*(X1-X))
      N = Z1+0.5
      IF(N .LT. 1) GOTO 20
      IF(N .GT. 7) GOTO 30
      GOTO(1,2,3,4,5,6,7),N
    1 WRITE (3,100)
  100 FORMAT(10H VERY DARK)
      GOTO 900
    2 WRITE (3,200)
  200 FORMAT(5H DARK)
      GOTO 900
    3 WRITE (3,300)
  300 FORMAT(4H DIM)
      GOTO 900
    4 WRITE (3,400)
  400 FORMAT(13H SATISFACTORY)
      GOTO 900
    5 WRITE (3,500)
  500 FORMAT(6H LIGHT)
      GOTO 900
    6 WRITE (3,600)
  600 FORMAT(7H BRIGHT)
      GOTO 900
    7 WRITE (3,700)
  700 FORMAT(12H VERY BRIGHT)
      GOTO 900
   20 WRITE (3,22)
   22 FORMAT(20H OFF BOTTOM OF SCALE)
      GOTO 900
   30 WRITE (3,33)
   33 FORMAT(17H OFF TOP OF SCALE)
  900 CONTINUE
      X = X1
      Y = Y1
      Z = Z1
      RETURN
      END
```

```
      SUBROUTINE THERML (ITOTL,WN,FF,SCALE,YY,H)
C           SUBROUTINE THERML CONTROLS THE PREDICTION
C           OF THERMAL SENSATION FOR EACH INTERVAL
C           ALONG THE ROUTE
      DIMENSION COEF(32),TSK(13),DISC(13)
      DIMENSION START (6,7)
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON WAIT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLMN,ILLMT,DFIMT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      COMMON T(500),P(500)
      DATA START/29.0,37.0,0.24,1.8,12.51,4.49,
     1            30.2,37.0,0.21,2.17,12.48,4.62,
     1            31.9,37.02,0.13,4.31,12.64,4.76,
     1            33.9,37.03,0.09,10.23,16.21,4.9,
     1            34.7,37.06,0.07,15.03,29.4,5.06,
     1            35.3,37.1,0.061,21.51,42.63,5.2,
     1            35.8,37.16,0.056,29.93,56.74,5.3/
      DATA COEF/58.2,0.0,2.9,0.696,69.8,0.0,3.1,0.725,
     1116.3,0.0,5.00,0.725,221.0,0.0,11.6,0.725,
     1422.35,52.54,5.0,0.725,782.28,53.15,11.6,0.725,
     1199.64,-52.54,0.0,0.725,369.33,-53.15,11.6,0.725/
      DATA DISC/-4.0,-4.1,-3.0,-3.1,-2.0,-2.1,-1.68,
     1-1.25,-0.95,-0.7,-0.5,-0.3,0.0/
      DATA TSK/28.0,28.5,29.0,29.5,30.0,30.5,31.0,31.5,
     132.0,32.5,33.0,33.5,34.0/
      SVP(T)=(10.**(23.59051-3.2*ALOG10(T+273.16)+2.4804E-03
     1*(T+273.16)-3142.31/(T+273.16))/1.333)*1000.
      ISW = -1
      TIM=0.
      WRITE (3,1700)
C           INITIALISE VARIABLES
C           PHYSIOLE
      WRITE (3,1500)
      READ  (1,1610) IVOTE
      RVOTE = IVOTE
      VOTE = RVOTE-4
      CALL VERBLT (VOTE,RVOTE,ISW)
      ISW = 1
      TSKO  = START (1,IVOTE)
      ALPHA = START (3,IVOTE)
      TCR   = START (2,IVOTE)
      SKBF  = START (4,IVOTE)
      EV    = START (5,IVOTE)
      CHR   = START (6,IVOTE)
      RINC=1.
      CALL SP (FF,SCALE,YY,H)
C           PRINT OUT INC
      READ  (1,1280) INC
      WRITE (3,1270) INC
      READ  (1,340) BDYH
      WRITE (3,542) BDYH
      READ  (1,340) BDYW
      WRITE (3,344) BDYW
      BDYA=0.00718*BDYW**0.425*BDYH**0.725
      KWAIT=0
      KSEC=0
      KINC=1
      RMOLD=116.3
```

```
      X = XYZ(1)
      Y = XYZ(2)
      Z = XYZ(3)
      CALL VPSPC (NN,X,Y,Z,ISP)
C           CLOTHING
      READ  (1,840) CLO
      WRITE (3,800) CLO
      CLOS=CLO
      WRITE (3,900)
      DO 205 KOUNT = 1,ITOTL
      PPHG = ARH(ISP)*SVP(ATA(ISP))/100.
      RH = ARH(ISP)/100.
      KK=KOUNT+KWAIT
      MODEK=MODE(KK)
      IF(MODEK.NE.1.AND.MODEK.NE.2) GOTO 210
      CALL INIT(COEF,MODEK,RMOLD,CHR,PPHG,ATA(ISP),CLO,ATR(ISP),RM,CHCS,
     1CTC,ERES,CRES,FCL,TO,N)
      I=WAIT(KOUNT)*60
      INCT=INC
      IF(I.LT.INCT) INCT=I
      KN = (ISP-1)*6+1
      CALL ORIGIN (S(KN+2),H,YY,FF)
      CALL SYMBOL (X,Y,1,0,11,0.0,-1)
      DO 220 KT=1,I,INCT
      CALL HUMAN (TSK,DISC,COEF(N),COEF(N+1),COEF(N+2),COEF(N+3),
     1CHR,EV,ALPHA,SKBF,TSKO,TCR,TIM,RINC,CLO,CLOS,ATA(ISP),
     1ATR(ISP),PPHG,
     1BDYA,BDYW,INCT,RM,CHCS,CTC,ERES,CRES,FCL,TO,RH,
     1TSENS,DISCO,PRSW)
      TKINC=KT-1+INCT
      WRITE (3,990) TSENS,DISCO,TKINC,ISP,ATA(ISP),ATR(ISP),RH
      CALL VERBLT (TSENS,RVOTE,ISW)
220   CONTINUE
      KWAIT=KWAIT+1
      KK=KOUNT+KWAIT
210   TIMEK=TIME(KK)
      KTIM=TIMEK+0.5
      MODEK=MODE(KK)
      IF(MODEK.EQ.10) GOTO 230
      CLON=CLO
      IF(MOD(MODEK,2).EQ.0)CLON=0.75*CLO
      CALL INIT(COEF,MODEK,RMOLD,CHR,PPHG,ATA(ISP),CLON,ATR(ISP),RM,CHCS
     1,CTC,ERES,CRES,FCL,TO,N)
      CALL VRIABL (KOUNT,X0,X1,Y0,Y1,Z0,Z1,XABS0,XABS1,YABS0,YABS1,
     1ZABS0,ZABS1)
      INCT=INC
      IF(KTIM.LT.INCT) INCT=KTIM
      DO 200   K   =1,KTIM,INCT
      CALL INTRVL (X0,X1,KOUNT,KTIM,K,Y0,Y1,Z0,Z1,X,Y,Z)
      CALL VPSPC (NN,X,Y,Z,ISP)
      PPHG = ARH(ISP)*SVP(ATA(ISP))/100.
      RH = ARH(ISP)/100.
      CALL HUMAN (TSK,DISC,COEF(N),COEF(N+1),COEF(N+2),COEF(N+3),
     1CHR,EV,ALPHA,SKBF,TSKO,TCR,TIM,RINC,CLO,CLON,ATA(ISP),
     1ATR(ISP),PPHG,
     1BDYA,BDYW,INCT,RM,CHCS,CTC,ERES,CRES,FCL,TO,RH,
     1TSENS,DISCO,PRSW)
      TKINC=K-1+INCT
      WRITE (3,990) TSENS,DISCO,TKINC,ISP,ATA(ISP),ATR(ISP),RH
      CALL VERBLT (TSENS,RVOTE,ISW)
      KN = (ISP-1)*6+1
      CALL ORIGIN (S(KN+2),H,YY,FF)
      CALL SYMBOL (X,Y,1,0,11,0.0,-1)
200   CONTINUE
205   CONTINUE
```

```
230   WRITE (3,1500)
      WRITE (3,1510) ALPHA,SKBF,EV,CHR,RM,TSKO,TCR
800   FORMAT(8H  CLO = ,F5.2)
810   FORMAT(9H     TA = )
820   FORMAT(9H     TR = )
830   FORMAT(9H     RH = )
840   FORMAT(F5.2)
842   FORMAT(8H BDYH = ,F5.2)
844   FORMAT(8H BDYW = ,F5.2)
 900  FORMAT(31H1      TSFHS      DISCO        TIM)
990   FORMAT(1H ,3F10.4,I10,3F10.4)
1200  FORMAT (17H INPUT X Y Z MODE)
1210  FORMAT (3F6.2,I2)
1220  FORMAT (36H TIME IN MINS AND MODE TO NEXT POINT)
1230  FORMAT (F5.2,I2)
1270  FORMAT(22H P/O PERIOD IN SECS = ,I2,/)
1280  FORMAT(I2)
1500  FORMAT(51H       ALPHA       SKBF          EV        CHR          RM,
     1        20H       TSKO        TCR )
1510  FORMAT(7F10.4)
1550  FORMAT(1H0,13HINITIAL STATE/)
1610  FORMAT(I1)
1700  FORMAT(1H1,53X,13HTHERMAL MODEL)
      RETURN
      END
```

```
      SUBROUTINE HUMAN (TSK,DISC,HR,WK,CHC,RTO,CHR,EV,ALPHA,
C           SUBROUTINE PREDICTS THE HUMAN PHYSIOLOGICAL
C           RESPONSE TO A GIVEN THERMAL ENVIRONMENT
C           FOR A GIVEN ACTIVITY, CLOTHING VALUE
C           AND PHYSIQUE.
     1SKBF,TSKO,TCR,TIM,RINC,CLO,CLOS,TA,TR,PPHG,
     1BDYA,BDYW,INCT,RH,CHCS,CTC,ERES,CRES,FCL,TO,RH,
     11SENS,DISCO,PRSW)
      DIMENSION TSK(13),DISC(13)
      REAL HR
      REAL LUMEN(20),ILLHT(20),ILLMA(20),ILLMN(20)
      COMMON WAIT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLHM,ILLMT,DFINT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      COMMON T(500),P(500)
      SVP(T)=(10.**(28.59051-8.2*ALOG10(T+273.16)+2.4804E-03
     1*(T+273.16)-3142.31/(T+273.16))/1.333)*1000.
      TINC=INCT
      VTIM = 60./TINC
  100 CONTINUE
      TCL=TO+FCL*(TSKO-TO)
      FACL=1.+0.25*CLO
      CHR=4.*5.67E-08*((TCL+TO)/2.+273.)**3.*FACL*RTO
      CTC=CHR+CHC
      FCL=1./(1.+0.155*CTC*CLO)
      DRY=CTC*FCL*(TSKO-TO)
      RFCR=RH-ERES-CRES-WK-(5.28+1.163*SKBF)*(TCR-TSKO)
      RFSK=(5.28+1.163*SKBF)*(TCR-TSKO)-DRY-(EV-ERES)
      TCCR=0.97*(1.-ALPHA)*BDYW
      TCSK=0.97*ALPHA*BDYW
      DTCR=(RFCR*BDYA)/TCCR
      DTSK=(RFSK*BDYA)/TCSK
      DTIM=(1./60.)/VTIM
      U=ABS(DTSK)
      IF(U-(0.1/VTIM))5,10,10
   10 DTIM = (0.1/VTIM)/(U*60.)
    5 CONTINUE
      U=ABS(DTCR)
      IF(U-(0.1/VTIM))105,110,110
  110 DTIM = (0.1/VTIM)/(U*60.)
  105 CONTINUE
      TIM=TIM+DTIM
      TSKO=TSKO+DTSK*DTIM
      TCR=TCR+DTCR*DTIM
      SKSIG=TSKO-34.0
      IF(SKSIG)15,15,20
   15 COLDS=(-SKSIG)
      WARMS=0.0
      GOTO 25
   20 COLDS=0.0
      WARMS=SKSIG
   25 CONTINUE
      CRSIG=TCR-37.0
      IF(CRSIG)30,30,35
   30 COLDC=(-CRSIG)
      WARMC=0.0
      GOTO 40
   35 WARMC=CRSIG
      COLDC=0.0
```

```
      DILAT=150.*PARHC
      STRIC=0.5*COLOS
      SKBF=(6.3+DILAT)/(1.+STRIC)
      REGSW=250.*(ALPHA*SKSIG+(1.-ALPHA)*CRSIG)*EXP(SKSIG/10.7)
      IF(REGSW)45,45,50
   45 REGSW=0
   50 CONTINUE
      ERSW=0.68*REGSW
      FPCL=1./(1.+0.143*CHC*CLO)
      EMAX=2.2*CHC*(SVP(TSKO)-PPHG)*FPCL
      PRSW=ERSW/EMAX
      PWET=0.06+0.94*PRSW
      EDIF=PWET*EMAX-ERSW
      EV=ERES+ERSW+EDIF
      IF(PWET-1.0)60,60,65
   65 EV=ERES+EMAX
      ERSW=EMAX
      EDIF=0.0
      PRSW=1.0
      DRIP=(ERSW-EMAX)/0.68
   60 CONTINUE
      ALPHA=0.0442+0.3509/(SKBF-0.01386)
      RH=AR+19.4*COLOS*CPLDC
      IF (TIM-RINC/(60.*VTIM))100,101,101
  101 CONTINUE
      RINC=RINC+1.
      STORE=RH-CRES-PK-EV-DRY
      PTSH=STORE*BDYA/(BDYW*0.97)
      CHRS=CHR
      CTCS=CHRS+CHCS
      FCLS=1./(1.+0.155*CTCS*CLOS)
      FPCLS=1./(1.+0.143*CHCS*CLOS)
      TDEW=(25.3+PPHG)/1.92
      A=CTC*FCL
      B=2.2*1.92*CHC*FPCL
      AS=CTCS*FCLS
      BS=2.2*1.92*CHCS*FPCLS
      TO=(CHR*TR+CHC*TA)/CTC
      STO=(A/AS)*TO+(1.-A/AS)*TSKO
      C=A+PWET*B
      TOH=(A*TO+PWET*B*TDEW)/C
      CS=AS+PWET*BS
      STOH=(C/CS)*TOH+(1.-C/CS)*TSKO
      SET=STOH
   80 TDEW5=(25.3+RH *SVP(SET))/1.92
      STOHS=(AS*SET+PWET*BS*TDEW5)/CS
      ERR=STOH-STOHS
      IF(ERR)70,70,75
   75 SET=SET+0.1
      GOTO 80
   70 CONTINUE
      IF(TSKO .GE. 34.0) GOTO 79
      DO 300 INUM=1,12
      INM1=14-INUM
      INM2=INM1-1
      IF(TSKO .LT. TSK(INM1) .AND. TSKO .GE. TSK(INM2)) GOTO 310
  300 CONTINUE
      DISCO=(-4.7)
      GOTO 80
  310 AVRG=(TSK(INM1)+TSK(INM2))/2.
      IF(TSKO .GE. AVRG) GOTO 320
      DISCO=DISC(INM2)
      GOTO 80
  320 DISCO=DISC(INM1)
      GOTO 80
```

```
79    DISCO=4.7*PRSW
89    TSENS=0.245*SET+0.033*RH *SVP(SET)-6.471
      RETURN
      END
```

```
      SUBROUTINE INIT (COEFF,INDEX,RHOLD,CHR,PPHG,TA,CLO,TR,RM,
     1CHCS,CTC,EBES,CRES,FCL,TO,N)
      DIMENSION COEF(32)
      N=INDEX*4-3
      IF(COEF(N),EQ,RHOLD) GOTO 205
      RM=COEF(N)
      RHOLD=RM
205   CHCS=COEF(N+2)
      CTC=CHR+COEF(N+2)
      EBES=0.0025*RM*(44.-PPHG)
      CRES=0.0012*RM*(59.-TA)
      FCL=1./(1.+0.155*CTC*CLO)
      TO=(CHR*TR+COEF(N+2)*TA)/CTC
      RETURN
      END
```

```
      SUBROUTINE VERBLT (TS1,RV,ISW)
C     SUBROUTINE VERBLT MODIFIES THE PREDICTED
C          RESPONSE ACCORDING TO IR 1/76. THE VALUE
C          IS ROUNDED TO THE NEAREST WHOLE NUMBER
C          ON THE SCALE AND THE VERBAL STATEMENT
C          RELATING TO THIS VALUE IS PRINTED.
      IF(ISW .LT. 0) GOTO 15
      IF(ISW .NE. 0) GOTO 10
      TS2 = RV
      ISW = 1
   10 TS1 = TS1+4
      TS3 = TS1*0.9+TS2*0.45
      TS4 = TS3+0.60*(TS3-TS2)+0.8
      TS2 = TS4
C     TEMPORARY CHECK
      WRITE (3,50) TS4
   50 FORMAT(F10.4)
C     ********
      N=TS4+0.5
      GOTO 17
   15 N = RV+0.5
   17 CONTINUE
      IF(N .LT. 1) GOTO 20
      IF(N .GT. 7) GOTO 30
      GOTO(1,2,3,4,5,6,7),N
    1 WRITE (3,100)
  100 FORMAT(5H COLD)
      GOTO 900
    2 WRITE (3,200)
  200 FORMAT(5H COOL)
      GOTO 900
    3 WRITE (3,300)
  300 FORMAT(14H SLIGHTLY COOL)
      GOTO 900
    4 WRITE (3,400)
  400 FORMAT(8H NEUTRAL)
      GOTO 900
    5 WRITE (3,500)
  500 FORMAT(14H SLIGHTLY WARM)
      GOTO 900
    6 WRITE (3,600)
  600 FORMAT(5H WARM)
      GOTO 900
    7 WRITE (3,700)
  700 FORMAT(4H HOT)
      GOTO 900
   20 WRITE (3,22)
   22 FORMAT(20H OFF BOTTOM OF SCALE)
      GOTO 900
   30 WRITE (3,33)
   33 FORMAT(17H OFF TOP OF SCALE)
  900 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SCALES (F,SCALE)
C           SUBROUTINE SCALES ALLOWS THE DATA TO BE
C           PLOTTED AT ANY ONE OF FOUR SCAES, 1:100,
C           1:200, 1:250, 1:500
      INTEGER SCALE
      READ  (1,100) SCALE
      N = (SCALE+10)/100
      GOTO (1,2,3,4,4),N
    1 F = 0.393438
      GOTO 5
    2 F = 0.196719
      GOTO 5
    3 F = 0.157375
      GOTO 5
    4 F = 0.078688
    5 CALL FACTOR (F)
      RETURN
  100 FORMAT(I3)
      END
```

```
      SUBROUTINE SH
C           SUBROUTINE SH IS AN ALTERNATIVE TO
C           SPECIFYING HEATING DATA AND ALLOWS
C           DIRECT STATEMENT OF AIR TEMP, RADIANT
C           TEMP AND RELATIVE HUMIDITY FOR ANY SPACE
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      INTEGER T
      COMMON DAIT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLMN,ILLMT,DFLIT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
   10 READ  (1,100) I,A,B,C
      ATA(I) = A
      ATR(I) = B
      ARH(I) = C
      READ  (1,120) T
      IF(T.EQ.0) GOTO 10
      RETURN
  100 FORMAT(I2,3F4.1)
  120 FORMAT(I1)
      END
```

```
      SUBROUTINE SHB (N,FF)
      INTEGER T
      REAL LUMEN(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON WAIT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLMN,ILLMT,DFINT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      SVP(T)=(10.**(28.59051-8.2*ALOG10(T+273.16)+2.4804E-03
     1*(T+273.16)-3142.31/(T+273.16))/1.333)*1000.
C            TIME OF YEAR
   10 READ (1,100) ITOY
      GOTO (20,50),ITOY
      GOTO 10
C            WINTER
   20 READ (1,110) TAO,RHO
   30 READ (1,120) N,TAI,IHEAT
      ATA(N) = TAI
      IF(IHEAT .EQ. 1) GOTO 40
      ATR(N) = TAI+3.
      GOTO 42
   40 ATR(N) = TAI-2.
   42 VP = RHO*SVP(TAO)/100.
      VP = VP+7.
      ARH(N) = 100.*VP/SVP(TAI)
      READ (1,100) T
      IF(T .EQ. 0) GOTO 30
      GOTO 90
C            SUMMERTIME
   50 CONTINUE
      CALL CURL (N,FF)
   90 CONTINUE
  100 FORMAT(I1)
  110 FORMAT(2F10.2)
  120 FORMAT(I2,F10.2,I2)
      RETURN
      END
```

```
      SUBROUTINE MOVE (ITOTL)
C             SUBROUTINE MOVE TAKES THE TOTAL NUMBER
C             OF POINTS ON THE ROUTE AND CALCULATES
C             THE TIME TAKEN TO TRAVEL BETWEEN EACH
C             CONSECUTIVE PAIR OF POINTS.
      REAL LUMEN(20),ILLOUT(20),ILLMA(20),ILLMN(20)
      COMMON WAIT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDE3(30),XYZ(90),MODE(59)
      COMMON ILLMA,ILLOUT,OPTIMT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON STAMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATB(20),ARH(20)
      KK=0
      KOUNT=0
   30 KOUNT=KOUNT+1
      KK=KK+1
      CALL VRIABL (KOUNT,X0,X1,Y0,Y1,Z0,Z1,XABS0,XABS1,YABS0,YABS1,
     1ZABS0,ZABS1)
C             IS X=X1
      IF(X0.EQ.X1) GOTO 40
C             IS Y=Y1
      IF(Y0.EQ.Y1) GOTO 50
C             IF EITHER X OR X1 NEG. GO TO 100
      IF(X0*X1.LT.0.0) GOTO 100
C             SIDEA SET AS SMALLER OF X AND X1 FROM LARGER
      SIDEC=ZABS0-ZABS1
      SIDEA=XABS0-XABS1
      IF(XABS0.LT.XABS1)
     1SIDEA=XABS1-XABS0
      GOTO 110
C             SIDEA SET AS SUM OF ABS VALUES OF X AND X1
  100 SIDEA=XABS0+XABS1
C             IF EITHER Y OR Y1 NEG. GO TO 120.
      CALL SYMBOL (X2,Y2,1.4,3,0.0,-1)
  110 IF(Y0*Y1.LT.0.0) GOTO 120
C             SIDEB SET AS SMALLER OF Y AND Y1 FROM LARGER
      SIDEB=YABS0-YABS1
      IF(YABS0.LT.YABS1)
     1SIDEB=YABS1-YABS0
      GOTO 130
C             SIDEB SET AS SUM OF ABS VALUES OF Y AND Y1
  120 SIDEB=YABS0+YABS1
C             DISTANCE SET BY PYTHAGORAS
  130 DISTK=SQRT(SIDEA*SIDEA+SIDEB*SIDEB)
      GOTO 60
C             IF EITHER Y OR Y1 NEG. GO TO 140
   40 IF(Y0*Y1.LT.0.0) GOTO 140
C             DISTANCE SET AS SMALLER OF Y AND Y1 FROM LARGER
      DISTK=YABS0-YABS1
      IF(YABS0.LT.YABS1)
     1DISTK=YABS1-YABS0
      SIDEB=DISTK
      GOTO 60
C             DISTANCE SET AS SUM OF ABS VALUES OF Y AND Y1
  140 DISTK=YABS0+YABS1
      SIDEB=DISTK
      GOTO 60
C             IF EITHER X OR X1 NEG. GO TO 150
   50 IF(X0*X1.LT.0.0) GOTO 150
C             DISTANCE SET AS SMALLER OF X AND X1 FROM LARGER
      DISTK=XABS0-XABS1
      IF(XABS0.LT.XABS1)
```

```
     1DISTK=XABS1-XABS0
      SIDEA=DISTK
      GOTO 50
C             DISTANCE SET AS SUM OF ABS VALUES OF X AND X1
  150 DISTK=XABS0+XABS1
      SIDEA=DISTK
C             IS Z=Z1
   50 IF(Z0.EQ.Z1) GOTO 70
C             IF EITHER Z OR Z1 NEG. GO TO 160
      IF(Z0*Z1.LT.0.0) GOTO 160
C             SIDEC SET AS SMALLER OF Z AND Z1 FROM LARGER
      IF(ZABS0.LT.ZABS1)
     1SIDEC=ZABS1-ZABS0
      GOTO 170
C             SIDEC SET AS SUM OF ABS.VALUES OF Z AND Z1
  160 SIDEC=ZABS0+ZABS1
C             DISTANCE SET BY PYTHAGORAS
  170 DISTK=SQRT(DISTK*DISTK+SIDEC*SIDEC)
   70 DIST(KOUNT)=DISTK
      SIDE1(KOUNT)=SIDEA
      SIDE2(KOUNT)=SIDEB
      SIDE3(KOUNT)=SIDEC
C             COMPUTE FOR THE DISTANCE BETWEEN CONSECUTIVE POINTS THE T
C             INTERVAL.
      MODEK=MODE(KK)
C             IF 'MODE' IS STATIONARY TIME=STATIONARY INTERVAL (IN SECS
      IF(MODEK.NE.1.AND.MODEK.NE.2) GOTO 210
      TIME(KK)=WAIT(KOUNT)* 60.
      KK=KK+1
      MODEK=MODE(KK)
C             MOVEMENT ON LEVEL
  210 CONTINUE
      IF(MODEK.EQ.10) GOTO 220
      SPEED = 1.1
      MODE(KK)=3
      IF(MODEK.EQ.3.AND.Z0.EQ.Z1) GOTO 200
C             MOVEMENT UP
      MODE(KK)=5
      IF(MODEK.EQ.3.AND.Z0.LT.Z1) GOTO 200
C             MOVEMENT DOWN
      MODE(KK)=7
      IF(MODEK.EQ.3) GOTO 200
C             MOVEMENT ON LEVEL
      SPEED = 2.2
      MODE(KK)=4
      IF(MODEK.EQ.4.AND.Z0.EQ.Z1) GOTO 200
C             MOVEMENT UP
      MODE(KK)=6
      IF(MODEK.EQ.4.AND.Z0.LT.Z1) GOTO 200
C             MOVEMENT DOWN
      MODE(KK)=8
  200 TIME(KK)=DISTK/SPEED
      IF(KOUNT.LT.ITOTL) GOTO 30
      IF(MODE(KK+1).EQ.10) GOTO 220
      TIME(KK+1)=WAIT(KOUNT+1)*60.
      ITOTL=ITOTL+1
  220 RETURN
      END
```

```
      SUBROUTINE VRIABL (KOUNT,X0,X1,Y0,Y1,Z0,Z1,
C           SUBROUTINE VRIABL INITIALISES COORDINATE
C           VARIABLES FOR USE IN OTHER ROUTINES.
     1XABS0,XABS1,YABS0,YABS1,ZABS0,ZABS1)
      REAL LINE1(20),ILLMT(20),ILLMA(20),ILLMN(20)
      COMMON/ UNIT(30),DIST(30),TIME(59),SIDE1(30)
      COMMON/ SIDE2(30),SIDE3(30),XYZ(90),NODE(50)
      COMMON/ ILLMX,ILLMT,DFINT(20),AREA(6,20)
      COMMON/ AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON/ SIGMA(20),ILLMA,LUMFN,S(120),G(5,140)
      COMMON/ D(10,120),W(10,120),REFS(6,20)
      COMMON/ ATA(20),ATR(20),ARH(20)
      J=3*(KOUNT-2
      X0=XYZ( J )
      X1=XYZ(J+3)
      Y0=XYZ(J+1)
      Y1=XYZ(J+4)
      Z0=XYZ(J+2)
      Z1=XYZ(J+5)
      XABS0=ABS(X0)
      XABS1=ABS(X1)
      YABS0=ABS(Y0)
      YABS1=ABS(Y1)
      ZABS0=ABS(Z0)
      ZABS1=ABS(Z1)
      RETURN
      END
```

```
      SUBROUTINE INTRVL (X0,X1,KOUNT,KTIM,K,Y0,Y1,Z0,Z1,XA,YA,ZA)
C           SUBROUTINE INTRVL DETERMINES THE 3-D
C           COORDS ALONG THE ROUTE AT EACH TIME
C           INTERVAL.
      REAL LPHI(20),ILLMT(20),ILLMA(20),ILLMW(20)
      COMMON WAIT(50),DIST(30),TIME(50),SIDE1(30)
      COMMON SIDE2(30),SIDES(30),XYZ(90),MODE(50)
      COMMON ILLMN,ILLMT,DEIHT(20),AREA(6,20)
      COMMON AGLAS(4,20),AGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),W(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      X=0.
      IF(X0.EQ.X1) GOTO 300
      X=SIDE1(KOUNT)/KTIM
  300 XA=X0-X*K
      IF(X1.GT.X0)
     1XA=X0+X*K
      Y=0
      IF(Y0.EQ.Y1) GOTO 310
      Y=SIDE2(KOUNT)/KTIM
  310 YA=Y0-Y*K
      IF(Y1.GT.Y0)
     1YA=Y0+Y*K
      Z=0
      IF(Z0.EQ.Z1) GOTO 320
      Z=SIDES(KOUNT)/KTIM
  320 ZA=Z0-Z*K
      IF(Z1.GT.Z0)
     1ZA=Z0+Z*K
C           XA,YA,ZA RETURNED FOR COORDS AFTER SEC. INTERVAL
      RETURN
      END
```

```
      SUBROUTINE VPSPC (N,X,Y,Z,ISPACE)
C           SUBROUTINE VPSPC TAKES THE NUMBER OF
C           SPACES WITHIN THE BUILDING COMPLEX,
C           THE 3-D COORDS OF THE VIEWPOINT AND
C           THE COORDS DEFINING EACH SPACE, AND
C           RETURNS ISPACE AS THE REF. NUMBER OF
C           THE SPACE CONTAINING THE VIEWPOINT.
C           N IS TOTAL NUMBER OF SPACES
      REAL LUMEN(20),ILLNT(20),ILLMA(20),ILLMN(20)
      COMMON MAST(30),PIST(30),TIME(59),SIDE1(30)
      COMMON SIDE2(30),SIDES(30),XYZ(90),NODE(59)
      COMMON ILLMN,ILLMT,DFIHT(20),AREA(6,20)
      COMMON AGLAS(4,20),VGAPS(4,20),F(60)
      COMMON SIGMA(20),ILLMA,LUMEN,S(120),G(5,140)
      COMMON D(10,120),U(10,120),REFS(6,20)
      COMMON ATA(20),ATR(20),ARH(20)
      DO 100 I = 1,N
      K = I*6-5
      IF(X.GE.S(K)) GOTO 10
      GOTO 100
   10 IF(X.LT.S(K+3)) GOTO 20
      GOTO 100
   20 IF(Y.GE.S(K+1)) GOTO 30
      GOTO 100
   30 IF(Y.LT.S(K+4)) GOTO 40
      GOTO 100
   40 IF(Z.GE.S(K+2)) GOTO 50
      GOTO 100
   50 IF(Z.LT.S(K+5)) GOTO 60
      GOTO 100
   60 ISPACE = I
      RETURN
  100 CONTINUE
      RETURN
      END
```

At present, the program is operative in batch mode. Input of data is on cards and the following is a description of the input format specifications. Throughout this section the * denotes a space.

MASTER EDIT

The master routine controls selection of the program's options. The following is a list of routines together with their respective calling numbers.

1	SUBROUTINE	SS
2	"	SG
3	"	SW
4	"	SD
5	"	SR
6	"	SP
7	"	SX
8	"	SL
9	"	SF
10	"	SK
11	"	ST
12	"	ROUTES
13	"	SI
14	"	PHOTIC
15	"	VISION
16	"	THERML
17	"	SCALES
18	"	SH
19	"	SHB
20	Terminator	

The input format for a call to one of these routines is I2. Routine 17 must always be called first and routine 20 must always be called to terminate a job.

SUBROUTINE SS

SUBROUTINE SS deals with the input of spaces. Whenever it is called, the first room to be described must be given a number. This may be the number of a room already described but if this is the case, then the room placed first and others of higher number will be replaced by the new rooms. The room number is input in I2 format. The room is defined by the bottom left and top right hand corners of the room , in that order (F4.0 format) and the floor height and room height (F3.0 format). Except for the first room described with each call of the routine, when the floor height switch is 0 it is presumed equal to the previous floor height.

The following describes two adjacent rooms, 4 x 4 metres on plan, 3 metres high with a floor level 2·5 metres above datum. Each new line is a new card. After each space, there is a terminator switch.

*1	(first room number)
0.0*0.0	(bottom left)
4.0*4.0	(top right)
1	(floor height switch)
2.5	(floor height)
3.0	(room height)
0	(terminator)
4.0*0.0	(bottom left)
8.0*4.0	(top right)
0	(floor height switch)
3.0	(room height)
1	(terminator)

SUBROUTINE SG

SUBROUTINE SG deals with the input of gaps. Each gap is defined by two diagonally opposite corners of a rectangle. The following describes a gap 2 metres wide and 2 metres wide on the left wall of room 1 in the previous example.

0.0*1.0	(corner 1)
0.0*3.0	(corner 2)
1	(base height switch)
2.5	(base height)
2.0	(gap height)
1	(terminator)

SUBROUTINE SW

SUBROUTINE SW deals with the input of windows. Each window is defined by two diagonally opposite corners of a rectangle. The following describes a window 1 metre by 1 metre and 0.9 metres from the floor, in the right hand wall of the previous example.

8.0*1.5	(corner 1)
8.0*2.5	(corner 2)
1	(cill height switch)
3.4	(cill height)
1.0	(window height)
1	(terminator)

SUBROUTINE SD

SUBROUTINE SD deals with the input of doors. A door is defined by two diagonally opposite corners of a rectangle. The following describes a door 0.8 metres wide, 2 metres high centred in between rooms 1 and 2 in the previous example.

4.0*1.6	(corner 1)
4.0*2.4	(corner 2)
1	(floor height switch)
2.5	(floor height)
2.0	(door height)
1	(terminator)

SUBROUTINE SR

SUBROUTINE SR deals with input of reflectance values of room surfaces. Each card must contain in the following order, the room number, the reflectances of the north wall, the east wall, the south wall, the west wall, the floor and the ceiling. The following specifies reflectances for room 1.

1.6*.4*.4*.4*.2*.8	(room number and reflectances)
1	(terminator)

SUBROUTINE SL

SUBROUTINE SL deals with the input of luminaires. Each card must contain in the following order, the room number, the number of lamps, design lumens of lamps and light output ratio of lamps. The following describes room 2 having three different types of lamp.

*2*3*6700*80	(luminaire description)
0	(terminator)
*2*1*8700*80	(luminaire description)
0	(terminator)
*2*1*5200*95	(luminaire description)
1	(terminator)

SUBROUTINE SF

SUBROUTINE SF deals with the description of obstructions to windows. Input required is room number, face number and angle of obstruction from the horizontal at the plane of the window. Each room has four faces, 1, 2, 3 and 4 (N, E, S and W respectively). The following describes an obstruction to the window in room 2 in the previous example, 50° above the horizontal.

*2	(room number)
*2*50	(face number and angle of obstruction)
1	(terminator)

SUBROUTINE SK

SUBROUTINE SK deals with sky illuminance. The input format is F7.0

SUBROUTINE ST

SUBROUTINE ST deals with the transmittance of glass. The input format is F3.2

SUBROUTINE ROUTES

SUBROUTINE ROUTES deals with the description of a route. A route is described by a series of points defined by their 3 - D coordinates. A mode of travel between points must be specified (see section 4.1). The following describes a route, walked along slowly, from the bottom left hand corner of room 1 to the bottom right hand corner of room 2 via the connecting door of the previous example.

*0.5*0.5*2.5*3	(x, y, z, mode)
*2.0*2.0*2.5*3	(")
*6.0*2.0*2.5*3	(")
*7.5*0.5*2.510	(x, y, z, terminator)

SUBROUTINE SI

SUBROUTINE SI deals with the direct input of the average luminance of rooms in cd/m^2 . The input required is the total number of rooms and the luminance of each room. The following defines the luminance of rooms 1 and 2 as 60 cd/m^2 and 90 cd/m^2 respectively.

*2	(number of rooms)
60.0	(luminance of room 1)
90.0	(luminance of room 2)

SUBROUTINE PHOTIC

SUBROUTINE PHOTIC deals with the calculation of average luminance and prediction of apparent brightness at required intervals. Input required is the print-out interval (in seconds) and the impression of apparent brightness at the starting point of the route (1 = very dark, 2 = dark, 3 = dim, 4 = satisfactory, 5 = light, 6 = bright, 7 =very bright). The following requests output at 1 second intervals along a route with the initial impression 'satisfactory'.

*1	(output interval)
4	(initial state)

SUBROUTINE THERML

SUBROUTINE THERML deals with the prediction of thermal sensations at required intervals. Input required, in the following order, is the thermal sensation at the start of the route (1 = cold, 2 = cool, 3 = slightly cool, 4 = neutral, 5 = slightly warm, 6 = warm, 7 = hot), the output interval (in seconds), body height (cm), body weight (kg) and clothing insulation (clo). The following requests output at 1 second intervals, along a route with the initial sensation 'slightly warm', for a man 180 cm high, 70 kg in weight with a clothing insulation of 1.2 clo.

5	(initial sensation)
*1	(output interval)
180.	(height)
70.	(weight)
1.2	(clothing insulation)

SUBROUTINE SCALES

SUBROUTINE SCALES deals with the scale of graphical output. This may be

1:100, 1:200, 1:250, or 1:500. The fllowing requests output at 1:500 scale.

500 (scale)

SUBROUTINE SH

SUBROUTINE SH deals with the direct input of the thermal conditions within the building. Input required , in the following order, is the room number, air temperature (^{o}C), mean radiant temperature (^{o}C) and relative humidity. The following describes the conditions where room 1 has an air temperature of 15°C, mean radiant temperature of 17°C and relative humidity of 50%. Room 2 has an air temperature of 20°C, mean radiant temperature of 21°C and relative humidity of 50%.

*1*15.*17.*50.	(room number,Ta,Tr,RH)
*2*20.*21.*50.	(room number,Ta,Tr,RH)

SUBROUTINE SHB

SUBROUTINE SHB deals with the estimation of the thermal conditions within the building. Either summer or winter conditions may be specified. Summer-time temperatures are calculated according to the admittance procedure outlined in the IHVE Guide, Book B 1970. Winter conditions need input of outside air temp and outside RH, the room number, the thermostat setting for room temp and type of heating (radiant = 0, convective = 1). The following requests winter conditions and specifies 5°C outside air temp, 30½ RH, room number 2, thermostat setting of 20°C and convective heating.

1	(winter)
5.0*******30.0	(Ta outside,RH outside)
*2*20.0******1	(room number,thermostat temp,convective heating)
1	(terminator)