THERMAL COMFORT AND PRODUCTIVITY

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ABSTRACT
This paper discusses the link between thermal comfort and productivity of office workers and presents some limited conclusions from a European field study of office buildings. The importance of productivity measurement and current methodologies of measurement are discussed and shortcomings highlighted. The paper concludes with an introduction to a new technology developed in Japan that may provide an alternative method of measuring productivity in the field.

INDEX TERMS
Thermal comfort, Productivity, Chaos Theory, Fatigue, Field Studies

INTRODUCTION
Despite the obvious importance of thermal comfort issues, building designers are still loath to spend time and effort in providing well-designed climate-control solutions. They argue that whilst thermal comfort is important, it is more vital to reduce construction and running costs of the building. This view is echoed by building owners/ managers who are concerned primarily with financial issues, mainly in connection with their businesses rather than with the building. But when one considers the cost of a building over its entire lifetime, the construction and running costs are relatively minor when compared with occupant salaries and business running costs (Edwards, 1989.) It would make sense, therefore, to optimise occupant working and ensure that absenteeism is minimised and productivity maximised.

In recent years, researchers have sought to establish a definite link between thermal comfort and occupant productivity. Whilst most researchers would agree that a link exists, it is difficult to prove scientifically or statistically since productivity is difficult to measure and quantify. In practice, there have been two main approaches to the assessment of productivity and the link to thermal comfort.

Specific Task Performance
Studies have shown that under strictly controlled conditions, the performance of certain carefully designed tasks is temperature dependent. The performance of some tasks improves with rising room temperature, while that of the others deteriorates (Wyon, 1986.) Despite the high quality of this research, it has proven difficult to relate the results to the circumstances of everyday office work as motivation and stress under test conditions differ from those in the workplace.

One of the few examples of productivity being measured in the field is a study by (Kroner and Stark-Martin, 1994.) In this study, a group of office workers whose job was to process files were monitored over two periods, pre- and post-installation of a new air-conditioning system. An 'in-house' system of counting the number of files that each employee processed per day

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was already in place and the researchers used this as a methodology for measuring their productivity. However, most office work does not involve repetitive tasks that can be easily measured and indeed modern working is becoming more multi-faceted. So although it is established that certain tasks are temperature sensitive, it has not proved possible to use this knowledge with conviction when specifying office thermal environments.

Perceived Productivity

An alternative approach is to use self-assessment questionnaires. During the course of their normal work, occupants are asked to assess their own 'perceived' productivity on a subjective rating scale. The results from these votes are then compared to measurements of the indoor environmental conditions to establish a link to thermal comfort. Studies of this kind tend to show that perceived levels of productivity fall as the perceived environmental conditions move away from an 'optimum' value. This method is the one most commonly used by thermal comfort researchers today. Two of the most prominent researchers in this area are Bill Bordass, Leaman and Ruyssevelt, in particular their work on the PROBE studies of the 1990s (Bordass, Leaman and Ruyssevelt, 2001.)

The strength of this approach is that it is not task dependent and is relevant to everyday office practice. As long as all occupants assessed in the same study vote on the same scale, results can be compared directly. However, the weakness is that this method is not an unbiased, objective measurement and therefore any conclusions drawn are somewhat tenuous.

This method was adopted for the SCATs project, as described below.

THE SCATS PROJECT

The Smart Controls and Thermal Comfort (SCATs) project ran from 1997 to 2000 with Oxford Brookes University acting as co-ordinator of a consortium of academic and industrial partners from around Europe. The project was funded by the European Project under its JOULE programme and was budgeted at approximately 1.4M Euros. The ultimate aim of the project was to develop a new method of controlling the internal climate of buildings based on Adaptive Comfort Theory, a concept first introduced by Nicol and Humphreys in the early 1970s (Nicol and Humphreys, 1972.) As part of the project, an extensive series of field studies was conducted on 25 buildings around Europe involving both subjective and objective measurements of the internal environmental conditions within those buildings. A full description of the project methodology can be found in a forthcoming paper by McCartney and Nicol [2002] or in the SCATs final reports to the European Union (Nicol and McCartney 2001a, 2001b.)

For the purposes of this paper we have investigated the potential link between actual temperature measurement, subjective response to temperature and perceived productivity. Subjective temperature responses were analysed using the ASHRAE 7-point thermal sensation scale (1 to 7, cold to hot, 4 neutral) and a 5-point preference scale (1 to 5, much warmer to much cooler, 3 no change). Perceived productivity was assessed using the question and scale below:

At present, how is your productivity being affected by the surrounding environmental conditions?	*Much higher than normal*	*1*
	Slightly higher than normal	*2*
	Normal	*3*
	Slightly lower than normal	*4*
	Much lower than normal	*5*

The results were analysed using Microsoft Excel® and SPSS 10.0 for Windows® and a summary is presented below.

RESULTS

Perceived productivity vote was plotted against quintiles of air temperature. The results are shown in Figure 1 below.

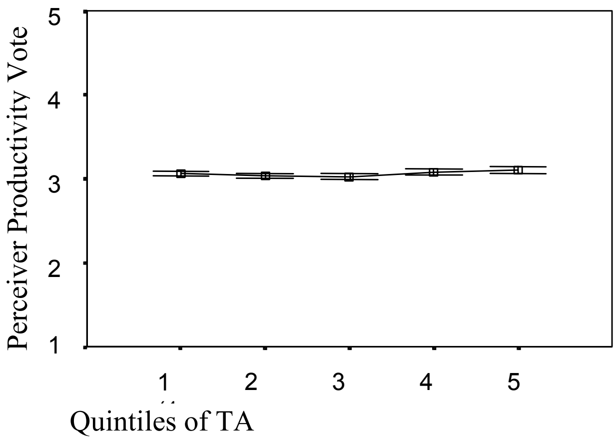

Figure 1: Perceived Productivity Vote versus Quintiles of Air Temperature, T_A. *(Note that the higher the Perceived Productivity Vote, the lower perceived productivity. The error bars represent the 95% confidence range of the productivity vote. The quintiles of air temperature represent an overall range of approximately 13.1°C to 31.1°C with categories as follows: 1(13.1 – 21.9°C), 2 (21.9 – 23.0°C), 3 (23.0 – 23.9°C), 4 (23.9 – 25.2°C), 5 (25.2 – 31.1°C)).*

The results show that perceived productivity does not vary with indoor air temperature. This is contrary to some research views that suggest that either a substantial increase or decrease in temperature will result in a fall in productivity. Certainly, studies by Wyon have highlighted problems at temperature extremes, but these were concerned with more manual tasks (Wyon, 1986.)

Perceived productivity was then plotted against the Temperature Preference Vote. The results are shown in Figure 2 below:

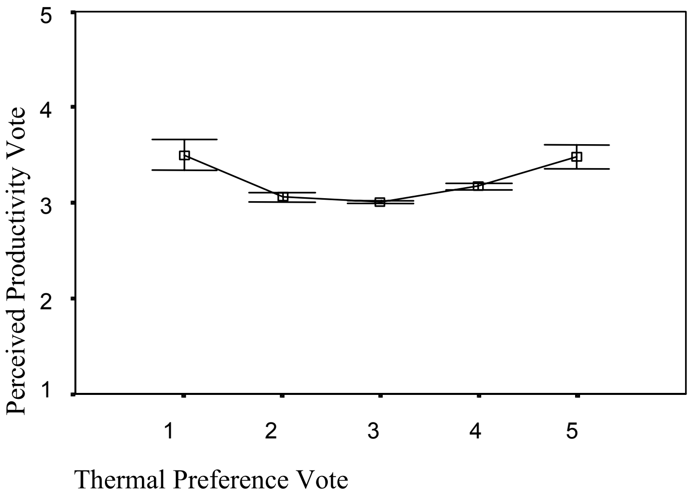

Figure 2: Perceived Productivity Vote versus Thermal Preference Vote, TP. (Note that TP scale goes from 1 to 5, Much Warmer to Much Cooler, with 3 No Change)

The results show that as thermal preference moves away from 'no change (3)', perceived productivity falls. Few perceived productivity votes below 3, i.e. slightly higher or much higher than normal, were received from occupants in the study.

Considering figures 1 and 2 together, it can be seen that whilst perceived productivity is not influenced by actual temperature itself, it is influenced by 'perception' of temperature, i.e. thermal comfort. The results add some weight to Adaptive Comfort Theory as they suggest that people may report no change in productivity at high or low temperatures providing they have adapted sufficiently to maintain comfort levels. The results also support the findings of Leaman and Bordass who suggest that productivity is influenced by more 'personal' variables like availability of environmental controls and office management issues (Leaman and Bordass, 1997.)

Whilst the above results are fairly crude, they do suggest a definite link between productivity and thermal comfort and certainly warrant further investigation. But the actual measurement of productivity remains a problem. The scale shown above is quite simplistic and open to much bias. Also, analysis of the SCATs databases has highlighted potential problems in translating semantic rating scales into different languages.

Many researchers are currently working on the subject of improved thermal comfort measurement and most are approaching the problem by designing better questionnaires for self-assessment that remove the potential for bias. However, what is really required is a methodology for measuring productivity that incorporates both the scientifically robust aspects of specific task performance *and* the more 'user-friendly' aspects of perceived productivity self-assessment. The method should also seek to avoid the use of scales that are prone to translation difficulties.

INVESTIGATING A NEW APPROACH

Researchers at the Electronic Navigation Research Institute (ENRI) in Tokyo, Japan have recently developed a method of analysing speech patterns for signs of drowsiness and fatigue. Their intention is to produce an automatic drowsiness detector for use in the aircraft industry. The researchers claim that their technology can detect fatigue 20 minutes before that person will actually feel fatigued (Shiomi and Hirose, 2000). This has great potential in the field of aircraft safety.

The prototype system developed by ENRI begins by recording a 30-second reference sample of speech from the subject when he is alert. Further speech samples are then recorded at random intervals. A 10-second sample is sufficient for the software to make an analysis, although accuracy is improved with a 30-second sample (Shiomi and Hirose, 2000.) Each sample is then compared to the reference in order to determine whether the subject is becoming fatigued. The speech pattern signal had a fractal structure whose strange attractor changes visibly with the onset of fatigue, well before the subject reports drowsiness. Figure 3 below shows the strange attractors produced by a 'normal' speech sample (on the left) and a 'fatigued' speech sample (on the right). A visual inspection shows a clear difference between the two.

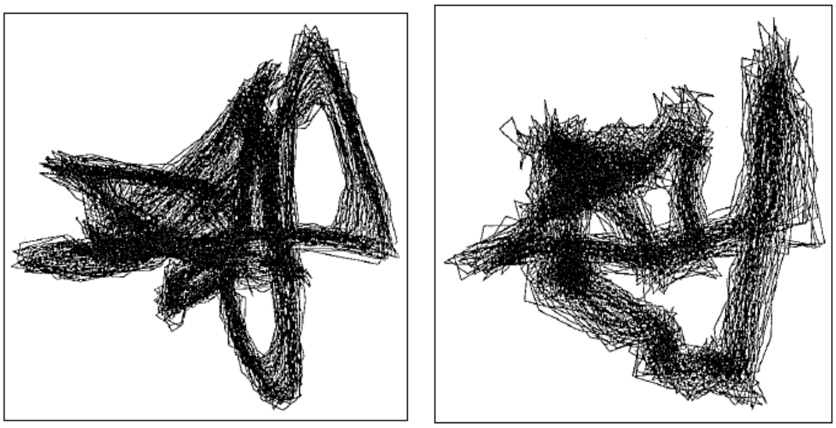

Figure 3: Strange Attractors for Speech Samples. 'Normal' Speech is shown on the left, 'fatigued' speech on the right

Using chaos theory mathematics, the strange attractors can be analysed to produce a Ljpunov exponent, a non-dimensional variable. For 'normal' speech, this should be in the range 300-400. As the subject becomes more fatigued, the exponent value increases. In aircarft applications, an audible alarm would sound on the Ljpunov exponent reaching a value of 600. Figure 4 shows a typical visual output from the system developed by ENRI. The Ljpunov exponents are calculated and the level of fatigue evaluated as a percentage. This can be expressed on a 'fatigue meter' that will flash red if the subject becomes sufficiently drowsy.

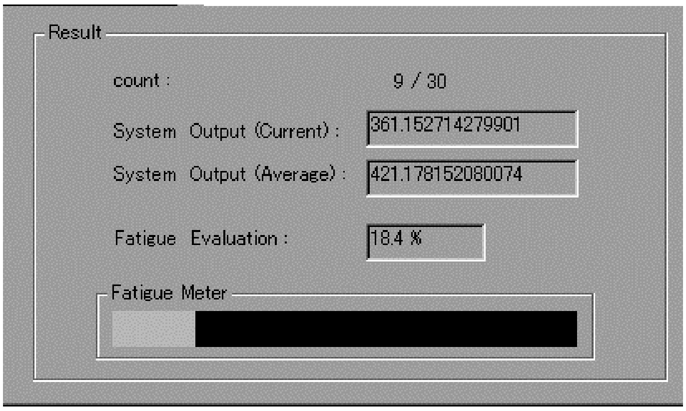

Figure 4: Visual Output from ENRI Software

Researchers at Oxford Brookes University are planning to use the above software in a building application to ascertain whether or not it could be a suitable method of measuring productivity in the field. It is proposed to test the system in a series of field surveys during which thermal comfort measurements would also be taken. The system would also be tested in a climate chamber with subject performing specific tasks to gain more scientifically robust data.

In postulating this system as a new method of measuring productivity, a number of assumptions have been made. First of all that fatigue and productivity are empirically linked. Whilst common sense would suggest that this is true, there may be other physiological responses with a stronger link to productivity. Secondly, that fatigue and thermal comfort are empirically linked. Again, common sense would suggest a link, but it is important to remember that fatigue is more likely to be caused by health and well-being issues. There are also some concerns over the software itself. To date, it has only been tested on Japenese subjects and whilst researchers at ENRI are convinced that the system will work independent of language, this has to be established via experimentation.

Despite the above concerns, a full test of the above system is warranted and Oxford Brookes University are currently seeking funding for a full research programme.

CONCLUSIONS

The link between thermal comfort and productivity must be proven to encourage buildings designers and owners to adopt climate control strategies that improve the comfort and well-being of the building occupants. However, a more robust methodology of measuring productivity in the workplace is urgently required. A combination of self-assessment questionnaires and some physical measurement may be an appropriate path to follow, but the semantics of rating scales should be chosen with care.

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