PMV-derived productivity model as a tool to assess productivity loss

Risto Kosonen[a,*], Freddie Tan[b]

[a]*Halton Oy, Finland;* [b]*Premas International Limited, Singapore*

ABSTRACT

A novel PMV index based productivity model is derived and it is used to estimate the effects of different thermal conditions on productivity. Past research findings are used as inputs in the creation of this productivity loss model. The PMV equation is useful to predict productivity loss that is due to the rate of change in thermal conditions. Using the model prediction, the theoretical maximum level of productivity occurs when the PMV value is –0.21. Admitting a 30% productivity loss in typing-task, the model predicts PMV value ought to be at least +0.63. In a similar case in thinking-task, the model predicts a higher PMV value of +1.28. For the productivity loss of 30%, the difference in temperature range can be a small margin of 2–3°C in typing tasks and a wider range of 4–6°C in thinking tasks depending on the level of the neutral temperature.

INDEX TERMS

Productivity; PMV index; Thermal comfort; Productivity assessment method

INTRODUCTION

The primary objective of an air-conditioning system in a commercial building is to provide an environment that will foster tenants' productivity and to increase the profitability of business. In the building process, it is common that the first cost is the main consideration when making choices between different systems. A lower initial investment can turn out to be more costly from the whole life-cycle viewpoint if the operation costs and the influence on productivity of workers are not taken into account.

It has been determined that in US office buildings, building energy, maintenance, annualized construction and rental costs far exceed, by a 100 times, the workers salary (Woods, 1989). Therefore, a modest increase in productivity can be a reasonable basis to justify initial value added expenditure that will lead a more efficient and economical solution. Thus, a primary design target should be to design indoor conditions that are conducive to the tasks being performed in that space so as to maximize productivity.

This study reports on the assessment of productivity loss in air-conditioned office buildings using the PMV approach and makes use of Wyon et al.'s (1975) and Wyon's (1996a,b) reviews as the basis to compare and to relate how the productivity loss could be minimized through improved thermal comfort design criteria. This 'retrospective' interpretation, by means of PMV parametric analysis, also helps to re-examine the nature of productivity loss reported in earlier studies.

METHODS

Earlier studies of the thermal comfort impact on human performance are mainly focus on the interdependence of one independent parameter to the productivity loss. In this study, the existing results are extended to form generic productivity loss model where the main parameter is the PMV index. In thermal comfort optimization, the PMV index is the most suitable platform to analyse the effect of all different combination of the thermal conditions

* Corresponding author. E-mail: risto.kosonen@halton.com

on the productivity loss. Also, PMV index is a suitable index to include in the traditional energy, life-cycle costs and air distribution design tools.

Wyon (1996b) has summarized thermal effects on performance in laboratory environments. Productivity loss is presented as a function of room temperature in different tasks. The main findings are twofold: (a) for thinking tasks, the rate of working was reduced by 30% at 27°C when the base neutral temperature was 21°C and it remained constant at 70% for higher temperatures above 27°C; and (b) for typing tasks, performance decreased to 70% over 4°C and remained at 70% at higher temperatures. Thus, productivity loss is strongly dependent on the temperature and the nature of the performed task. The approach makes use of two main tasks: typing and thinking. Probably the best approach, when the exact job description is unknown, is to fit the general pool of job descriptions by using the time weighting factors for the tasks.

These past findings provide the impetus to model the simulated subjective responses of occupants in buildings, using the PMV parametric analysis, with respect to the rate of change in thermal conditions and the impact of the changing thermal conditions on both the thinking and typing tasks where the thermal neutral balance situations are fully documented. Wyon et al.'s (1975) and Wyon's (1996a,b) results are therefore used and reconstructed in this study to create a generic productivity loss model using the PMV index as a 'navigating' search and assessment tool.

RESULTS

Basis for a Generic Productivity Model

Table 1 reports the results of the parametric analysis that is carried out at a room temperature of 21°C and relative humidity of 50%, in a condition that is somewhat akin to Wyon's (1996b) review. The base case depicts the estimated conditions in the conducted review. The reference cases 1–4 in Table 1 are examples of the other possible combinations of thermal conditions during this cited but unfortunately not fully documented test condition.

In the base case, the clo-value has been adjusted exactly to 1.16 to reach the thermal neutral conditions (PMV = 0). At the same way in the reference cases 1–4, the requested theoretical clo-values are calculated to reach thermal neutrality at the starting temperature of 21°C.

The effect of the temperature difference from the neutral conditions on PMV index is slightly different with the various combinations of the thermal neutral condition. Still, the PMV values at different room air temperatures of the reference cases are almost similar than in the base case that is estimated to describe the conditions in the reviewed study. Thus, the reconstructed conditions are reasonable accurate for use to predict the PMV-productivity loss analysis and generalize the previous temperature correlation to cover PMV and productivity interdependence.

This base case comparison has shown that the PMV parametric analysis is a suitable approach to create the causal relationship between the PMV index and results of both the productivity loss for thinking and typing office tasks that are reported by Wyon (1996b) (Table 2).

Table 1 Comparison of PMV values at different temperature differences from the neutral conditions in the selected cases

Temperature difference using a starting base temperature of 21°C	Estimated conditions for Wyon's review (base case)	Other simulated reference cases			
		1	2	3	4
	DT_{rad} = 0°C *v*=0.15 m/s clo=1.16 MET=1.2	DT_{rad} = 0°C *v*=0.15 m/s clo=1.2 MET=1.1	DT_{rad} = 0°C *v*=0.25 m/s clo=1.25 MET=1.2	DT_{rad} =-2°C *v*=0.15 m/s clo=1.23 MET=1.2	DT_{rad} = 2°C *v*=0.15 m/s clo=1.03 MET=1.2
	Reconstructed PMV results	Other simulated reference cases—PMV results			
0	0	0	0	0	0
+1	0.21	0.21	0.21	0.19	0.23
+2	0.42	0.43	0.42	0.39	0.46
+3	0.63	0.65	0.63	0.59	0.68
+4	0.84	0.87	0.85	0.79	0.91
+5	1.06	1.09	1.07	0.99	1.14
+6	1.28	1.32	1.28	1.19	1.38

Table 2 PMV prediction of thinking and typing tasks at different temperatures

Temperature difference from base temperature of 21°C	PMV prediction	Predicted percentage dissatisfied (PPD) (%)	Wyon's productivity loss in thinking (%)	Wyon's productivity loss in typing (%)
–1	–0.21	6.3	0.0	0.0
0	0	5.0	1.9	4.9
+1	0.21	6.0	5.4	13.5
+2	0.42	9.0	10.1	23.2
+3	0.63	14.0	15.3	30.0
+4	0.84	21.0	20.6	32.8
+5	1.06	29.0	25.7	33.4
+6	1.28	38.0	30.0	33.5

The PMV prediction describes that the peak level (assumed = 100%) in productivity should occur when the PMV value is –0.21 at a temperature of 20°C. The PPD in this case has a low value of 6.3%. This hypothetical benchmark is aimed to offer a better insight of thermal responses at the corresponding higher temperatures. The results show that, as air temperature increases above the neutral temperature of 21°C for the envisaged productivity losses in thinking and typing, the corresponding PMV values would increase from 0 (neutral sensation) to 1.28 (warm sensation). At an air temperature of 24°C, the productivity loss in typing task reaches 30% already with a predicted PMV value of 0.63 (slightly warm sensation). This is significantly smaller value than the PMV value of 1.28 in thinking task.

Using the previous correlation for thinking and typing tasks, it is possible to calculate the productivity loss as a function of PMV, and as a function of PPD using the time weighting factors for typing and thinking tasks. The results are shown in Figures 1 and 2.

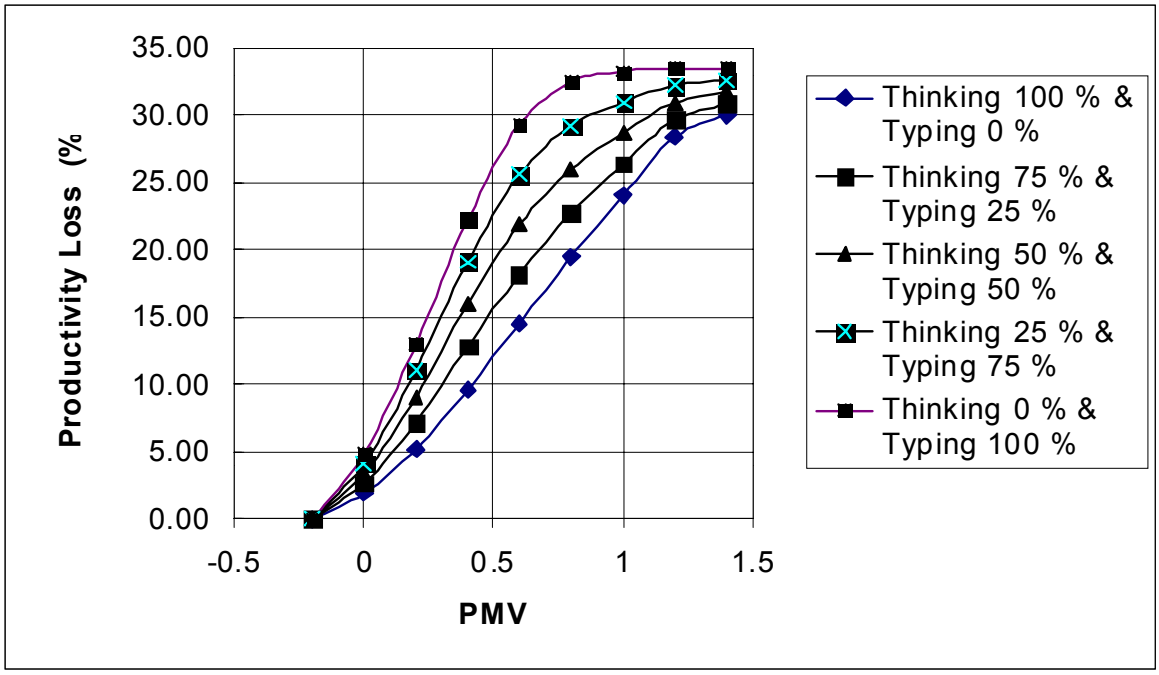

Figure 1 Productivity loss as a function of PMV for different combination of tasks.

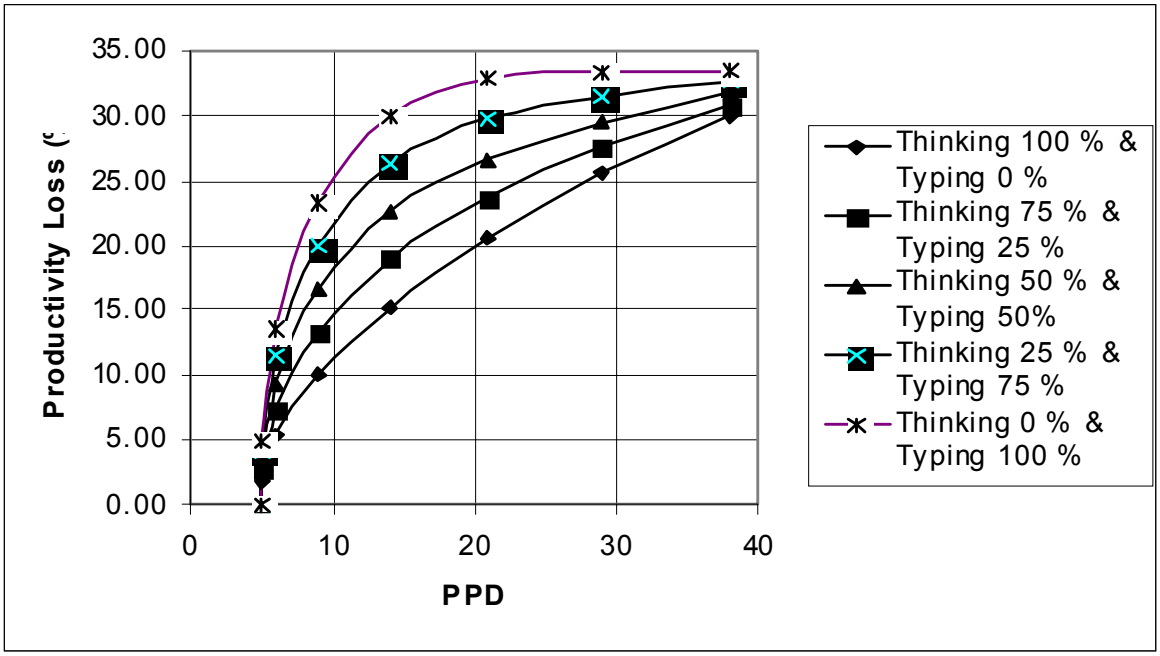

Figure 2 Productivity loss as a function of PPD for different combination of tasks.

Impact of Temperature Change from Different Neutral Temperatures on Productivity

The comfort range decrease when the neutral room temperature rises up. Normally, the acceptable thermal range of PMV index is adjusted to be between –0.5 and + 0.5. In tandem with the acceptable PMV range, the respective neutral temperatures of 21, 23 and 25°C would

produce a temperature range of +2.5, +2.0 and +1.5°C, respectively. This condition is only valid when all other parameters are constant.

Figures 3 and 4 show the decline of productivity at the different neutral temperatures for thinking and typing tasks, respectively. The envisaged productivity for typing tasks will decline to 70% when the temperature difference between room temperature and neutral temperature is 3°C. For thinking tasks, the tolerance threshold is higher than that of typing tasks. The temperature difference for a 30% productivity loss is 4–6°C depending on the neutral temperature.

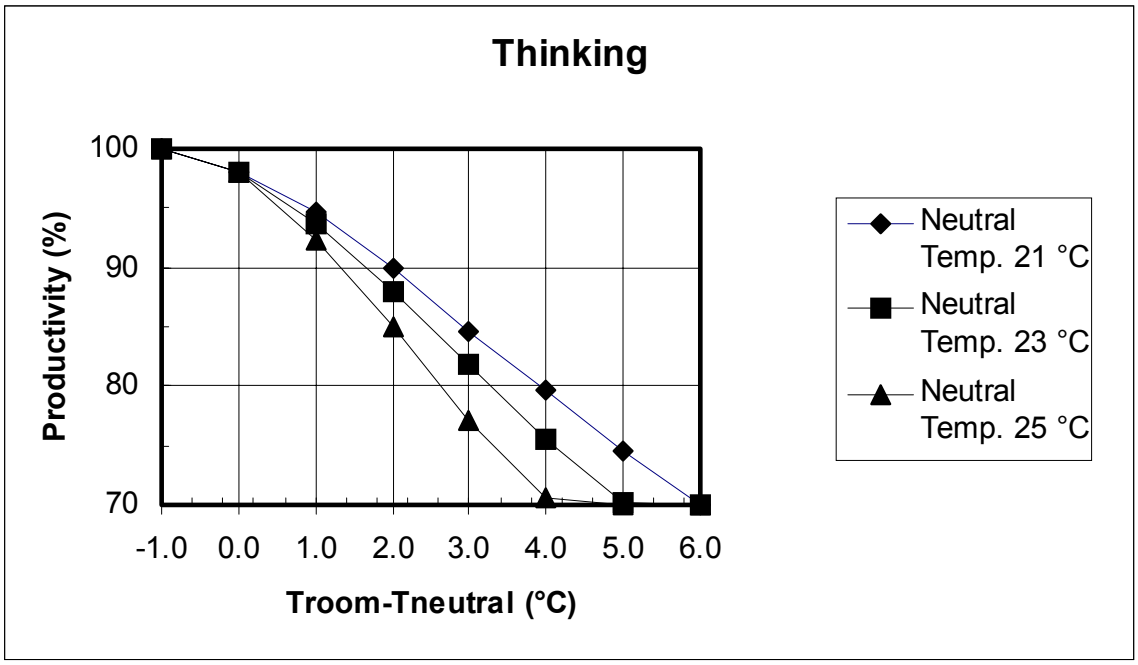

Figure 3 Neutral temperatures and their impact on productivity for a thinking task.

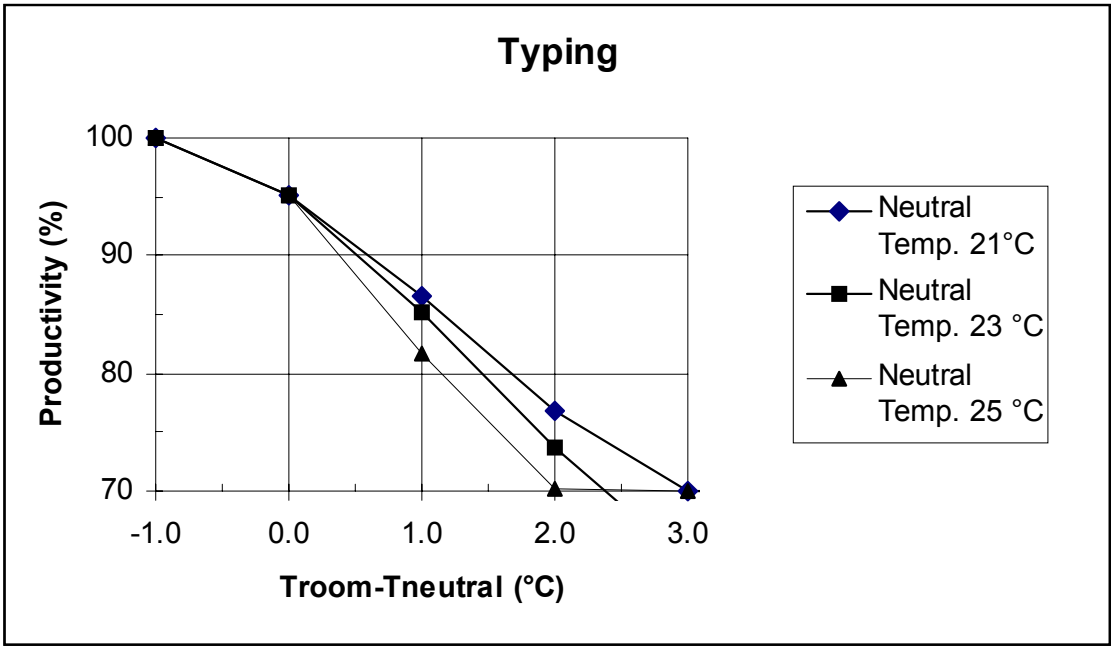

Figure 4 Neutral temperatures and their impact on productivity for a typing task.

DISCUSSION

Based on the model, the numerical value of the productivity loss in thinking is somewhat close to the PPD value. In typing tasks, the productivity loss is even two times higher than PPD value when PMV is less than 0.65. This indicates that the productivity could decrease quite significantly when people are coming more dissatisfied for their thermal environment.

The accepted range of the PMV is normally between –0.5 and 0.5. It should be noted that based on the productivity model this normally accepted PMV value of +0.5 leads about 12% productivity loss in thinking and 26% loss in typing.

The level of the neutral temperature is an important factor. The rate of the productivity change is strongly dependent on the level of the neural temperature when the room temperature will change. This means that temperature changes affect more productivity at higher neutral temperature levels and the effect of the temperature rise is not constant for the productivity.

The current PMV estimation is based on the causal relationship between temperatures and productivity; but is limited to experiments that have been previously carried out. In that respect, more experiment data would be required to validate the model. In the model, the office work is described by using simple thinking and typing tasks. The challenge here is to describe the nature of office work that is naturally more diversified. Also, the test chambers findings may not be directly applicable to the real office environment.

The previous studies have estimated that when the room temperature will reach certain level, the productivity has been assumed to be constant. Also, the true implication in air-conditioning buildings in hot-and-humid tropical climates remains relatively unknown. These assumptions and concerns should be verified in the future studies.

CONCLUSIONS

Using the developed model, the theoretical maximum level of productivity occurs when the PMV value is –0.21. Admitting a 30% productivity loss in typing task, the model predicts PMV value ought to be at least +0.63. In a similar case, in thinking-task, the model predicts a higher PMV value of +1.28. The rate of the productivity change is strongly dependent on the level of the neutral temperature when the room temperature will change. For the productivity loss of 30%, the difference in temperature range can be a small margin of 2–3°C in typing tasks and a wider range of 4–6°C in thinking tasks depending on the level of the neutral temperature.

ACKNOWLEDGEMENTS

The respective co-authors also wish to acknowledge the past support coming from the Finnish Technology Agency (TEKES) and CapitaLand, respectively. The authors thank Dr David Wyon for many insightful comments on this work.

REFERENCES

Wood, J.E. (1989). Cost avoidance and productivity in owning and operating buildings, *Occupational Medicine* **4** (4), 753–770.

Wyon, D.P. (1996a). Individual microclimate control: required range, probable benefits and current feasibility. *Proceedings of Indoor Air '96*, Institute of Public Health, Tokyo.

Wyon, D.P. (1996b). Indoor environmental effects on productivity. *IAQ 96 Paths to Better Building Environments*, Keynote address, Y. Kevin. Atlanta, ASHRAE, pp. 5–15.

Wyon, D.P., Fanger, P.O., Olesen, B.W., Pedersen, C.J.K. (1975). The mental performance of subjects clothed for comfort at two different air temperatures. *Ergonomics* **18**, 358–374.