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Control of Temperature for Health and Productivity in Offices

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ABSTRACT

Indoor temperature is one of the fundamental characteristics of the indoor environment. It can be controlled with different accuracy depending on the building and its HVAC system. The purpose of this study was to evaluate the potential benefits of improved temperature control, and apply the information for a cost-benefit analyses. The indoor temperature affects several human responses, including thermal comfort, perceived air quality, sick building syndrome symptoms and performance in work. In this study we focused on the effects of temperature on performance in work. We collected and analyzed the literature relating the performance in work and temperature. The results of multiple studies are relatively consistent and show an average relationship of 2% decrement in work performance per degree ^oC when the temperature is above 25^oC. Less data were available on the performance in low temperatures. However, studies show a strong effect on manual tasks with temperatures below thermal neutrality as soon as the temperature of hands decreased due to control of blood flow. When the estimated productivity decrement from elevated temperetures was applied to data from a study of night-time ventilative cooling, the estimated value of productivty improvements were 32 to 120 times greater than the cost of energy to run fans during the night.

KEYWORDS

productivity, performance, temperature, offices

INTRODUCTION

In many commercial buildings, thermal conditions are not well-controlled due to insufficient cooling or heating capacity, high internal or external loads, large thermal zones, improper control system design or operation, and other factors. Thermal conditions inside buildings vary considerably with time, e.g., as outdoor conditions change, and spatially within buildings. While the effects of temperature on comfort are broadly recognized, the effects on worker productivity have received much less attention.

For example, in a large US study, 50% of the subjects preferred a change in their thermal state, 38% of subjects in winter were dissatisfied with thermal conditions, and almost 50% of the thermal conditions during summer were outside of the thermal comfort zone (Schiller et al. 1988). Federspiel (2001) reported that 18.4% of complaints were classified as indoor environmental complaints in a dataset which was collected from 575 buildings in the USA. 77% of indoor-environmental complaints were about conditions perceived too hot or too cold. He showed that the rate of complaints depends on the average room temperatures and its standard deviation in the building.

Increased evidence shows that indoor environmental conditions substantially influence health and productivity. Building services engineers are interested in improving indoor environments and quantifying the effects. Potential health and productivity benefits are not yet generally considered in conventional economic calculations pertaining to building design and operation. Only initial cost, and energy and maintenance costs are typically considered. A few sample calculations have also shown that many measures to improve indoor air environment are cost-effective when the health and productivity benefits resulting from an improved indoor climate are included into the calculations (Djukanovic et al. 2002, Fisk 2000, Hansen 1997, Seppänen and Vuolle 2000, Tuomainen et al. 2002). There is an obvious need to develop tools so that economic outcomes of health and productivity can be integrated in cost benefit calculations with initial, energy and maintenance costs. We assembled existing information on how temperature affects productivity so that these productivity effects could be incorporated in cost benefit calculations related to building design and operation, and demonstrated with an example how the date are used.

LINKAGE BETWEEN PRODUCTIVITY AND TEMPERATURE

High temperatures and productivity

Room temperature could influence productivity indirectly through its impact on prevalences of SBS symptoms or satisfaction with air quality; however, for cost-benefit calculations it is most feasible to use the available data directly linking temperature, or thermal state, to productivity. The studies on this linkage are described shortly in the following.

Niemelä et al. (2001) reported decrement in productivity of call centre workers corresponding 1.8% per ^{o}C when the temperature was above 25^{o}C. In a second experiment performed in the same call center, Niemelä et al. (2002) reported a productivity decrease of 2.2% per ^{o}C when the temperature increased above 25^{o}C. Federspiel et al. (2002) measured the productivity of call center workers in the US. They found no significant relationship of temperature to productivity in the comfort zone but reported a 15% decrease in productivity as the temperature increased from 24.8 to 26^{o}C. Link and Pepler (1970) measured productivity in an apparel factory. They found a reduction of 8% in productivity in sewing work as the temperature increased from 23.9 to 32.2^{o}C.

Wyon (1996) summarized his earlier experimental work and developed a relationship to estimate the productivity decrement in office work based on experimental data from tests which measured thinking, and typing skills and speed. He gave equal weigh to each skill and ended up with a relationship between an over-all decrement of performance in office work as a function of the difference between the actual temperature and the temperature for thermally neutrality. Berglund et al. (1990) used the data from a test relating the performance of wireless telegraph operator in a wide range of thermal conditions from comfortable to very hot. Berglund used physiological thermal model to relate performance to “effective temperature” (ET*) and then used this relationship to predict how the productivity of normally clothed office workers would vary for a typical range of indoor temperatures. His analysis is based on an assumption that the thermal stress is the best indicator of the performance and productivity. Roelofsen (2001) used this model further and converted Berglund’s ET*-values to two commonly used thermal comfort parameters, predicted mean vote (PMV) and predicted percent of dissatisfied (PPD) which enables the model to be used for various combinations of thermal factors. Johansson (1975) exposed 18 boys and 18 girls with light clothing in a climate chamber to effective temperatures of 24, 27 and 30^{o}C, corresponding normally-clothed subjects with the same degree of thermal strain at 23, 30 and 36^{o}C. Several tests were used to evaluate the effect of thermal environment on performance. Most tasks were impaired for higher two temperatures. Performance in tests of learning, addition and multiplication tests were 10 –14% worse at the effective temperatures of 27, 29^{o}C than in 24^{o}C. Perceptual tasks measuring cue-utilization and attention had an inverted U-shape relationship with temperature with the best performance in 27^{o}C. Pepler and Warner (1968) performed experiments with 36 female and 36 male students in a climate chamber. They found an inversed U-shape relationship between time to complete a task and temperature, with the longest time to complete assignments work at 26.7^{o}C. However, the error rate, was lowest at 26.7^{o}C.

The findings described above are summarized in Figure 1. It shows the decrement in work performance as a function of temperature from all of these experiments. The results from laboratory studies were given as the average results from the tests. All data were normalized using the best value of the productivity in each experiment as a reference.

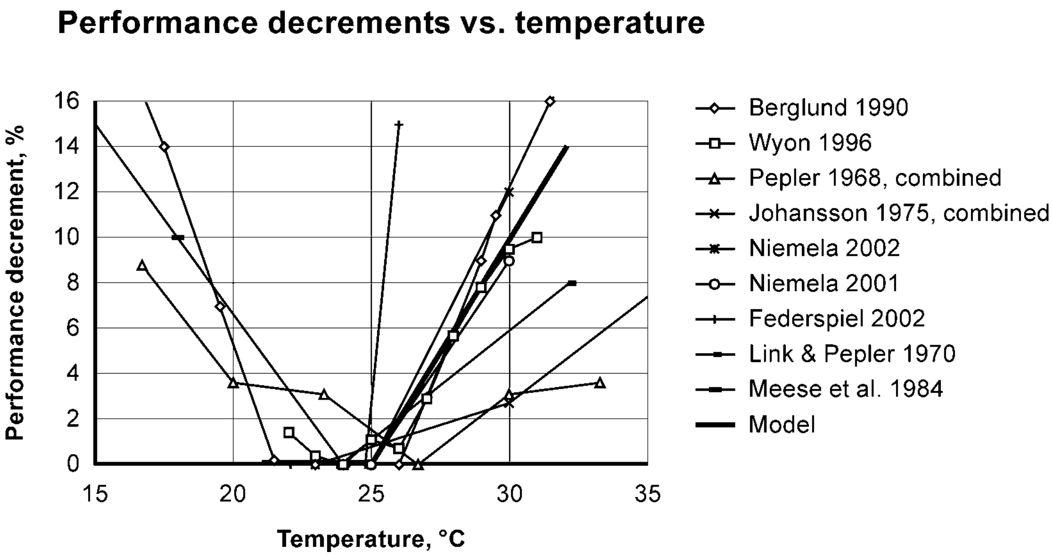

Figure 1 Summary of the studies on the effect of room temperature on decrement of performance and productivity.

No-effect range of temperature

Some research [e.g. Griffiths and McIntyre (1975) Gonzales (1975)] indicates that the most comfortable temperature yields optimal work performance, while others research provides evidence of better performance outside the comfort zone due to arousal effect of the environment (Wyon et al. 1979). The data do not provide compelling or consistent evidence that temperature variations within the comfort zone significantly affect worker performance.

Several studies support the hypothesis that there is a temperature range with **no** significant effect on productivity. For example, in the study within a call center by Federspiel et al. (2002), temperature variations between 21.5 and 24.75°C did not appear to significantly affect work speed; however, work speed was significantly diminished at 26°C. In a different study of the relationship of air temperatures with occupants´ hot or cold complaints, Federspiel (2001) found that the complaint rate was very low in the temperature range of 22.2 - 23.9°C. Avoiding complaints might also prevent productivity decrements. This gives the approximate correspondence with the 21 to 25°C range for which productivity decrements in our model are assumed negligible. The no-effect range can be supported also with studies by Witterseh (2001). He did not find significant differences of performance in simulated office work (multiplication, text typing and addition tests) in laboratory experiments for subjects thermally neutral at 22°C and 25°C or for the subjects slightly warm discomfort. The 21 to 25°C temperature range is also close to range of temperatures considered comfortable in thermal comfort standards. Some studies support, actually, the use the thermal comfort as optimal also with respect to self-estimated productivity. For example, McCharthy and Humpreys (2002), found that the decrement in self estimated productivity corresponded with the thermal preference vote, which determines if occupants would like to be cooler or warmer.

Low temperatures and productivity

Less information is available on the degree to which productivity is affected by slightly low temperatures or cold thermal sensations. Only some [Wyon (1996) and Berglund et al. (1990)] of the studies reporting the effect on warm temperatures report the relationship with cold temperatures. These are shown also in the Figure 1. Much more information is available on the effects of extremely low (or extremely high) temperatures not commonly experienced in office buildings.

Low temperatures have been found to be related to performance of manual tasks through the dexterity of the hands. In the tests of manual dexterity, performance depends on the temperature of fingers and hands which in turn depends on the thermal balance of the body. In low temperatures blood flow to the hands is restricted which causes the hand temperature to drop before the core of the body cools down. The dexterity of hands is deteriorated already with indoor air temperatures between 20 - 22°C. Meese et al. (1984) reported significant decrement in finger strength and speed in pencil rolling task with different levels of retardation, and pegboard, screwplate, block treading and knot-tying tests. The performance in all tests was 5 to 15% lower with an ambient temperature of 18°C than with the reference temperature of 24°C.

It is obvious that the dexterity of hands and fingers is important in manual work but it may also be important in modern office work where a major part of work is done with computers. However, we cannot relate quantitatively decrements in dexterity of fingers to performance of word processing in office work. Large individual variations of finger temperature vs. ambient temperature have been recorded by Humpreys et al. (1999). The data also show that significant portion of people have finger temperature close to ambient globe temperature when this ambient temperature is below 24°C, the limit of the temperature effect on the dexterity of hands.

The dexterity of fingers may affect also on the word processing work, and have an influence on the productivity. The information for this relation, however, is not yet available.

Temperature and sick building syndrome symptoms

Several studies have shown the linkage between high temperatures and a higher prevalence of symptoms as reviewed by Mendell 1993. Warm room air temperature in the winter seem to cause a higher number of typical sick building symptoms than cooler air. The relationship between the number of symptoms and temperature was close to linear in the temperature range from 20 to 26°C in a study in cold climate Seppänen and Jaakkola (1989). In a later experiment Mendell et al. (2002). reported decrease of the prevalence of typical SBS-symptoms 12 – 24% per degree of °C in the temperature range of 22.2 – 25.6°C in warmer climate with indoor relative humidity 42 –50%.

In a recent experiment by Fang et al. (2002) subjects in a laboratory experiment reported significantly more intense SBS symptoms associated with decreased productivity, including fatigue, headache and difficulty in thinking clearly, when they were exposed to raised levels of temperature and humidity (20°C and 40% vs. 26°C and 60%).

SBS symptoms may also be related to reduced performance or productivity. Based on the reviewed studies (Seppänen and Fisk 2004), subjects who report more SBS symptoms also report more IEQ-related absence and IEQ-related decreases in productivity. However, the validity of the self-reported absence and productivity data is unclear. Also, these data do not confirm that increased SBS symptoms are the cause of the decreased self-reported productivity or increased absence. Due to these uncertainities we propose to use the direct relation between temperatures and productivity instead of the linkage via SBS-symptoms.

Model for the effect of temperature on productivity loss

After plotting all findings between temperature and performance in the Figure 1, for cost- benefit analyses we conducted that productivity is unaffected by temperature in the 21 to 25°C range. While the case for productivity decrements at elevated temperatures seems relatively strong, the relative weight that should be applied to different studies is unknown, thus, we concluded that deriving a linear or non-linear statistical best fit to the available data was not warranted. Thus, we drew a line, shown in Figure 1 (labelled "Model" in the legend), with a linear productivity decrease of 2% per degree centigrade as the temperature increased above 25°C. Yielding the following relationship between decrement in productivity P in % and temperature T in °C:

$$25 < {}^{o}C < 33 \qquad P\ (\%) = [2 \times (T, {}^{o}C)] - 50$$

$$21 < {}^{o}C < 25 \qquad P\ (\%) = 0$$

Use of the model

The model can be used to estimate the value of the improved thermal environment. The temperature data from the building simulations can be used in calculations. As the relationship between temperature and productivity decrement is linear, an easy method is to calculate degree hours of the temperature above 25°C during working hours. 2% of this number corresponds lost working hours due to high temperatures. Multiplying this number by hourly value of work gives the potential savings due to improved control of thermal environment. Seppänen and Vuolle (2000 and 2003) calculated value of degree hours for a typical Finnish office building above 25°C to be 890°Ch which corresponded potential savings of $330 per employee per year. This was much higher than the annual cost of the improved thermal control.

EXAMPLE COST-BENEFIT ANALYSIS OF NIGHT-TIME VENTILATIVE COOLING

Natural and mechanical night-time ventilative cooling is a cooling strategy that has been used throughout the centuries especially in climate regions with hot summers. Recently, there is a renewed interest in night-time ventilative cooling in both hot and moderate climates due to its potential benefits in indoor temperature control with low energy use and, hence, with low environmental impact. Its principle is based on the daily temperature swings during hot periods. A typical daily temperature swing is around 12°C; however, it can be considerably smaller (e.g., on cloudy days) or higher with clear skies and a continental climate. The cool night-time air can be used to cool the building during night. This cools the structure and furnishings, which become a heat sink during the day, thus, reduce the day-time temperatures. Kolokotroni et al. (2001) provided measured room air and slab temperature for an office room with and without night-time ventilation. We used these data in conjunction with the simple productivity decrement model and an estimate of the cost of fan energy to perform a cost-benefit analysis of providing night-time ventilative cooling in an non air conditioned office building (Seppänen et al. 2003).

Table 1 provides temperatures based on the data of Kolokotroni et al. (2001). We estimated the operative temperature as average of air and slab temperatures for the room with and without night-time ventilation, and summed the degree hours above 25 °C for both cases. Without the night-time ventilation there were 21°C-hours above 25°C. With the night-time ventilative cooling, there were only 1.5°C-hours above 25°C. The difference of 19.5°C-hours per day is the benefit of night-time ventilation.

Using the linear relation between loss of productivity and temperature, with a 2% productivity loss per degree when the temperature is above 25°C, the productivity increase with night-time ventilative cooling is equivalent to 0.39 hours of work per day (19.5°C-hours per day x 0.02 per °C = 0.39 h/day). If we assume that the average value of an hour of work is $30 hourly, the productivity benefit is $11.7 per day per person. Of course, this benefit can be only realized during periods of hot outdoor daytime temperatures, and the magnitude of the benefit will depend on both the daytime temperatures and the daily temperature swing.

TABLE 1

Hourly temperatures (°C) without (above) and with night-time ventilation and hourly temperature differences above limit temperature of 25°C

Hour	8-9	9-10	10-11	11-12	13-14	14-15	15-16	16-17	°C-h per day
Without night-time ventilative cooling									
$T_{outdoor}$	19	21.5	24.5	26.5	26.8	27.0	27.1	27.3	
$T_{air,\ indoor}$	26.3	26.6	27.3	27.5	27.6	27.6	27.7	27.7	
T_{slab}	27.8	27.8	27.9	28	28	28.1	28.1	28	
$T_{operative}$	27.05	27.2	27.6	27.75	27.8	27.85	27.9	27.85	
$T_{operative}$-25	2.0	2.2	2.6	2.75	2.8	2.85	2.9	2.85	21
With night-time ventilative cooling									
$T_{air,\ indoor}$	23.5	23.6	24	24.5	25.9	26.1	26.1	26	
T_{slab}	23.2	23.4	23.8	24	24.6	24.7	24.8	24.8	
$T_{operative}$	23.35	23.5	23.9	24.25	25.25	25.4	25.45	25.4	
$T_{operative}$-25					0.25	0.4	0.45	0.4	1.5

The night-time ventilative cooling can be accomplished either by opening the windows or running the HVAC system. For security and other reasons we did not consider the window opening option, instead we assumed the air handling system was used for night ventilation with a running time of 8 hours a night. The use of fans requires some energy. We estimated the fan power based on the common Scandinavian building code value D2 (2002) for total energy consumption of return, exhaust and supply fans of 2.5 kW per m^3/s of air flow. For the basic night ventilation rate we assumed a 4 air change per hour flow rate, typical of the capacity of many HVAC systems, and assumed a room volume of 83 m^3 per occupant. The resulting costs of fan energy with electricity prices from US$ 0.05 to US$ 0.20 per kWh are shown in Table 2. The table also shows the corresponding benefit-to-cost ratios which range from 32 to 120.

TABLE 2

Cost of electricity and value of improved productivity due to night ventilation. All values per occupant per day.

Price of electricity, $ kWh	Use of electricity by fans for 8 hours of ventilative cooling, kWh	Cost of fan electricity, $	Productivity benefits, $	Benefit cost ratio
0,05	1.84	0.09	11.7	120
0,10	1.84	0.18	11.7	64
0,15	1.84	0.28	11.7	42
0,20	1.84	0.37	11.7	32

CONCLUSION AND DISCUSSION

We have developed an initial quantitative relationship between work performance and temperatures within and above the comfort zone. This relationship has a high level of uncertainty; however, use of this relationship may be preferable to the current practice which ignores productivity. The quantitative relationship between temperature and productivity may vary depending on other building features, and on the characteristics of building occupants and their type of work. Remedial measures will generally also be more cost effective in buildings that have poorer initial IEQ or more existing adverse health effects. We also have demonstrated with a simple example using night-time ventilative cooling that energy efficient methods are available to improve the indoor environment. For this example, the ratio of productivity gains to energy used by fans varied from 32 to 120 depending on cost of the electricity.

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