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# Sensitivity to Temporal Variations in Thermal Conditions

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# Sensitivity to Temporal Variations in Thermal Conditions

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This paper describes an experiment in which 16 people each experienced four levels of change in temperature and reported their sensations. Changes were of 0°, 3°, 6° and 9°C and were symmetrical about a centrepoint of 23°C and linear over an exposure period of 6 hours. Changes occurred in both upward and downward directions. Subjects reported their warmth sensations at hourly intervals and gave a summary assessment on 11 semantic differential scales at the end of the period of exposure. The smallest rate of change was reliably detected and changing environments were reported to be less pleasant and more uneven than the steady state. Degree of extraversion of the subjects and direction of changes in temperature were non-significant variables. A method of estimating the degree of dissatisfaction produced by temperature changes is briefly described.

## 1. Introduction

In commercial buildings it is frequently the case that thermal conditions vary over time. Thus, offices may be heated by heat storage devices which provide high temperatures at the beginning of the working day and lower temperatures later on. Factories and other workplaces often rely on incidental heat gains from machinery, lighting and people to provide a large part of the heat requirement: in this case, conditions will be cool in the early part of the working day and warmer at the end.

Research into the effects of thermal conditions on performance and comfort has shown a bias towards study of the effects of constant conditions. In a sense this is remarkable since, because of human adaptability, effects would more likely be seen under dynamic conditions. For convenience, it is possible to distinguish three sorts of temperature variation on which experimentation has taken place:

step changes (Gagge *et al.* 1967);
cyclic changes (Sprague and McNall 1970, Wyon *et al.* 1973);
and ramp or monotonic changes (Wyon *et al.* 1971).

Only the last-mentioned of these is relevant to the problem raised here. Eight subjects were exposed, either naked or in 0·6 clo clothing, to changes in air temperature at a rate of 0·15°C/min or 0·50°C/min, either while performing a mental task or resting. They were asked to signal ' too hot ' or ' too cold ' when they noticed that the temperature was no longer comfortable, and the direction of the change was reversed. The change in mean radiant temperature (m.r.t.) was about 25% of the change in air temperature. For clothed subjects the median tolerated range was 8°C if working and 5·6°C if resting (both at 0·5°C/min). At the lower rate only naked subjects were investigated. The tolerated ranges are apparently very large and the rates of change very fast if considered in relation to the working day. The authors themselves conclude that such large values for tolerance cannot be taken to apply in reality without further investigation. The present experiment was designed to approach more realistically the conditions in workplaces.

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## 2. Experimental Design and Analysis

### 2.1. *Purpose of the Experiment*

The purpose of the experiment was to examine human sensitivity to monotonic temperature changes over a working day. A subsidiary purpose was the investigation of differential sensitivity to environmental changes in people of differing personality. Eysenck would predict differences between extraverts and introverts in their response to change (Eysenck 1967).

### 2.2. *Physical Conditions*

The experiment was carried out in the ECRC thermal environment chamber, a 4 m × 4 m × 2·5 m room with controlled-temperature surfaces and an air-conditioning system providing air at a controlled temperature and humidity. Three conditions of changing temperatures and a control condition at a constant temperature constituted the experimental conditions. The three varying conditions were presented as both rising and falling temperatures, producing a total of six experimental conditions and one control condition: any subject or group of subjects would experience a control condition and the three experimental conditions of one direction only.

The control temperature was 23°C (thermally neutral for lightly clothed sedentary subjects) and the experimental conditions varied about this temperature. The ranges of temperature were 3°C, 6°C and 9°C; mean radiant temperature was always equal to air temperature. The settings for the chamber surface and air temperature controls are given in Table 1. Changes in temperature were made at half-hourly intervals but only temperatures at hourly intervals are given in the table. Changes were

Table 1. Temperatures at hourly intervals for each experimental condition

| Condition | 1030 | 1130 | 1230 | 1400 | 1500 | 1600 | Temperature |
|---|---|---|---|---|---|---|---|
| Control (1) | 23·0 | 23·0 | 23·0 | 23·0 | 23·0 | 23·0 | Planned |
| | 23·0 | 23·0 | 23·0 | 23·0 | 23·1 | 23·0 | Actual (Mean) |
| | 0·1 | 0·0 | 0·0 | 0·1 | 0·8 | 0·4 | (Range) |
| 2 (Up) | 21·5 | 22·1 | 22·7 | 23·0 | 23·6 | 24·2 | Planned |
| | 21·6 | 22·2 | 22·8 | 23·1 | 23·8 | 24·3 | Actual (Mean) |
| | 1·2 | 1·2 | 0·7 | 0·6 | 0·4 | 0·2 | (Range) |
| 2 (Down) | 24·5 | 23·9 | 23·3 | 23·0 | 22·7 | 22·1 | Planned |
| | 24·5 | 23·8 | 23·1 | 23·0 | 22·3 | 21·8 | Actual (Mean) |
| | 0·1 | 0·3 | 0·3 | 0·4 | 0·3 | 0·2 | (Range) |
| 3 (Up) | 20·0 | 21·2 | 22·4 | 23·0 | 24·2 | 25·4 | Planned |
| | 20·4 | 21·3 | 22·5 | 23·1 | 24·2 | 25·5 | Actual (Mean) |
| | 0·8 | 0·7 | 0·8 | 0·2 | 0·2 | 0·6 | (Range) |
| 3 (Down) | 26·0 | 24·8 | 23·6 | 23·0 | 21·8 | 20·6 | Planned |
| | 26·0 | 24·8 | 23·6 | 22·9 | 21·7 | 20·7 | Actual (Mean) |
| | 0·2 | 0·4 | 0·7 | 0·2 | 0·4 | 0·7 | (Range) |
| 4 (Up) | 18·5 | 19·4 | 21·2 | 23·0 | 23·9 | 26·6 | Planned |
| | 18·8 | 20·4 | 22·2 | 23·0 | 24·8 | 26·6 | Actual (Mean) |
| | 0·5 | 0·9 | 0·4 | 0·1 | 0·4 | 0·2 | (Range) |
| 4 (Down) | 27·5 | 25·7 | 23·9 | 23·0 | 21·2 | 19·4 | Planned |
| | 27·5 | 25·9 | 23·9 | 22·9 | 21·2 | 19·3 | Actual (Mean) |
| | 0·3 | 0·8 | 0·2 | 0·2 | 0·3 | 0·5 | (Range) |

effectively linear against time because of the chamber's slow response to control changes. Air velocities were low ($v < 0{\cdot}1$ m/s) and vapour pressure was held within the range 10 mb $\pm$ 2·2 mb.

### 2.3. *Subjects and Procedures*

The subjects were 32 students from a college of further education, 16 male and 16 female, ranging in age from 16 to 19 years. The means and standard deviations of their scores on the *Eysenck Personality Inventory Form B* (Eysenck and Eysenck 1964) were as follows:

Neuroticism: mean 13·2, s.d. 3·9 (population 10·4, s.d. 4·7):

Extraversion: mean 15·2, s.d. 4·2 (population 14·2, s.d. 3·9).

The subjects were randomly allocated to 8 experimental groups of 4 people each: each group experienced the control condition and the three experimental conditions (all of the same direction) in a different randomized order.

Before entering the experimental chamber subjects removed outdoor clothing and items such as jackets and jumpers. The experimental session began at 10.00 and finished at 16.30, with a lunch break outside the chamber between 13.00 and 13.30. Subjects could obtain hot and cold drinks in any quantity as required and could leave the chamber for short periods as needed. Every hour, beginning 30 minutes after the morning or afternoon entry, subjects recorded their warmth sensation according to the *Bedford Warmth Scale*.

Near the end of the experimental period (at 16.15) a fuller questionnaire, described below, was completed by each subject. This was followed by completion of the *Eysenck Personality Inventory* (Eysenck and Eysenck *op. cit.*). Subjects were asked not to discuss environmental conditions during their time in the chamber, where they were allowed to read, play cards, listen to the radio, and so on. Subjects each attended four six-hour sessions and were paid £2·00 for each attendance. The experiment was carried out in 36 sessions in May, June and July, 1972.

### 2.4. *Questionnaire*

Subjects recorded their warmth on the *Bedford Warmth Scale* at hourly intervals. The scale has the following seven named points:

1. Much too cool.
2. Too cool.
3. Comfortably cool.
4. Comfortable and neither cool nor warm.
5. Comfortably warm.
6. Too warm.
7. Much too warm.

At the end of the session subjects recorded their assessment of the environment over the day on 11 seven-point rating scales, which were presented by slide projector in a different random order for each session. The end-points of the rating scales are given in Table 2. Subjects recorded the responses on 80 column data cards. Included in the 11 scales was a final assessment on the *Bedford Warmth Scale*.

Table 2. List of subjective rating scales

| Scale No. | Point 1 | Point 7 | Comments |
|---|---|---|---|
| 1 | Pleasant | Unpleasant | |
| 2 | Even | Uneven | |
| 3 | Much too cool | Much too warm | *Bedford Warmth Scale* |
| 4 | Dry | Moist | |
| 5 | Comfortable | Uncomfortable | |
| 6 | Hot | Cold | |
| 7 | Steady | Changing | |
| 8 | Invigorating | Dozy | |
| 9 | Pleasing | Annoying | |
| 10 | Warmer | Cooler | This is in answer to a direct question 'During the day, has it been getting warmer or cooler?' |
| 11 | Draughty | Still | |

### 2.5. *Analysis of Results*

The method of analysis for both hourly warmth vote and terminal questionnaire assessment was analysis of variance (Winer 1962). In the case of the analysis of the hourly warmth vote a separate analysis was carried out for each experimental condition and each of these analyses was a two factor design with repeated measures on one factor (Winer *op. cit.*, p. 302): the factors were extraversion and time of day. The responses to the fuller questionnaire constituted a three-factor design with repeated measures on one factor (the factors were experimental condition, extraversion, and direction of temperature change; the repeated measures factor was the first of these).

## 3. Results

### 3.1. *Hourly Warmth Votes*

The analyses yielded significant time effects in all conditions (all $p < 0{\cdot}001$). It is reasonable to describe these time effects as temperature effects except in the case of the control condition, where there was no temperature variation and hence no confounding of time and temperature. Figures 1–4 show the means of warmth votes at each hour of exposure. The mean of the variances at each

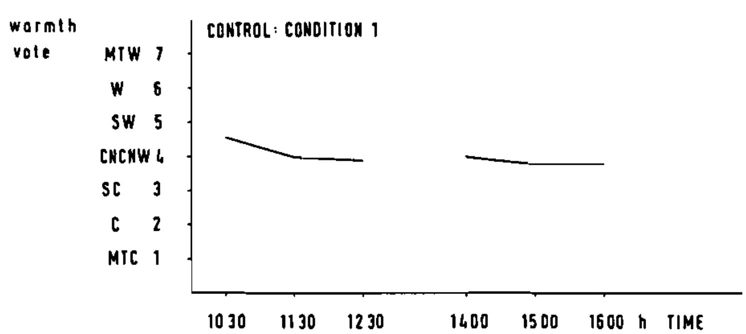


Figure 1. Mean Bedford Scale warmth votes against time (control condition).

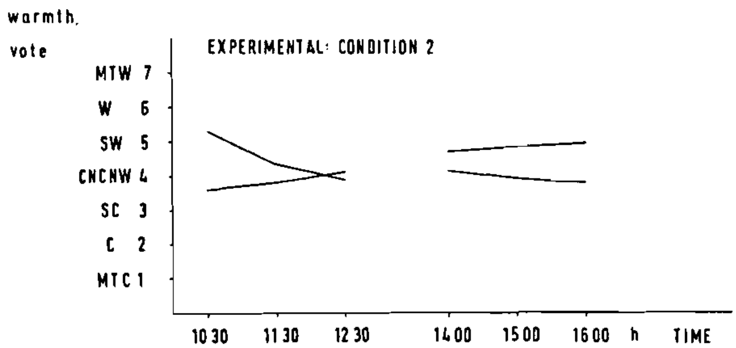


Figure 2. Mean Bedford Scale warmth votes against time (condition 2, up and down).

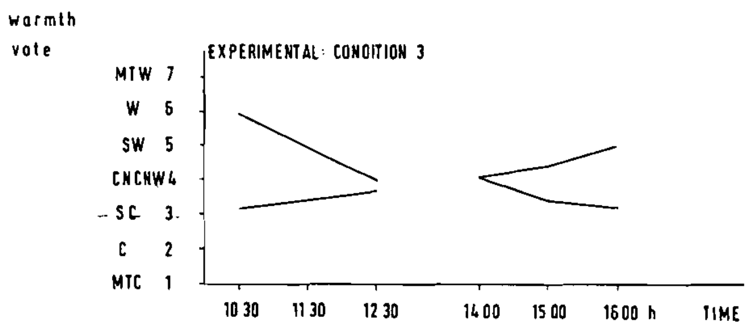


Figure 3. Mean Bedford Scale warmth vote against time (condition 3, up and down).

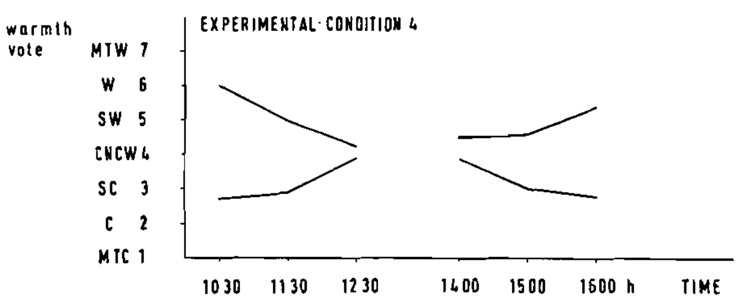


Figure 4. Mean Bedford Scale warmth vote against time (condition 4, up and down).

hour was 0·64, which corresponds to a standard deviation of 0·80. The correlation coefficient between vote and temperature for all conditions taken together (excluding the control) was $r = 0{\cdot}69$ ($n = 570$, $p < 0{\cdot}001$). The regression equation was $W = 0{\cdot}395T - 4{\cdot}96$, where $W$ = *Bedford Warmth Scale* score and $T$ = air or mean radiant temperature. This compares with the regression equation from a previous experiment (McIntyre and Griffiths 1972) of $W = 0{\cdot}209T_A + 0{\cdot}146T_R - 4{\cdot}19$ ($W$ as before, $T_A$ = air temperature, $T_R$ = mean radiant temperature). The regression coefficients in these two equations are significantly different, but the magnitude involved is rather small for practical purposes: thus the predicted mean warmth votes at 23°C air and mean radiant temperature are 3·96 (earlier equation) and 4·14 (new equation). In general this level of similarity was maintained but, as can be seen from Figures 1–4, there are two visible discrepancies: the earliest means in all descending conditions are higher than expected and there is also a constant elevation of means in condition 2 up. These probably explain the greater slope in the present experiment.

Extraversion and the interaction of extraversion with time never reached significance.

### 3.2. *End of Session Assessment*

Table 3 gives means for all the questions in the final assessment which showed significant $F$ ratios. In general only the temperature change effects were significant and the effects of direction of change, personality, and the interaction were without significance.

Table 3. Means for significant effects

| | Scale | | Condition 1 | 2 | 3 | 4 | Source | $f$ | $df$ | $p$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Pleasant—unpleasant | | 3·31 | 3·56 | 3·44 | 4·28 | C | 4·54 | 3·79 | <0·01 |
| 2 | Even—uneven | | 3·50 | 3·06 | 4·19 | 4·22 | C | 5·68 | 3·79 | <0·01 |
| 5 | Comfortable—uncomfortable | | 3·13 | 3·09 | 3·37 | 4·03 | C | 4·85 | 3·79 | <0·01 |
| 7 | Steady—changing | | 4·03 | 3·28 | 4·66 | 5·19 | C | 8·74 | 3·79 | <0·01 |
| 9 | Pleasing—annoying | | 3·31 | 3·56 | 3·44 | 4·28 | C | 5·34 | 3·79 | <0·01 |
| 10 | Warmer—cooler | Up | 4·19 | 2·94 | 2·06 | 2·25 | DC | 12·35 | 3·79 | <0·01 |
| | | Down | 4·69 | 5·06 | 6·25 | 6·19 | | | | |
| | | | Up | Down | — | — | | | | |
| 3 | Bedford Warmth Scale | | 4·61 | 3·97 | | | D | 6·17 | 1·23 | <0·05 |
| 6 | Hot—cold | | 3·61 | 4·11 | | | D | 4·52 | 1·23 | <0·05 |
| 7 | Steady—changing | Introverts | 4·66 | 3·84 | | | DP | 11·08 | 1·23 | <0·01 |
| | | Extraverts | 3·72 | 4·94 | | | | | | |
| 8 | Invigorating—dozy | | 4·52 | 3·84 | | | D | 5·25 | 1·23 | <0·05 |

C = Condition. D = Direction of change. P = Personality.

It is most convenient to consider the significantly affected responses in terms of classes of question rather than in the form of individual questions. If we consider the degree of sensitivity to the changes in temperature, then question 10 is directed specifically to this problem and shows a highly significant effect of the interaction of experimental conditions and direction of change. Scrutiny of the means shows clearly that all conditions are differentiable from the control. Two other scales of a similar sort, question 2 (even–uneven) and question 7 (steady–changing) show similar effects. The latter of these is significantly affected by the interaction of personality and direction of change.

The next problem to be considered is that of comfort and pleasantness, which, once again, differentiate between conditions but not between personalities or directions of change. Assessed pleasantness (Q.1), discomfort (Q.5) and annoyance (Q.9) all show effects of experimental condition significant at the 1% level.

Warmth votes taken at the end of the day also show significant effects at the 5% level, but these are restricted to direction of change: responses indicate upward changes to be, on average, warmer.

Responses to two questions which do not fall readily into the classification made above also showed significant effects. Question 8 (invigorating–dozy) showed a significant ($p < 0{\cdot}05$) effect of direction of change: the downward change is more invigorating. Responses to draughty–still (Q.11) are significantly affected by condition ($p < 0{\cdot}05$), but there is no clear direction to this effect.

## 4. Discussion and Conclusions

### 4.1. *Hourly Warmth Votes*

Sensations of warmth clearly follow temperature very closely, even when temperature changes are as small as 3°C over 6 hours (0·5°C/h). In general warmth votes, and their dispersion, are very close to the results of earlier experiments (with the exception of the unexplained discrepancies early in the day and during the afternoons of condition 2). It is possible (Fanger 1972) to use mean votes to predict the percentage of people dissatisfied (PPD) from a particular value of the mean vote, and the results of this experiment show that it is also possible to predict instantaneous mean votes during linear changes by use of the normal equations. Using these possibilities, one can easily forecast the PPD at any instant, and from this the percentage of time for which a given PPD will obtain within a period of changing temperature. This process is described elsewhere by the present authors (Griffiths and McIntyre 1973).

### 4.2. *End of Session Assessment*

The results of analysis of the warmth votes are confirmed by analysis of the final results: questions concerned with sensitivity to the changes all show significant effects of condition. The group of votes concerned with comfort and pleasantness also show significant effects of experimental condition. Although these are of apparently small magnitude, it would be unwise to dismiss them as of no importance since in previous experiments fairly extreme conditions have not produced changes in pleasantness. The present results indicate that it is probably unwise to exceed 6°C variation (i.e. 1°C/h). It is interesting to note that there is no evidence of the often-postulated ‘ thermal boredom ’ in these results: the existence of this phenomenon would be supported by signs of preference for changing conditions as compared with constant temperature. Such a preference might still arise, however, with cyclic rather than linear changes in temperature.

Although it is generally hypothesized (Eysenck *op. cit.*) that extraverts are less sensitive to changes in stimulation than introverts, this has not been supported by the present experiment; although our only significant effect involving personality was in fact on the axis steady–changing, this is in the form of an interaction with direction of change which is not readily interpretable under the hypothesis.

Warmth votes in the final assessment were significantly affected by direction of change and the finding that upward changes are perceived as warmer is probably indicative of shortness of memory. The invigorating effect of downward changes is presumably due to the colder afternoons in these conditions. The weak effect of condition on draughtiness may be taken to be a chance effect.

An overall summary of these results might be as follows. Even the smallest rates and ranges of change were detected and the instantaneous mean warmth vote of a group is easily predicted by use of the normal equations. Although pleasantness votes differ significantly from those in constant conditions in those with bigger changes, the differences are apparently small, and on this basis the warmth votes could be used as a design criterion. A 3°C range (i.e. a deviation from mean comfort temperature of $\pm 1{\cdot}5$°C) produces a maximum percentage dissatisfied of 10, and the increment in percentage dissatisfied is relatively large and rapid at a range of 6°C (i.e. $\pm 3$°C) where the maximum percentage is 24. On this basis it would seem reasonable to take a figure between these two values, let us say a range of 4·5°C (0·75°C/h) as a desirable maximum.

The author's gratitude is due to the 32 subjects who took part in the experiment and to Adrian Bristow, M.A.(Cantab.), Principal, and Brian Bracegirdle, B.A., Vice-Principal, of Chester College of Further Education, for their willing co-operation.

Cet article décrit une expérience dans laquelle 16 sujets étaient soumis chacun à quatre niveaux de variations de la température ambiante et devaient évaluer la sensation ressentie. Ces variations étaint de 0°, 3°, 6° et 9°C symétriques de part et d'autre d'une valeur centrale de 23°C et linéaires sur une période d'exposition de 6 heures. Les variations se produisaient aussi bien dans les directions ascendantes que descendantes. Les sujets donnaient une estimation de leur sensation thermique toutes les heures. Une évaluation à l'aide de 11 échelles de différenciateurs sémantiques leur était proposée à la fin de la période d'exposition. L'échelon de variation le plus faible était détecté par les sujets et chaque variation était jugée comme moins agréable et plus inégale que la constance de l'environnement. Le degré d'extraversion des sujets et la direction de la variation des températures sont apparus comme étant des variables non significatives. Une méthode d'évaluation du degré d'insatisfaction induit par les variations de températures est brièvement décrite.

Die Arbeit beschreibt ein Experiment, in dem jede von 16 Personen 4 Stufen der Änderung der Temperatur ausprobieren und ihre Empfindungen wiedergebn musste. Die Änderungen betrugen 0°, 3°, 6° und 9° und lagen symmetrisch um einen Mittelpunkt von 23°C und linear über eine Versuchszeit von 6 Stunden verteilt. Änderungen erfolgten auf-wie abwärts. Die Versuchspersonen berichteten ihre Wärmeempfindungen in stündlichen Intervallen und am Ende der Versuchszeit in einer summarischen Feststellung. Die geringste Änderungsgrösse wurde zuverlässig entdeckt. Änderungen der Umgebung wurden weniger angenehm empfunden als konstante Bedingungen. Der Grad der Ablehnung der Versuchsperson und die Richtung der Temperaturänderung waren keine signifikanten Variablen. Eine Methode zur Schätzung des Grades der Unzufriedenheit bei Temperaturwechsel wird kurz beschrieben.

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